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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
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<tbody>
<tr>
<td>FE</td>
<td>Finite Element</td>
</tr>
<tr>
<td>PCVD</td>
<td>Plasma Enhanced Vapour Deposition</td>
</tr>
<tr>
<td>APPCVD</td>
<td>Atmospheric Pressure Plasma Enhanced Vapour Deposition</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>EDX</td>
<td>Energy Dispersive X-ray</td>
</tr>
<tr>
<td>FTIR</td>
<td>Fourier Transform Infra-red Spectra</td>
</tr>
<tr>
<td>CSF</td>
<td>Coefficient of Static Friction</td>
</tr>
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<td>Dyneema® Yarn Based Model</td>
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<tr>
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<td>Ultra-high Molecular Weight Polyethylene</td>
</tr>
<tr>
<td>S.D.</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>C.V.</td>
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ABSTRACT

Manufacturing more reliable and lighter body armour using the fabrics with high-performance fibres is the development trend of ballistic protection device. However, increasing the reliability of the body armour normally needs to increase weight. This investigation aims to develop better ballistic performance of body armour without affecting weight. Inter-yarn friction in quasi-static state in fabrics constructed for body armour is one of the important factors affecting ballistic performance. This research focuses on increasing inter-yarn friction by surface modification methods for superior ballistic protection of woven fabrics. Finite element (FE) simulation is employed to analyse the effects of inter-yarn friction on ballistic performance theoretically. Both APPCVD and sol-gel methods are used to achieve the purpose of practically increasing inter-yarn friction. Ballistic experiments are conducted to evaluate ballistic performance of the fabrics with different levels of inter-yarn friction after treatments.

Through both numerical and experimental investigation, it is confirmed that increasing inter-yarn friction in quasi-static state can improve ballistic performance of fabrics. The overall energy absorption will be increased with the increase of inter-yarn friction because higher inter-yarn friction generates higher resistance to the projectile, makes fabric structure more stable, leads to more involvement of the secondary yarns and increases both KE and FDE percentages. Moreover, higher levels of inter-yarn friction will flatten the trauma and make the fabric response more globalised owing to the less transverse deflection ability. However, over high inter-yarn friction is counterproductive because of stress concentration on the primary yarns.

For the surface modification, one of the aramid yarns, Twaron® yarn and one of the UHMWPE yarns, Dyneema® yarn, and their fabric products are used as the substrates. SEM analyses are used to characterise the morphology changes. Both FTIR and EDX analyses are conducted to identify the coated substance. Based on coefficients of friction test and yarn pull-out test, the APPCVD treatment and sol-gel treatment have been proved as two effective ways to increase inter-yarn friction and at the same time the tensile properties of the yarns and the weight are almost unaffected.

Moreover, sol-gel treatment has been established as an effective method for improving ballistic performance without significant weight increase, where the energy absorption of the Dyneema® fabric can be increased by 6.74%, and the trauma depth can be decreased by16.99% for Twaron® fabric panel and by10.73% for Dyneema® fabric panel.
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ACKNOWLEDGEMENTS

I would like to express my very great appreciation to my supervisor Dr Xiaogang Chen for his valuable and constructive suggestions during the planning and development of this research work. His willingness to give his time so generously has been very much appreciated. I also would like to thank him for the enthusiastic encouragement and useful critiques as well as for allowing me to grow up as a research scientist.

I also would like to thank my employer Zhongyuan University of Technology for the financial support and allowing me the three years’ time for my PhD study at the University of Manchester.

I am also grateful to DSM for providing Dyneema® yarns and Teijin Aramid for providing Twaron® yarns for this research. Prof. David Sheel and Dr John Hodgkinson of University of Salford collaborated with us for APPCVD treatment, which is greatly appreciated.

My gratitude is also extended to Mr Adrian Handley for the support in mechanical test, to Mr Thomas Kerr and Mr Mark Chadwick for assistance in weaving the fabrics, to Mr Phillip Cohen and Mr David Kenyon for their help in Dye House, to Ms Xiangli Zhong and Mr Teruo Hashimoto for the high resolution of SEM imaging.

Special thanks should be given to the previous colleagues Dr Ying Wang and Dr Yi Zhou, for their assistant in studying the Abaqus software and extended to Dr Zhaoquan Du and Dr Binjie Xin for their helps in useful discussions and to Mr Weihong Gao for guiding me to measure the sizes of particles in liquid. I also thank to Ms Shengnan Min, Mrs Yanfei Yang, Ms Weiwei Jia for their assistant in the experimental work. I am extremely obliged to the friendly talk and sincere care from Ms Nang Wang, Ms Yue Xu, Mr Haoxian Zeng, Mrs Jowan, Mr Zishun Yuan and Mr Yuan Chai.

Finally, a special thanks to my family. Words cannot express how grateful I am to my grandmother, mother, father and younger sister for giving me the emotional support and taking care of my child when I stay in Manchester. At the end I would like to express a grateful appreciation to my beloved husband Mr Long Gao who was always my support.
in the moments when there was no one to answer my queries and share my happiness and sadness in hardship.
PUBLICATIONS


2. Yanyan Chu, Xiaogang Chen, Qing Wang, Shizhong Cui, An investigation on sol-gel treatment to aramid yarn to increase inter-yarn friction, Applied Surface Science, 2014(320):710-717

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4. Xiaogang Chen, Yanyan Chu, Nan Wang, Study on inter-yarn friction and engineering of ballistic fabrics, Proceedings to 14th AUTEX World Textile Conference, 26th to 28th May 2014, Bursa, Turkey

5. Xiaogang Chen, Yanyan Chu, Nan Wang, Inter-yarn friction and engineering of woven fabrics for ballistic protection, Proceedings to the 7th Cross-Strait Symposium on Textile Science and Technology, 5th to 10th May 2014, Fujen University, Taipei, Taiwan


7. Xiaogang Chen, Yanyan Chu, A mechanism-based study and the engineering of ballistic fabrics and ballistic panels, a chapter for a Elsevier book, Advanced Fibrous composite materials for ballistic protection, Edited by Xiaogang Chen, to be completed
Chapter 1 Introduction

1.1 Background

Human beings have been confronted with greater threats and disasters since the invention of firearms\(^1,\)\(^2\). In World War I and World War II, thousands of people lost their lives or were injured due to insufficient body protection. After the two world wars, although no large-scale wars occur, the regional wars and conflicts, for example Iraq war, Syrian conflict and so on, still continue to happen, causing numerous deaths\(^3\). Additionally, due to potential and uncertain threats at any time coming from terrorist incidents, leaders of a country, policemen, and law enforcement officers need to take precautions against such threats. Consequently, it is imperative to develop and manufacture better ballistic body armour to save more lives.

The performance of body armour is largely dependent on used materials. Throughout the whole history of human civilisation, people are always trying to seek better materials to protect themselves from injured. With the application of firearms, the traditional protective devices for weapons like swords, spikes and arrows no longer work for firearms. A large number of steel plates were initially manufactured as protective shields to firearms. With the development of new materials, alloy and ceramic materials started to be extensively adopted in ballistic body armour. The body armour constructed from the hard plates using these materials is termed as hard body armour which perform satisfactorily in protection. However, it is heavy and bulky. Wearers, who are equipped with such armour, cannot move flexibly in battle, not to mention for daily life protection to policemen or leaders of the country.

As such, seeking for lighter and reliable body armour attracts more attentions. The fibre materials become the candidates for manufacturing soft body armour because of their light weight. Cotton, silk, and polyamide fibres were used as ballistic materials. However, their properties, especially the mechanical properties are inadequate. It was the late 1960s when the Kevlar® fibre was developed by DuPont a new era for soft body armour was ushered, making the idea of manufacturing lighter, more reliable and more
comfortable soft body armour possible because Kevlar® fibre has higher strength but lower weight\cite{4}. Subsequently, other types of high-performance fibres appeared in succession.

The fibres as candidates used in ballistic application are mainly divided into three groups\cite{1, 2}, aramid fibre, ultra-high molecular weight polyethylene (UHMWPE) fibre and poly($p$-phenylene benzobisoxazole) (PBO) fibre. Their structures are shown in Figure 1-1. Aramid is a fibre family containing long benzene ring chains bonded by amide linkage. The commercial products used as ballistic materials are Kevlar® and Twaron® fibres. UHMWPE, an ultra-high strength polyethylene fibre, is obtained from the gel-spun manufacturing technology. It is firstly commercialised by Honeywell. Spectra® and Dyneema® are two common commercial names. PBO fibre is a polymer with aromatic heterocyclic rings.

![Chemical structures of Aramid, UHMWPE, and PBO fibres](image)

Figure 1-1 The chemical structures (a) Aramid fibre (b) the UHMWPE fibre (c) PBO fibre\cite{5}

The tensile properties of these three types of fibre are shown in Table 1-1. Among these three, PBO fibre is the strongest, but it is likely to be degraded under synergistic action of heat and moisture\cite{6}. Therefore, the other two types of high-performance fibres, aramid fibres and UHMWPE fibres, are more extensively used in manufacturing soft body armour.
Two mature manufacture methods are currently employed\cite{1,2}. One is to use resin to adhere the fibres together and form a unidirectional cross-plied nonwoven shield, commonly abbreviated as unidirectional shield (UD) or termed as armour-grade composite. Spectra® UD and Dyneema® UD are the products. The other one is woven fabric. It employs the traditional weaving technology to fabricate yarns into a fabric. Typically, soft body armour is constructed by either multiple layers of UD fabrics or woven fabrics. In the light of mature weaving technology, easy processing, wearing comfort, body armour constructed from woven fabrics using high-performance yarns attracts more attentions from researchers.

### 1.2 The problems

Generally, the hard body armour with ceramic plates or metal plates can provide more protection than soft body armour, but it is heavier and much more cumbersome. They are usually worn under high-risk circumstances. For routine use, soft body armour is appropriate and they can be worn like an ordinary shirt or jacket. Based on the current
technology, it was reported that the soft body armour requires 28-layer Kevlar\textsuperscript{®} fabrics to achieve level IIIA protection in NIJ standard\[11\]. It is still very heavy and very bulky. As soft body armour, they should satisfy both requirements, reliability and light weight. However, the ballistic performance of soft body armour is related to its areal density. In other words, increasing the reliability commonly means the weight will increase as well. Nevertheless, the trend of development of the daily used armour is to manufacture more reliable soft body armour with lighter weight.

Currently, fibre materials for soft body armour are limited to two types of fibres, the aramid fibre and the UHMWPE one. It seems impossible to develop other higher-performance ballistic materials in a short time. It would be more practical that the soft body armour becomes lighter without affecting the reliability, or the ballistic performance increased with the weight unchanged. In order to increase ballistic performance without affecting the weight of the armour, controlling the factors affecting ballistic performance would be a route. Inter-yarn friction in quasi-static state has been regarded as one of the important factors in a fabric subjected to ballistic impact\[8,9\], and increasing inter-yarn friction shows positive influences on ballistic performance based on previous investigations \[10-20\]. However, the inter-yarn friction in the fabrics made from both aramid and UHMWPE yarns are relatively low.

Higher inter-yarn friction in the fabrics can be achieved through introducing gripping insertion\[17,21,22\] and surface modification\[10,23-35\]. The present investigation focuses on surface modification of fabrics for increasing inter-yarn friction. It is essential that the weight should be unaffected in improving ballistic. However, the previous researchers either pay little attention to this aspect such as, Brisco and Motamedi\[10\], or the treatment methods significantly increase the weight of fabrics, such as natural rubber coating\[24\] and the shear thickening fluid (STF) method\[25-35\]. In addition, the inter-yarn friction should not be over high because over high inter-yarn friction will reduce energy absorption. The general chemical finishing used by Hearle \textit{et al.}\[23\] would increase the inter-yarn friction beyond the optimal value. Hence, other surface modification methods should be developed.

In addition, although the positive influences of inter-yarn friction have been observed,
the mechanism for improving ballistic performance of the fabrics with higher inter-yarn friction is still not clear. For the effects of inter-yarn friction on the ballistic performance, most of the investigations concentrated on the energy absorption behaviours of the fabrics, the effects of inter-yarn friction on the trauma in non-perforation test were usually ignored.

1.3 Aims and objectives

The aim of the present research is to improve ballistic performance of fabrics without affecting weight. To achieve this aim, three parts of work need to be carried out. The first part focuses on FE simulation of the effects of inter-yarn friction on ballistic performance. The objectives for the first part are presented below:

1. To establish and validate FE model for a projectile-fabric system for theoretical analyses;
2. To theoretically uncover the mechanism of inter-yarn friction in quasi-static state on ballistic performance and build up the relationship between them;
3. To provide guidelines for practically increasing inter-yarn friction to improve ballistic performance.

The second part concentrates on practically increasing inter-yarn friction by two surface modification methods, one being atmospheric pressure plasma-enhanced chemical vapour deposition (APPCVD) and the other sol-gel method. The objectives in this part are:

1. To develop APPCVD and sol-gel treatment processes for modification of the fibre surface;
2. To identify the surface changes of fibres after treatments by FTIR, EDX and SEM analyses and understand how parameters associated with the two treatments affect the inter-yarn friction;
3. To evaluate the effects of two surface modification methods with respect to inter-yarn friction, yarn weight and yarn tensile properties.

The last part is about empirical investigation of the effects of inter-yarn friction in quasi-static state on ballistic performance. The objectives are as follows:
(1) To evaluate inter-yarn friction in fabrics after treatments by quasi-static yarn pull-out test;
(2) To test perforation performance and non-perforation performance of fabrics with different levels of inter-yarn friction by ballistic impact experiment;
(3) To establish the relationship between inter-yarn friction in quasi-static state and ballistic performance with regard to energy absorption and blunt trauma empirically;
(4) To verify the effects of inter-yarn friction on ballistic performance from FE analyses in comparison with those from empirical investigation;
(5) To evaluate the effects of surface modification on ballistic performance.

1.4 Thesis layouts

The whole thesis is divided into eight chapters:
Chapter 1 is about the research background, the main problems to be addressed, the aims and objectives as well as the thesis layouts.

Chapter 2 is the literature review. The investigations about the fabric subjected to ballistic impact and the work related to the effects of the inter-yarn friction on the ballistic performance will be reviewed. At the end of the chapter, the methods to increase the inter-yarn friction will be proposed.

Chapter 3 is the introduction of the main methodologies used in this investigation, including ballistic test, finite element (FE) modelling approach, methods of coating characterisation, coefficients of friction test and weight add-on test.

Chapter 4 presents FE analyses of the effects of inter-yarn friction on ballistic performance during the event of a single-layer fabric subjected to ballistic impact.

Chapter 5 is about the application of the APPCVD treatment method for improving the inter-yarn friction.

Chapter 6 is about the surface modification of the yarns by sol-gel method for increasing
inter-yarn friction.

Chapter 7 is the investigation on evaluation of ballistic performance of fabrics with different levels of inter-yarn friction by both perforation and non-perforation tests.

Chapter 8 is the conclusions of the whole work and the inadequacies for the future investigation.
Chapter 2 Literature Review

To improve ballistic performance of soft body armour constructed from woven fabrics, it is imperative to get thorough understanding of the progress in the research field of fabric behaviours upon ballistic impact. The progress would be reviewed in the following parts, wave propagation in a fabric under ballistic impact, evaluation methods for ballistic performance of the fabric, available research approaches and the factors affecting ballistic performance. Since the main purpose of this research is to increase inter-yarn friction for improving the ballistic performance, the previous numerical work and empirical work about effects of inter-yarn friction on ballistic performance would be reviewed in detail. At the end of this chapter, the methods available to increase the inter-yarn friction will be proposed.

2.1 Wave propagation under ballistic impact

Woven fabrics with high-performance fibres or yarns for soft body armour application attract more attention owing to their reliable ballistic resistance, lightweight and comfort. Improving the quality of soft body armour constructed from woven fabrics requires full understanding of the wave propagation during the ballistic impact process. A bullet or projectile striking a piece of fabric is a complex physical process because of the instantaneity of impact process and the complexity of fabric structure. The better cognition of wave propagation manifested in ballistic impact would start from a single yarn subjected to ballistic impact.

2.1.1 Wave propagation in a yarn

Many researchers have covered the field of investigating a single yarn transversely impacted by a high-speed projectile. Smith et al.\cite{36} developed the theory for describing the transverse impact on a single yarn. Morrison\cite{37} tried to verify the accuracy of Smith’s equation through using computer simulation methods, and they found that the
two methods agreed in all given cases. The mechanics of a yarn impacted by a bullet have been described in the work done by many researchers, such as Lynch et al.\[^{38}\], Roylance et al.\[^{39}\], Cunniff et al.\[^{40}\] and Cheeseman and Bogetti\[^{41}\]. When a single yarn is subjected to ballistic impact, a tent-shaped transverse deflection develops in the yarn because the yarn is forced to have a forward movement with the projectile. Simultaneously, a longitudinal wave gradually builds up in the yarn and rapidly propagates away from the impact centre at the velocity of sound in the material, travelling in the direction of the axis of the yarn. In the longitudinal wave front, the yarn material is set in motion inwardly toward the impact centre due to the stretching. The inwardly flowing material continues to feed the advancing transverse deflection until the strain in the yarn reaches its breaking strain. The responses of a yarn subjected to ballistic impact is illustrated in Figure 2-1. The existence of longitudinal wave propagation in the yarn has been corroborated by Stewart et al.\[^{42,43}\] and the velocity of it has been measured by Freeston et al.\[^{44}\].

According to the theoretical work done by Smith\[^{36}\], the behaviours of a single yarn subjected to ballistic impact are governed by the following equations. If the yarn is elastic, Equation 2-1 can be simplified as Equation 2-2.

\[
C(\varepsilon) = \sqrt{\frac{1}{\rho} \frac{d\sigma}{d\varepsilon}} \quad (2-1)
\]

\[
C = \sqrt{\frac{E}{\rho}} \quad (2-2)
\]

\[
u_{lag} = C \frac{\varepsilon}{\sqrt{(1+\varepsilon)}} \quad (2-3)
\]

\[
u_{lab} = C (\sqrt{\varepsilon(1+\varepsilon)} - \varepsilon) \quad (2-4)
\]
\[ V = C \sqrt{2\varepsilon \varepsilon (1 + \varepsilon)} - \varepsilon^2 \]  

(2-5)

where \( C \) is longitudinal wave velocity; \( E \) is fibre tensile modulus and \( \rho \) is yarn density; \( u_{lag} \) is the transverse wave velocity in Lagrangian coordinate, which is the coordinate used in fluid dynamics in which the coordinate is fixed to a given parcel of fluid, but moves in space. \( u_{lab} \) is the transverse wave velocity in laboratory coordinates; \( \varepsilon \) is the strain level between strain wave front and point of impact; \( \sigma \) is stress; \( V \) is impact velocity.

### 2.1.2 Wave propagation in a fabric

Normally, yarns in a fabric are divided into primary yarns (or principal yarns) and secondary yarns according to their relative positions to the projectile, as depicted in Figure 2-2. The yarns directly contact with the projectile are termed as primary yarns and the others are defined as secondary yarns. Cheeseman \textit{et al.}\textsuperscript{[41]} and Cunniff\textsuperscript{[40]} noted that the responses of a fabric to the ballistic impact have some similarity to that of the single yarn. When a projectile strikes a single-layer fabric, analogously, the impact produces the transverse deflection in the primary yarns and the longitudinal wave, propagating away from the impact centre along the axes of the primary yarns\textsuperscript{[40]}. At the same instant, the secondary yarns, intersecting with the primary yarns away from the impact centre, are then driven out of the original fabric plane by the primary yarns to different extents depending on the distances between the secondary yarns and the impact centre. These secondary yarns experience a deformation and develop a strain wave like those in the primary yarns, and these secondary yarns then pull yarns with which they interlace. These yarn–yarn interactions, which by nature are a function of inter-yarn friction and introduced by the woven structure, force the secondary yarns to engage in the transverse deflection. The transverse deflection proceeds until the strain of the yarn at the impact centre rises up to the breaking strain\textsuperscript{[41]}. Figure 2-3 describes the responses of a fabric subjected to a high-velocity impact by a spherical projectile. Due to the increased linear density at the crossovers, the longitudinal wave velocity in the yarns in a woven fabric structure was found slower than the expected value in a single yarn subjected to ballistic impact by a factor of \( \sqrt{2} \textsuperscript{[45]} \).
2.2 Evaluations of ballistic performance

As the investigation of ballistic impact progresses, the evaluation methods used for assessing ballistic performance of body armour have been established as well. According to the requirements of ballistic soft body armour, there are three test methods frequently
used. They are perforation test, non-perforation test and ballistic limit test. These three methods are applied to evaluate the different aspects of ballistic performance. The perforation test is mainly to assess energy absorption. The non-perforation test is to assess the blunt trauma caused by the deformation of the soft body armour during actual application. Ballistic limit test aims to evaluate the limit of ballistic performance, in other words, the pass or fail performance.

2.2.1 Perforation test

The perforation test is described by that a projectile or a bullet fully getting through a testing target during the impact process. In the perforation test, the impact velocity and the residual velocity can be measured. Thus, variation in projectile energy loss can be calculated from these two velocities\(^ {46-50}\), as shown in Equation 2-6. In order to compare the projectile energy losses of panels with different weights, an indicator of total energy loss divided by the areal density of the fabric panel is also used.

\[ \Delta E = \frac{1}{2} m (v_i^2 - v_r^2) \]  

(2-6)

where \( \Delta E \) is projectile energy loss; \( m \) is the mass of a projectile; \( v_i \) is impact velocity, and \( v_r \) is residual velocity.

Without any other external force action and without considering energy loss by heat, intermolecular friction, air resistance, acoustic energy and so on, the projectile energy loss can be assumed to be fully absorbed by the fabric based on the law of energy conservation. The energy dissipation in the fabric takes place mainly in three ways\(^ {12-15, 51-53}\) : (i) kinetic energy due to the movement of the fabric caused by longitudinal wave and transverse wave; (ii) strain energy due to the deformation of yarns stressed; and (iii) frictional dissipation energy because of inter-yarn friction. The energy transfer between the projectile and fabric can be simply described in the following equation:

\[ E_p = E_f = E_{KE} + E_{SE} + E_{FDE} \]  

(2-7)

where \( E_p \) means projectile energy loss; \( E_f \) means energy absorption of a fabric; \( E_{KE} \)
means kinetic energy (KE); $E_{SE}$ indicates strain energy (SE); $E_{FDE}$ represents frictional dissipation energy (FDE).

### 2.2.2 Non-perforation test

The non-perforation test is used to understand ballistic resistance of soft body armour in real situations. Normally, in the test, a fabric panel is positioned on the surface of a backing material, which is made of oil-based clay and used for simulating human skin. After impacting, a hole would be left on the surface of the backing material due to the transverse deflection of the panel. The hole is an indication of blunt trauma brought to a wearer, which is also harmful to the wearer. Although the fabric deflection is a manner to dissipate the projectile energy, it is still anticipated that the fabric would transversely deflect as little as possible at the end of impacting.

The blunt trauma of a fabric panel is usually evaluated by the depth of the hole, depressed on the backing material. The depth of the hole is measured from the plane defined by the front edge of the backing material fixture\(^{[54]}\) as shown in Figure 2-4. The measurements have been comprehensively described in the US National Institute of Justice (NIJ) standard\(^{[54]}\) and the Home Office Scientific Development Branch standard (HOSDB)\(^{[55]}\), both of which are widely used as trauma test models.

![Diagram of non-perforation test](image.png)

**Figure 2-4 Methods of measuring back-face deformation**

According to National Institute of Justice (NIJ) Standard 0101.04, ballistic armour is classified into seven levels as shown in Table 2-1. Type I, II A, II and IIIA offer
increasing levels of protection from handgun threats. Types III and IV armour are levels for measuring protection against high powered rifle rounds, which are intended for application only in tactical situations\textsuperscript{[54]}. The maximum deflection of a soft armour vest can undergo without perforation is 44 mm for all levels of ballistic threats\textsuperscript{[54]}. The apparatus for the test is shown in Figure 2-5.

Table 2-1 The NIJ Standard-0101.04 P-BFS performance test summary\textsuperscript{[54]}

<table>
<thead>
<tr>
<th>Armor Type</th>
<th>Test Round</th>
<th>Test Bullet</th>
<th>Bullet Weight</th>
<th>Reference Velocity (at 30 ft/s)</th>
<th>Hits Per Armor Part at 0° Angle of Incidence</th>
<th>BFS Depth Maximum</th>
<th>Hits Per Armor Part at 30° Angle of Incidence</th>
<th>Shots Per Panel</th>
<th>Shots Per Sample</th>
<th>Shots Per Threat</th>
<th>Total Shots Req’d</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
<td>22 caliber LR LRN</td>
<td>2.6 g 40 gr.</td>
<td>329 m/s (1000 ft/s)</td>
<td>4 - 44 mm (1.73 in)</td>
<td>2 - 6</td>
<td>12</td>
<td>24</td>
<td>48</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>380 ACP FMJ RN</td>
<td>6.2 g 95 gr.</td>
<td>322 m/s (1055 ft/s)</td>
<td>4 - 44 mm (1.73 in)</td>
<td>2 - 6</td>
<td>12</td>
<td>24</td>
<td>48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IIA</td>
<td>1</td>
<td>9 mm FMJ RN</td>
<td>8.0 g 124 gr.</td>
<td>341 m/s (1120 ft/s)</td>
<td>4 - 44 mm (1.73 in)</td>
<td>2 - 6</td>
<td>12</td>
<td>24</td>
<td>48</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>40 S&amp;W FMJ</td>
<td>11.7 g 180 gr.</td>
<td>322 m/s (1055 ft/s)</td>
<td>4 - 44 mm (1.73 in)</td>
<td>2 - 6</td>
<td>12</td>
<td>24</td>
<td>48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>1</td>
<td>9 mm FMJ RN</td>
<td>8.0 g 124 gr.</td>
<td>367 m/s (1205 ft/s)</td>
<td>4 - 44 mm (1.73 in)</td>
<td>2 - 6</td>
<td>12</td>
<td>24</td>
<td>48</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>357 Mag JSP</td>
<td>10.2 g 158 gr.</td>
<td>436 m/s (1430 ft/s)</td>
<td>4 - 44 mm (1.73 in)</td>
<td>2 - 6</td>
<td>12</td>
<td>24</td>
<td>48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IIIA</td>
<td>1</td>
<td>9 mm FMJ RN</td>
<td>8.2 g 134 gr.</td>
<td>436 m/s (1430 ft/s)</td>
<td>4 - 44 mm (1.73 in)</td>
<td>2 - 6</td>
<td>12</td>
<td>24</td>
<td>48</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>44 Mag JHP</td>
<td>15.6 g 240 gr.</td>
<td>416 m/s (1340 ft/s)</td>
<td>4 - 44 mm (1.73 in)</td>
<td>2 - 6</td>
<td>12</td>
<td>24</td>
<td>48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>1</td>
<td>7.62 mm NATO FMJ</td>
<td>9.6 g 148 gr.</td>
<td>838 m/s (2780 ft/s)</td>
<td>6 - 44 mm (1.73 in)</td>
<td>0 - 6</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>1</td>
<td>30 caliber M2 AP</td>
<td>10.8 g 166 gr.</td>
<td>809 m/s (2680 ft/s)</td>
<td>1 - 44 mm (1.73 in)</td>
<td>0 - 1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Special</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>* - 44 mm (1.73 in)</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2-5 Test range configuration\textsuperscript{[54]}

For the HOSDB standard, it is a method used for evaluating ballistic performance of body armour system for British Police, which is required to protect the human body sufficiently against both projectile perforation and blunt trauma. The number of the
ballistic performance level is five, including HG1/A, HG1, HG2, SG1 and RF1. The maximum indentation depth permitted from any test shot is 25 mm measured from the top edges of a steel tray containing the backing material except that the maximum indentation depth for HG1/A is 44 mm.

The depth of the hole is a simple indicator for the blunt trauma of a fabric panel\cite{24, 27, 56-60}. Other indicators are also developed to denote it. Karahan\cite{61} tried to regenerate the volume of the hole by Spline curve fitting technique. It may be suitable to regular hole formed on backing material. However, when it encounters irregular shape, it would fail. In most cases, the geometry of the hole left on the backing material is irregular. The energy absorbed by backing material is associated with the volume of the hole formed on the backing material. Due to the difficulty in measurement of the volume, the energy absorbed by the fabric in the non-perforation test is still difficult to obtain.

### 2.2.3 Ballistic limit test

To evaluate the fail or pass property of body armour in a ballistic impact event, ballistic limit test is applied. Ballistic limit designates a velocity at which a projectile completely perforates specific armour when hitting at a specified angle of obliquity. This velocity is named as ballistic limit velocity. It is the incident impact velocity for a specific projectile and target combination, which would lead to complete perforation of the target with the projectile tip reaching the back-face of the target with zero residual velocity\cite{2, 62}. Villanueva and Cantwell\cite{63} derived an equation for estimating the ballistic limit of laminates, expressed in Equation 2-8.

\[
V_b = \frac{\pi \tau \sqrt{\rho_t \sigma_e D^2 T}}{4m} \left(1 + \sqrt{1 + \frac{8m}{\pi \tau^2 \rho_t D^2 T}}\right)
\]  \hspace{1cm} (2-8)

Where \(V_b\) is ballistic limit, \(\tau\) is a projectile constant determined experimentally, \(\rho_t\) is the density of the laminate, \(\sigma_e\) is the static linear elastic compression limit, \(D\) is the diameter of the projectile, \(T\) is the thickness of the laminate, \(m\) is the mass of the projectile.

Due to the cost of ballistic impact tests, the impossibility of controlling impact velocity
exactly and the difficulty to distinguish complete perforation from partial perforation under apparently identical conditions, statistical approaches are necessary, based upon limited firings\[^{64}\]. Hence, \( V_{50} \) is commonly used instead of \( V_b \). \( V_{50} \) is defined as the average of equal number of highest partial perforation velocities and lowest complete perforation velocities for a specific projectile and target system, which occurs within a specified velocity range. In other words, \( V_{50} \) defines incident impact velocity at which there is 50% probability of partial and 50% probability of non-perforation.\[^{2,62}\]. The normal up-and-down firing procedure is applied. A 0.51 mm thick 2024 T3 sheet of aluminium is positioned 152 ± 12.7 mm behind and parallel to the target to witness complete penetrations. Normally, A minimum of two partial and two complete perforation velocities are used to compute \( V_{50} \). Four, six, and ten-round ballistic limits are frequently used. The maximum allowable velocity span depends on the armour material and test conditions and spans of 18, 27, 30 and 38 m/s are commonly used\[^{64}\]. In addition, Nilakantan et al.\[^{16}\] attempted to approximate the complete perforation velocity and no complete perforation velocity. They derived two ballistic limit velocity, \( V_1 \) and \( V_{99} \), for evaluating the ballistic limit performance of almost non-perforation impact and almost perforation performance respectively with consideration of the probabilistic nature. The method for calculating \( V_1 \) and \( V_{99} \) are shown in Equation 2-9 and Equation 2-10 respectively.

\[
V_1 = \delta - 2.3263\gamma \tag{2-9}
\]
\[
V_{99} = \delta + 2.3263\gamma \tag{2-10}
\]

Where \( \delta \) represents the \( V_{50} \) velocity and \( \gamma \) means standard deviation of the cumulative normal distribution.

### 2.3 Research approaches for ballistic textiles

It is understood that impacting the fabric in the transverse direction with a high-velocity projectile is a dynamic, complicated and instantaneous physical process. It is far different from the quasi-static mechanical action. Currently, three methodologies are frequently adopted in the analysis of this complex physical phenomenon: empirical, analytical and numerical. These three approaches can be applied individually in research
or combined to provide more understandings about the damage and failure mechanism of the fabric subjected to ballistic impact.

### 2.3.1 Empirical approach

Empirical methodology usually acquires the first-hand data based on a certain experimental design and the device provided. Through analyses of data, the response characters of a fabric can be examined and the constitutive relations can be established. The analysis process may consist of curve fitting, nonlinear regression analysis of experimental data, and the use of statistical distributions\(^{[11]}\). It is powerful and useful when a few numbers of variables are to correlate to\(^{[65-70]}\). Majumdar et al.\(^{[28, 29]}\) and Park et al.\(^{[25, 26]}\) used it to investigate the ballistic performance of treated fabrics. However, the disadvantage is also obvious for that it is a time consuming and material costly process. Additionally, the accuracy of the obtained results to a large degree depends on the correctness and completeness of collected data.

### 2.3.2 Analytical approach

Analytical methodology is mainly from a physical perspective and relies on general mechanic laws to set up governing equations using various parameters involved in the ballistic impact process. In the analysis, the whole process is divided into \( n \) steps by a small increment of time. At the first increment, the equations are usually derived based on energy conservation, impulse theory and Newton’s second law. Analogously, step by step, until the ultimate time, all the equations at every time increment are derived.

Up till now, numerous researchers devoted themselves to making contribution to this field and applied this method to provide insight into the mechanism of damage and failure of a fabric in the impact event\(^{[36, 71-83]}\). The results predicted by this method are usually validated by comparing with experimental results. Compared with the empirical method, the analytical method consumes fewer materials and relies on less labour. However, it needs complete understanding of ballistic impact process. Additionally, in order to simplify the process, some of the parameters tend to be neglected. Inter-yarn friction are one of those factors. The truth is that the inter-yarn friction plays a
significant role in energy absorption during the impact\textsuperscript{12, 13}.

### 2.3.3 Numerical approach

Over the previous decades, continuing efforts are made to reduce the extent of experimental test programs. Investigation about ballistic impact is developing towards the direction of simulating. Owing to the advent of the computer, study of ballistic impact with computer-based analyses and simulations is possible. The numerical investigation is an investigation approach on the basis of the Finite Element (FE) theory and commercial computer software, such as Abaqus, Ansys and LS-DYNA, to establish projectile-fabric simulation model for elucidating the mechanism behind a fabric subjected to impact. FE theory is better suited to analyse dynamic mechanic problems and a bullet striking a piece of fabric is rightly a dynamic mechanics problem. The conception of FE theory is that the integrity is divided into limited and small units, which is called mesh, and the displacement, strain and stress of individual mesh are computed step by step when loaded. Eventually, varieties of stress and strain experienced by a yarn can be acquired. It is an efficient and effective approach because the complex and instantaneous process would be converted into a controllable and visual process through the simulation. Consequently, a large number of researchers started to investigate ballistic behaviours of fabrics using FE simulation.

For the modelling, the difficulty lies in how to model fabric structure. Up till now, three mature methods are commonly used, and they are pin-jointed model, full 3D model and mesoscale unit-cell based model. The creation of a numerical model of any structural system directly depends on the success in capturing characteristics of its essential components. There are two views about fundamental elements of the fabric. One is from the view of textile woven technique, regarding that the fabric is constructed by warp and weft yarns. The pin-jointed model and full 3D continuum model fall into this category. Alternatively, the fabric is regarded as an assembly of crossovers. The unit-cell based model is the example of this conception.
2.3.3.1 Pin-jointed model

Due to the limitation of the computer in the past two decades, a fabric is firstly modelled as constructing from simple pin-jointed rods, named as the pin-jointed model. It models a fabric as a two-dimensional assembly of pin-jointed yarns, resulting in a net-like structure, as shown in Figure 2-6. Discrete nodal masses are located at the crossings of yarns and the masses are inter-connected by cable (string) elements in orthogonal in-plane directions representing warp and weft yarns of the fabric\[84\]. For a balanced plain-woven fabric, the geometry of it can be completely described by two parameters: the distance $L_0$ between neighbouring nodes on a yarn and the distance $L_1$ between a pair of nodes at a crossover point. $L_0$ can be determined by the thread density along warp/weft directions and $L_1$ can be obtained from the fabric thickness\[85\], as shown in Figure 2-6.

![Figure 2-6 Pin-jointed model for the fabric\[85\]](image)

The model was firstly established by Roylance and Wang\[86\]. Zeng et al.\[85\] carried out an investigation on effects of different boundary conditions on a fabric subjected to ballistic impact based on this model. Billon and Robinson\[76\] compared the results between a pin-jointed model and an analytical model developed in their research. Shim et al.\[48\] considered the viscoelastic responses in the model. Novotny et al.\[84\] extended the model to multi-layer for investigation of multi-layer fabric behaviours in the ballistic impact process. Meanwhile, other researchers tried to make some improvements to achieve higher accuracy of the model. Cuniff team\[87, 88\] refined it by representing the crossover by two nodes, which allowed the bending and the orthotropic properties of the yarn at nodes to be taken into account. Termonia\[89\] introduced the slippage into the model and Tan et al.\[90\] considered the crimp of a yarn in the model.
The pin-jointed approach has the unquestionable advantage of efficiency in predicting general dynamic behaviours of woven fabrics subjected to ballistic impact, particularly, for the multi-layer and the full target analysis. However, the discrete nature of the hinged lattice model makes it more susceptible to wave oscillations during wave propagation. In addition, absence of details associated with yarn geometry and weave architecture make it ineffective to incorporate yarn-yarn contact conditions and layer-layer contact in multi-layer fabrics. Furthermore, the discrete nature of the model also leads to difficulties in simulating yarn pull-out mechanism, which has been found as an important mechanism for energy absorption during ballistic impact\cite{8,9}.

2.3.3.2 3D continuum model

The pin-jointed model has advantages with respect to prediction of the global response of a fabric system. However, an apparent limitation of this model is that the yarn geometry is ignored. As such, a more detailed modelling technique, 3D continuum model, has been developed. It is able to capture the precise geometry of each yarn and allow each yarn to be assembled into a fabric, as shown in Figure 2-7. Shockey et al.\textsuperscript{91,92} firstly attempted to use this model to explicitly simulate individual yarn and combined them to form a fabric. Based on 3D modelling method employed in Shockey’s investigation, Duan et al.\textsuperscript{13,53} studied the influences of inter-yarn friction on the time history of energy absorption of a single-layer fabric. This modelling method has also been used by Rao et al.\textsuperscript{20}, Talebi et al.\textsuperscript{93} and Nilakantan et al.\textsuperscript{94-96}.

![Figure 2-7 The 3D continuum solid model\textsuperscript{13}](image)
With the advance of the computer, this model has been used by some researchers on more complicated fabric structure. Jin et al.\textsuperscript{[97]} applied this method to simulate the 3D interlock fabric for ballistic investigation. Chen et al.\textsuperscript{[98]} developed a 3D constitutive model to explore ballistic performance of hybrid fabric panel. However, although the modern computer is more powerful and runs faster than before, simulating the yarn geometry explicitly in the case of multi-layer fabric subjected to ballistic impact is also challenging by this modelling method. Hence, three techniques emerged and were used to balance the accuracy and the fineness of modelling resolution without significant increase of computational cost. They are: (1) replacing the 3D solid element with 2D shell element, (2) using hybrid elements, and (3) using coarse mesh.

The conception of replacing 3D solid element with 2D shell element is to ignore the thickness of a yarn because the yarn is so thin that it can be seen as a shell or a membrane. This conception can refer to the work of Grujicic et al.\textsuperscript{[99]} and Ha-Minh et al.\textsuperscript{[100]}. The hybrid element technique is developed because the main deformation mode of yarns located in the different areas of a fabric is different. In the impact centre, the yarns are subjected to more transverse effect such as compression, shearing and bending but in the area far from the impact centre, the yarns are less deformed. Thus, the impact centre is modelled with higher resolution and the areas away from the impact centre are with lower resolution. The work done by Barauskas et al.\textsuperscript{[101]} and Rao et al.\textsuperscript{[102]}, Jia et al.\textsuperscript{[103]}, and Nilakantan et al.\textsuperscript{[104, 105]} are examples of this technique. The coarse mesh method is to reduce the resolution of the mesh slightly to increase the computational efficiency. Chocron et al.\textsuperscript{[106]} used this approach and investigated ballistic performance of 10-layer full-size fabric and Zhou\textsuperscript{[52]} applied this technique to 8-layer fabric.

All in all, how to balance computational efficiency and computational accuracy is still a significant barrier in the field of ballistic impact investigation. To simulate the process of multi-layer fabric subjected to non-perforation is still a problem. Recently, Shen et al.\textsuperscript{[107]} in their research employed the numerical method to investigate the interaction among bullet, body armour and human organ targets. Since the research is mainly concerned with the influences of different types of back material on armour back-face deformation, it simplifies the armour as several sheets of shell element. Obviously, it is insufficient to capture the behaviours of yarns.
2.3.3.3 Mesoscale unit-cell based model

To both account for yarn geometry and computation efficiency, meso-scale unit-cell based model is developed. The term mesoscale denotes yarn-level details about millimeter length scale of a fabric architecture. The unit-cell means the basic structural unit in a woven single-ply fabric. For example, the unit-cell representing a single-ply woven plain fabric structure is allotted to a single yarn crossover in its initial undeformed configuration. In the mesoscale unit-cell, the yarn geometry is taken into consideration as shown in Figure 2-8. The properties of the unit-cell is computed based on mechanical analysis from Kawabata\textsuperscript{[108,109]} and the properties includes (a) biaxial in-plane response; (b) in-plane shear response; and (c) out-of-plane (transverse) shear response. The mesoscale unit-cell based material model described is written into a material user subroutine, VUMAT, the commercial FE program in Abaqus\textsuperscript{[110]}. This subroutine is compiled and linked with the FE solver. During the analysis, this unit-cell based material will be implicitly implanted into a large-scale model on behalf of the fabric, as shown in Figure 2-9(a)\textsuperscript{[111,112]}. Figure 2-9(b) displays the corresponding fully explicit 3D continuum model method.

![Figure 2-8](image)

**Figure 2-8** The unit-cell representative of crossover\textsuperscript{[51]}

![Figure 2-9](image)

**Figure 2-9** The initial configurations of the projectile/fabric systems for (a) the effects of yarn weaving are included implicitly through the use of a meso-scale unit-cell based material model; and (b) yarn weaving is modeled explicitly\textsuperscript{[111]}. 

43
Unit-cell based modelling approach has been applied widely in textile based composite investigation \cite{113-115}. For the application to woven fabrics subjected to ballistic impact, the research carried out by Ivanov and Tabiei\cite{116} and King et al.\cite{117} is the embryonic form of this conception. Nadler \textit{et al.}\cite{118} formulated a multi-scale constitutive model from the unit-cell conception, but the difference was that a coupling method to join all the unit-cells together was used. Recently, Shahkarami and Vaziri\cite{112} compared the results from the unit-cell model to those from experimental work, pin-jointed model and detailed 3D solid model. They found that the unit-cell based model was shown to be effective in capturing the impact response of plain weave fabric panels. Grujicic \textit{et al.}\cite{119,111,51} extended the work done by Shahkarami and Vaziri\cite{112} and investigated the multi-layer fabric response to the ballistic impact.

Compared with the pin-jointed model and 3D continuum model, the unit-cell model has proved to have computational efficient in predicting mechanical responses of multi-ply fabric panels to ballistic impact\cite{112} and at the same time, keeping the information about yarn geometry is involved. However, it is infeasible to examine the behaviours of the primary and secondary yarns in the fabric based on this model because the yarn is not explicitly modelled. It is noted that the stress distributions on the primary yarns and secondary yarns are different\cite{45}.

### 2.4 Factors affecting ballistic performance

Over the past several decades, the fundamentals of fabrics when undergoing ballistic impact have been investigated by the above three approaches. It is observed that the ballistic performance of woven fabrics is affected by a number of factors in the impact process. These factors have been covered in two reviews written by Cheeseman and Bogetti\cite{41}, and Tabiei \textit{et al.}\cite{11}. The following discussions will focus on factors from three parts, projectile, fabric target and boundary conditions. It is needed to point out that the effects of one factor is difficult to be isolated from the other because the effects of one factor is investigated under certain conditions. For example, the fabric panel is impacted by different geometric projectiles at varying velocities. In this case, the effects of geometry of the projectile is coupled with the effects of the impact velocity.
2.4.1 Factors related to the projectile

2.4.1.1 Geometry

The geometry of a projectile of interest is the nose shape and it usually categorised into four groups, spherical, flat, ogival and conical as shown in Figure 2-10. The nose geometry can significantly affect ballistic resistance behaviours of fabrics. The sharper projectile leads to less energy absorbed than the flat and the hemispherical one\textsuperscript{[120, 121]}. Montgomery\textsuperscript{[122]} stated that the effects of projectile nose are different in perforation and non-perforation cases. In perforation case, as the number of plies increases, the differences in energy absorption due to the change of the projectile shape are less noticeable while in the non-perforation case, as the projectile bluntness increases, the depth and diameter of the trauma are smaller than the corresponding values for the more pointed bullets. Additionally, Tan\textsuperscript{[120]} found that different nose shapes of the projectile result in different failure mechanisms of yarns. Hemispherical projectiles are found to perforate the fabric specimens mainly by stretching the yarns to rupture while flat projectiles can shear the yarns in addition to extending them because of their angled edges. Comparatively, conical and ogival projectiles are sharper and thus bowing and windowing are two principal modes of fabric perforation for these projectiles. The effects of nose shape on failure mechanism were confirmed by the FE simulation investigation carried out by Talebi \textit{et al}.\textsuperscript{[93]} and Nilakantan \textit{et al}.\textsuperscript{[96]} \textsuperscript{[122]}.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{Figure_2-10}
\caption{Types of projectiles\textsuperscript{[120]}}
\end{figure}

2.4.1.2 Impact velocity

The failure mechanism of a yarn or fibre in a single-layer fabric is affected by the impact velocity\textsuperscript{[123-125]}. At relative lower impact velocities (up to \textasciitilde300 m/s), the fibre fails
preferentially because of intermolecular slippage or secondary bond failure, also termed as tensile failure. Also, fabric failure due to yarn pull-out becomes more predominant. It results in larger transverse deflection of the fabric, in other words, a more globalised response. At relative higher impact velocities (around 1000 m/s), primary bond failure of the fibre molecule would be pronounced because the yarns stiffening according to their viscoelastic behaviours. Under this circumstance, local damage around the impact centre is dominant for the fabric and the transverse deflection is minimal. As the impact velocity approaches critical velocity (400-700 m/s), the fabric failure mechanism is a mixture of tensile failure and shear failure in the ballistic impact event\[125\]. The critical velocity is defined in Equation 2-11\[126\]. It is reported by Carr\[124\] through experiment that the critical velocities for individual Kevlar® and Dyneema® fibre during ballistic impact are estimated as 620 and 685 m/s, respectively. The impact velocity also indicates the lethality of a projectile that would take to a target. It is denoted by the impact energy density (KED), as given below in Equation 2-12, involving information about the mass \(m\), impact velocity \(V\) and shape via the cross-sectional area \(A\) of contact. The larger impact energy density also indicates the greater possibility of shearing yarns.

\[
V^* = \frac{4\sigma_f^2}{\sqrt{E\rho^2}} \quad (2-11)
\]

where \(V^*\) stands for critical velocity; \(\sigma_f\) refers to fibre breaking strength; \(E\) means Young’s modulus and \(\rho\) indicates the fibre density.

\[
KED = \frac{mv^2}{2A} \quad (2-12)
\]

2.4.1.3 Obliquity

In a real situation, a bullet or fragment can impact protective body armour from different directions. A full understanding of influences of striking obliquity during the process is, therefore, necessary. Results from Yong et al.\[127,128\] showed that ballistic limit increases with the increase of impact obliquity and the fabric absorbs more energy for a larger impact angle, especially for high-speed impact. This finding was also observed by Cunniff\[129\] in the case of multi-layer fabric. The computational simulation results from Tan et al.\[130\] and experimental work from Shim et al.\[131\] showed that the effect of
obliquity on the energy absorbed by a fabric depends on the striking speed. Shim et al. also found that his results do not consist with the results from Young et al. and Tan et al.. He identified the asymmetric deformation along weft yarns as well as sliding between the projectile and the fabric as the two primary mechanisms that governed the variation of ballistic limit with impact obliquity. The asymmetric deformation decreases the ballistic limit while sliding tends to counteract the effect of asymmetric deformation. It should be noted that the shapes of the projectile used in their investigation are different. The effects of obliquity of the projectile are also associated with the nose shape of a projectile. A sharp shape nose at larger obliquity would enlarge the contact area between a projectile and a target, thus decreasing the projectile energy density on the target and in turn delaying the failure time and increase the energy absorption. Nevertheless, for a flat projectile, a larger impact obliquity would lead to the edge of the projectile cutting off the fibre and thus the failure time would be shorter, leading to less energy absorption. In the case of a spherical one, obliquity plays little role.

2.4.1.4 Material

A bullet is composed of the bullet jacket and inside metal. The material inside the bullet jacket could be 100% lead or lead with a penetrator or just a penetrator. Handgun bullets typically consist of softer, more easily deformable materials to inflict maximum damage to human tissues. The rifle bullets are usually small in diameter and, based on their functions, can be filled with lead or lead with a metal pin, or hardened steel. The hardness of the bullet material affects its perforation ability and deformation ability. The full metal jacketed (FMJ) bullets filled with lead show relatively small deformation but are known for their capacity to perforate armour. On the other hand, a full lead bullet, without any jacket, deforms easily and inflicts damage to a much larger tissue area\textsuperscript{132}. For example, the 0.357” Magnum, a powerful handgun, usually uses a soft-point ammunition that is designed to mushroom and dissipate its energy quickly upon impact with a human body\textsuperscript{133}, as shown in Figure 2-11. In addition, the hardness of a penetrator influences the backing material. If the penetrator is a soft steel (AK 47, 7.62 x 39), it is easily deformed with 100% UHMWPE composite without a hard ceramic surface blunting the tip of the penetrator. However, for a hardened steel penetrator, ceramics are used backed with lightweight composites to blunt the penetrator and catch
the blunted penetrator and ceramic fragments in the composite backing\textsuperscript{[132]}. 

\begin{figure}
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{(a) A 0.357” Magnum soft point projectile before firing, and (b) deformed after impact with a textile armour\textsuperscript{[132]}.}
\end{figure}

\section*{2.4.2 Factors from a target}

To a fabric panel used for protective ballistic armour, a number of factors associated with it are responsible for ballistic performance during the impact event. Comparatively, the fundamental element in the fabric panel is the yarn. Therefore, a better understanding of those factors responsible for ballistic resistance behaviours would start from a yarn to a single-layer fabric and then extend to multi-layer fabric.

\subsection*{2.4.2.1 Mechanical properties of a yarn}

Based on equations 2-2, 2-3 and 2-4 used for calculating the longitudinal wave speed and transverse wave speed, apparently, the yarns having better ballistic performance are those with inherent high tensile modulus, high strength and large failure strain. The high modulus yarn is capable of distributing high initial stress generated in the impact centre into a larger area. This effect can prevent the strain from accumulating at impact point. Larger failure strain and tensile strength would give a yarn more time to reach its breaking strain\textsuperscript{[41]}. Rao \textit{et al.}\textsuperscript{[20]} reported that high modulus leads to a fast reduction of the projectile impact velocity, and high strain allows yarns to deform more before fabric failure thereby absorbing more energy. Nevertheless, much larger strain is not necessary because the back-face deflection of the fabric panel would be greater.
Although tensile strength, modulus and failure strain of a yarn have significant effects on ballistic responses of a fabric, individual property does not determine the final ballistic performance. In other words, for a yarn only with high modulus or high tenacity or high strain, the ballistic performance of it will not be satisfactory. The high-speed photographic investigation carried out by Field and Sun\textsuperscript{[134]} showed that the fibre with combined high modulus and large failure strain outperforms other fibres in ballistic impact. Roylance and Wang\textsuperscript{[135]} carried out research to compare the ballistic performance of four types of fibre, Nylon\textsuperscript{®}, Kevlar\textsuperscript{®} 29, Kevlar\textsuperscript{®} 49 and graphite. They found that although the graphite has the highest modulus of the four materials, the ballistic performance of it is not the best because it only has 1.1% failure strain. When comparing the performance of high-strength polypropylene to that of Nylon\textsuperscript{®}, of which the strength is two-thirds of polypropylene, the Nylon\textsuperscript{®} outperforms polypropylene\textsuperscript{[136]}. Prosser et al.\textsuperscript{[121]} stated that if ballistic performance were solely based on yarn toughness, Nylon\textsuperscript{®} would exceed Kevlar\textsuperscript{®}. In fact, it is not.

Cunniff\textsuperscript{[137]} also noted that the ballistic performance of a fibre is not decided by one of the tensile properties but the combination of them. He developed a dimensionless fibre property $U^*$, to describe the relationship between ballistic performance and the tensile properties of the fibre. It is defined as the product of the specific fibre toughness multiplied by its longitudinal strain wave velocity as shown in Equation 2-13. However, in a recent investigation conducted by Afshari et al.\textsuperscript{[138]}, they found that Cunniff’s equation works well for super-high-performance fibres such as Kevlar\textsuperscript{®} that has a relatively low breaking elongation ranging from 3.6% to 4.4%. However, this was not the case for their experimental fabrics made from polyethylene naphthalate (PEN) fibres, of which the elongation varies from 8 to 18%. Since the strain of the fibre used for ballistic protection is relatively low, Equation 2-13 is still a useful indicator for comparing the possible ballistic performance of fibres.

\[ U^* = \frac{\sigma \varepsilon}{2 \rho E} \left( \frac{\varepsilon}{\rho} \right) \]  

(2-13)

$\sigma$ and $\varepsilon$ refer to breaking tenacity and breaking strain respectively. $E$ is the elastic modulus of a fibre and $\rho$ is the density of the fibre individually.
Apart from tensile stress loaded on yarns upon a projectile impacting a fabric, the yarns also experience shear stress, particularly when the sharp-edged fragments impact the fabric or at high impact velocity. Under these circumstances, a cutting mechanism assists the tensile failure of a yarn. Nevertheless, due to the testing difficulties, most of the numerical investigations assumed values of yarn transverse properties in their models for ballistic behaviours analyses. A recent numerical study carried out by Ha-Minh investigated the effects of yarn transverse properties on the ballistic impact behaviours of Kevlar® KM2 fabric. Their results showed that Poisson’s ratio can be negligible in the impact cases, and a large assumed value of shear modulus of a yarn would cause the single yarn to break in a pure shearing mode.

Another fibre mechanical property that would affect ballistic performance is the strain rate. Gu et al. studied the effects of strain-rate on ballistic performance and found that the projectile would lose more energy at higher strain-rate. As such, many researchers conducted work about the tensile behaviours of a fibre at different strain rates. Figucia et al. performed static and dynamic tests on selected high-performance polymeric materials and observed the stiffening in the stress-strain responses of polymeric materials at higher rates of loading. Termonia and Smith reported in both their modelling and experimental work that orientated polyethylene and PPTA show an increase in the tensile strength with increasing strain rate. Wang and Xia used a Weibull distribution analysis method and found that the mechanical properties of Kevlar® 49 displays a dependence on the loading rate, as shown in Figure 2-12. In a ballistic impact event, strain rate was identified through FE simulation between 800/s to 1200/s as the impact velocity increases from 248m/s to 550m/s. In the numerical investigation, it is of importance using tensile properties at high strain rate.
2.4.2.2 Construction of a single-layer fabric

Mechanical properties of individual yarns are essential for fabrics to resist ballistic impact. Nevertheless, the way of the interlacement of these yarns into a fabric structure also play roles and cannot be ignored. Roylance et al.\cite{45} noted that responses of a single-layer fabric to the ballistic impact cannot be determined from the properties of the fibres alone but from the combined material properties and fabric structure. It is well agreed that fibre property and yarn structure determine the yarn property. Analogously, yarn properties and fabric structure would determine the fabric properties.

2.4.2.2.1 The weave pattern

The weave pattern is one of the important factors affecting ballistic performance. The commonly used weave patterns for 2D (2-dimensional) fabric are plain, twill and satin/sateen. According to results from Figucia\cite{144}, satin weave structure having more floating yarns outperforms basket or plain weave fabric in both single and multi-ply systems. However, the structure stability of the satin/sateen is the worst among three elementary weaves. Cunniff found that loosely woven structure and unbalanced weaves would result in inferior ballistic performance\cite{40}. Tran et al. reported that the basket weave evidently shows more flexibility but lower energy absorption compared with plain weave\cite{145}. To the author's knowledge, the plain weave is widely used because the structure is more stable, which is more effective to prevent the projectile from perforating through the openings in fabrics. In addition, compared with other weave
pattern, the inter-yarn friction in plain fabric is more because of more interlacement, which is beneficial for better ballistic resistance.

2.4.2.2 Thread density and linear density

Thread density means the number of yarns placed in a unit length along one direction of the fabric and it is normally classified as warp density and weft density along warp direction and weft direction respectively. The linear density is an indicator of the yarn fineness, which usually uses tex as unit. One tex means that the weight of a yarn with one thousand meter is one gram. Shockey et al.\textsuperscript{[92,11]} investigated fabrics with four different thread densities of 30×30, 35×35,40×40 and 45×45 yarns/in, and discovered that the specific energy absorbed (SEA) was not strongly dependent on the thread density in perforation test at impact velocity of 80m/s. Figucia\textsuperscript{[144]} reported that the fabrics constructed with the finer yarn absorbed energy more efficiently than the fabric with the coarse yarn, based on an equal areal density in V\textsubscript{50} test. Considering the case of fabrics with different thread densities and yarns with linear densities, Cork and Foster\textsuperscript{[68]} defined a mass squareness factor account for the two parameters thread density and linear density in Equation 2-14. The squareness close to 1 means that the fabric is nearly square constructed. They found that the fabric with squareness factor close to 1 performed better. In addition, for the same squareness factor, the fabric with finer yarns outperforms that with coarser yarns. The cover factor is also an indicator derived from the thread density and the yarn linear density, which shows the percentage of gross area covered by a fabric and represents the tightness of the fabric. Chitrangad\textsuperscript{[146]} suggested that ballistic fabrics should possess cover factors from 0.6 to 0.95 to be effective when utilised in ballistic applications. When the cover factor is greater than 0.95, the fabric would be too tight and when the cover factor falls below 0.6, the fabric may be too loose. For too loose fabric, ‘wedge through’ would be the failure mode of the fabric, especially if the projectile is relatively small or with a sharp angle nose. In other words, the projectile can perforate through the openings between yarns,

\[
S = \min\left(\frac{n_1 T_1}{n_2 T_2}, \frac{n_2 T_2}{n_1 T_1}\right)
\]

Where \(n_1\) and \(T_1\) are the thread density and yarn linear density in one fabric direction and \(n_2\) and \(T_2\) are the same parameters in the other direction\textsuperscript{[68]}. 
2.4.2.2.3 Crimp

Yarn crimp refers to yarn undulation in a fabric and is a structure parameter by virtue of woven process. Tan et al.\cite{90} found that the way of incorporation of crimp into the fabric model would affect the prediction results. Chitrangad\cite{146} proposed using the weft yarns that has a larger elongation than the warp yarns to delay the breakage of weft yarns. He reasoned that the weft yarns possesses less crimp and they would break before the warp yarns. Using weft yarns with the larger elongation would delay the failure time. The hybridised weave demonstrates to have a higher $V_{50}$ velocity than weaves composed entirely of an identical crimp. Additionally, Sadegh and Cavallaro\cite{147} argued and demonstrated that highly crimp imbalanced plain-woven fabrics can perform in a way superior to iso-crimped (refer to equally crimped) plain woven fabric. The crimp is a distinct feature of woven fabrics. When loaded at low impact velocity, the cramped yarn has time to be straightened, which is called as de-crimping process, leading to minimal resistance at this stage. The fabric only begins to resist the load when the yarns have been straightened. In this sense, the crimp is helpful to delay the yarn failure. However, larger crimp means yarns have to be more waved, which will slow down the stress wave propagation speed. Therefore, the crimp of the yarn in a fabric is suggested to be less.

2.4.2.2.4 Crossover

Crossover also shows influences on ballistic responses of fabrics because a typical woven fabric has the order of a million crossovers per square meter. Through controlling the fabric weave pattern and thread density, the number of crossover of a fabric is determined. For example, there are one million crossovers per square meter for a plain fabric with both warp and weft yarn density of 10 ends/cm. The crossover can affect the intensity of stress wave propagation \cite{148}. Roylance et al.\cite{148} noted that the influence from crossover on the wave diversion is much stronger than that on the wave reflection but the influence of crossover diminishes as the extent of sliding increases. Freeston\cite{44} observed that the stress wave reflected and transmitted at the crossover in a woven fabric significantly influences the strain generated in the fabric in the impact event. However, the crossover would delay the speed of stress wave propagation with a coefficient of $\sqrt{2}$ \cite{45}. The crossover on one hand assists the stress diversion; on the other hand, it retards the stress wave propagation. These two effects are not inflicted. The exist of crossover
diverts the stress wave propagation along one yarn to other yarns intersecting with this yarn through the inter-yarn friction at the crossover and thus lessen the stress wave on it.

2.4.2.2.5 Sample size
Cork and Foster\textsuperscript{[68]} investigated the performance of narrow fabrics. Two narrow fabrics were compared with a full-width sample of the same structure. The results suggested that the narrow fabrics has improved ballistic performance over larger clamped fabric sheets, or wider strips. Cunniff\textsuperscript{[40]} applied a sample holder with three sizes of aperture to clamp a single-layer fabric. Apparently, the size of the aperture determines the size of the sample in the test. The ballistic test indicated that the residual velocity of the projectile is strongly affected by the sample holder aperture size at impact velocities near the ballistic limit of the fabric. In this velocity range, the smaller the aperture is, the higher the residual velocity is. He ascribed this effect to the more constraints to the transverse deflection and longitudinal deflection provided by the smaller aperture. Nevertheless, the effect of sample holder aperture size decreases rapidly as the impact velocity exceeds the ballistic limit.

2.4.2.2.6 Yarn twist
Yarn twist has long been known to improve the strength of staple fibre and also used to give continuous yarn integrity and force the assembly of single fibres to behave as a single unit. However, for high-performance fibres, twist affects yarn properties such as modulus and strength. There is an optimum degree of twist (around surface twist angle of 7°) for the yarn to achieve maximum strength. The modulus would decrease with the increase of twist angle\textsuperscript{[149]}. In addition, twist will tight the filament and not allow the filaments to spread in the fabric, which may produce larger gaps and lead to a perforation through these gaps\textsuperscript{[52]}. Therefore, twist is not necessary for yarns used in ballistic fabric. Sometimes, for facilitating weaving process, low twist is employed, or for stitching the fabrics and preventing the stitching point to be a weaken point, a high twist sewing yarn is used\textsuperscript{[150]}.

2.4.2.3 Construction of a fabric panel

The soft body armour made from woven fabric is constructed with several layers of
fabrics. The way in which each layer stacks together in a fabric panel also bring effects to ballistic performance. The following concerned factors include the number of fabric layers, the space between each layer, the hybrid ways and the stitching methods.

2.4.2.3.1 Number of layers

Generally, increasing layer number would increase energy absorption of fabrics in a ballistic impact event. Chen et al.\[98\] reported that the back layers absorbs more strain energy than the front layers because of the longer engagement time of the rear layers with the front layers, as shown in Figure 2-13. However, the relationship between the number of fabric layers and the resulting energy absorption capability is not linear. Each layer plays different roles in the multi-layer system. In the perforation case, Gogineni et al.\[15\] found that an addition of new layer would make the increase percentage of the fabric strain energy decrease, as shown in Table 2-2. He concluded that adding fabric layer is beneficial only to a certain degree, exceeding which the add-on layer is redundant because more layers make the panel bulky but contribute less to energy absorption. In the non-perforation case, Joo et al.\[151\] reported that the energy absorption is the highest for the first layer followed by the rest layers while the sequence is reversed in the mature-perforation case. Increasing layer number is an easier way to improve the protection level but the number should not be too large because of the heavy weight.

<table>
<thead>
<tr>
<th>Impact velocity (m/s)</th>
<th>Number of layers</th>
<th>The increase percentage in strain energy for each add-on layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>332</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>124%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>33%</td>
</tr>
</tbody>
</table>

Table 2-2 The increase percentage in strain energy\[15\]
2.4.2.3.2 Space between layers

In multi-ply system, it is generally believed that in a sufficiently spaced armour system, each ply performs independently and there is no interaction between plies. The system’s ballistic performance is a direct sum of each ply’s performance. Adding subsequent plies will adversely affect the performance of the system because of the constraint from the subsequent layers to the transverse deflection of front layers. Cunniff \textit{et al.} \cite{40} conducted impacting test on two-ply panels with chisel-pointed fragment simulation projectiles (FSPs), and found that theoretically, the spaced ply system dissipates more energy than the two-ply system without space. From the analytical investigation of multi-layer system, Porwal and Phoenix \cite{78} acquired the following observations from their study. The $V_{50}$ velocity of a target degrades progressively as the space between layers decreases by the sum of layer thickness without spacing. However, in the experimental work carried out by Lim \textit{et al.} \cite{152}, they found that the interaction between plies in a plied system can result in better ballistic performance for certain impact velocities and projectile shapes. The spaced systems had inferior ballistic limits except for flat-nosed projectiles. Based on the pin-jointed model, Novotny \textit{et al.} \cite{84} suggested that it would be beneficial to have the least amount of inter-layer gap to achieve the best performance in terms of an early stage of energy absorption. Based on above investigations, the effects of space between layers still need to be explored due to the conflicting results. It is advised that the space should not be too large because of the bulky with more space.
2.4.2.3.3 Hybrid

Another hot topic in the multi-ply fabric panel system is the hybridisation. The work from Cuninifer[153] implies that the response of the impact face is dominated by inelastic impact. He proposed that the material in the front layer can be replaced by less expensive materials at same time still maintaining the ballistic performance of armour. Chen et al.[82] conducted an analytical research to study failure mechanism of the primary yarns in different layers in a 15-layer of Kevlar® plain woven fabric panel. Their results indicated that the front layers mainly fails because of shear action and the rear layers are broken by tensile load. Also, they proposed that the fibre materials and their products with high shear strength should be placed in the front, and those with high tensile strength should be positioned at the back of the panel. More investigations for better ballistic performance by hybrid methods can refer to the studies from Larsson and Svenson[154], Cork and Foster[68], Chitrangad[146] and Chen et al.[98].

2.4.2.3.4 Stitching

Stitching is another method to improve the ballistic performance of multi-layer fabrics effectively. Karahan et al.[150] applied three types of stitching methods, as given in Figure 2-14 and a reduction of 6.7% in the trauma depth was found with type C stitching compared to the other two stitching methods. This result had been confirmed by the investigation of Bilisik and Korkmaz[60]. Stitching is a method to lessen the trauma depth but it increases the panel stiffness, which would affect the comfort of the ultimate soft body armour. This being so, loose stitching is suggested to be used in manufacturing ballistic armour. Additionally, Carr et al.[155] investigated the effects of stitching on energy absorption of fabric panels. She discovered that for the lower velocity impacts (-500m/s), the energy absorption of the stitching fabric panels equals to the non-stitching one. For faster impacts (-1000m/s), the diamond stitching method still shows superior energy absorption than the non-stitching method irrespective of the number of layers and shot position. However, the square stitching only performs better when the number of the layer was 3-5.
2.4.3 Boundary conditions

For soft body armour, no real boundary condition exists during wear. Nevertheless, in the ballistic impact test, the sample is required to be fixed. It was observed that different boundary conditions lead to different fabric responses under ballistic impact\[16, 51\] and the effects of boundary condition have been explored \[85, 156, 157\]. Using both numerical and experimental methods, Zeng et al.\[85\] reported that the fabric with only two sides clamped exhibits more energy absorption than the fabric with all four sides clamped near the low-speed impact. Similarly, from the investigations of Lee et al.\[156\] and Zhang et al.\[157\], lower clamping pressure increases energy absorption of the fabric. With the help of numerical investigation, Zeng et al.\[85\] found that the fabric with two sides clamped can undergo transverse deflection more easily and so that 90% proportion of energy absorbed by the fabric is in the form of KE; On the other hand, clamping four sides promotes more conversion to SE and SE accounts for 30%. In addition, the stress wave would reflect at all boundaries for the fabric with four sides clamped while the reflection of stress wave only occurs at the two sides for the fabric with two sides clamped. As such, the stress level in the yarns would be more amplified in the fabric with four sides clamped than that in the fabric with two fabric clamped, leading to the earlier failure of the fabric with four sides clamped.

The effects of boundary conditions will be different at higher impact velocity. Duan et al.\[12\] found that the fabric with four sides clamped is better in energy absorption than other boundary conditions at 800 m/s. The projectile velocity is reduced most quickly for the fabric with all four sides clamped and slowest for the fabric with four sides free, leaving the reduction of projectile velocity by the fabric with two sides clamped in middle. Nevertheless, they did not give the reasons. Additionally, Zeng et al.\[85\] found that when the impact velocity regime is above 240m/s, the fabric with four sides...
clamped also absorbs more energy than that with two sides clamped. His investigation results confirmed the findings from Shockey et al.\textsuperscript{[91]}.

### 2.5 Numerical study of the effects of inter-yarn friction

During the ballistic impact, under the pulling by the projectile forward movement, inter-motion would occur between the yarn and the other yarns passing over it at the crossovers in the fabric, leading to friction generated at the crossover. This friction is named as inter-yarn friction. The hint of the inter-yarn friction action can be perceived from the residual displacement of the yarns, especially the positions between primary yarns and secondary yarns\textsuperscript{[231]}. The inter-yarn friction between individual yarns is usually measured by strand method or capstan method\textsuperscript{[158]} and the inter-yarn friction in fabric is normally assessed by yarn pull-out tests \textsuperscript{[159, 160]}. These tests are usually conducted in low loading speed because the limitation of the equipment itself. The inter-yarn friction at low speed is termed as inter-yarn friction in quasi-static state. It has been reported that the inter-yarn friction in quasi-static state relates to ballistic performance\textsuperscript{[8-10, 17, 21, 22]}. The inter-yarn friction mentioned below refers to the inter-yarn friction in quasi-static state.

The investigations about inter-yarn friction on ballistic performance comprises numerical study and empirical work. The numerical study is that the effects of inter-yarn friction are usually theoretically investigated by FE simulation, where different levels of coefficients of friction were used as the input information indicating the levels of inter-yarn friction\textsuperscript{[12-20]}. The empirical work about the effects of inter-yarn friction will be understood in later section 2.6. Understanding previous work about the effects of inter-yarn friction on ballistic performance is essential to the current investigation. In this section, numerical study of the effects of inter-yarn friction on ballistic performance will be reviewed in detail with respect to energy absorption, ballistic limit, stress distribution and structure stability.
2.5.1 Energy absorption of fabrics

2.5.1.1 Overall energy absorption

A range of inter-yarn friction is employed by Gogineni et al.\textsuperscript{[15]} in their small size model for Twaron\textsuperscript{®} CT709 plain weave fabrics. They noticed that the energy absorption increases with coefficient of friction from 0.01 to 0.3 whereas the energy absorption begins to decrease at frictional levels higher than 0.3. In addition, higher inter-yarn friction reduces the projectile energy more quickly, as shown in Figure 2-15. They explained that higher inter-yarn friction can hold the projectile for a longer time and make more yarns involved. As the inter-yarn friction increases beyond the level of 0.30, the fabric would fail earlier because it hinders the relative motion between yarns and resists decrimping.

![Figure 2-15 Variation in kinetic energy lost by the projectile\textsuperscript{[15]}](image)

Zhou \textit{et al.}\textsuperscript{[17]} also found a turning point for the overall energy absorption as the function of inter-yarn friction. Their results showed that the overall energy absorption of Dyneema\textsuperscript{®} fabric increases as the coefficient of friction varies from 0.10 to 0.40, after which it started to decrease, as shown in Figure 2-16. Their model was based on the 3D solid continuum method for Dyneema\textsuperscript{®} fabric with length of 10 cm subjected to impact from a cylindrical projectile with the velocity of 500m/s. The explanation for the curve was that the higher levels of inter-yarn friction serve to give more gripping for the weft and warp yarns. If the frictional force is over large, yarn mobility will be over-constrained leading to the primary yarns being damaged at an early stage. In addition,
they found out that at higher inter-yarn friction, there would be more strain energy distributed on secondary yarns, as shown in Figure 2-17.

![Figure 2-16 Fabric energy absorption as a function of yarn–yarn coefficient of friction][17]

![Figure 2-17 Time history of strain energy on the secondary yarns][17]

Sun et al.[18] modelled a cylindrical projectile with a velocity of 500 m/s impacting a plain fabric woven from 158 tex Kevlar® yarn with thread density of 7.6/cm. Figure 2-18 plots their results. The overall energy absorption of the fabric increased with coefficient of friction rising from 0.01 to 0.70 and higher inter-yarn friction would result in faster energy absorption rate from 2μs onwards. They observed that increasing inter-yarn friction can lead to higher peak yarn pull-out force, thus would increase ballistic performance. It was reported that higher yarn pull-out force give rise to better ballistic performance[8, 9].
Parsons et al.\cite{161} investigated the effects of slippage during ballistic impact. More slippage between yarns indicates less inter-yarn friction. They proposed that the effect of slippage depends on the impact velocity. At high projectile velocity, the reduction in yarn tension occurs at a time when the failure would otherwise occur. Failure is therefore delayed, and the fabric with yarn slippage absorbs up to 220% more energy than the fabric without. However, yarn slippage is not helpful in increasing the energy absorbed at intermediate projectile velocity. At intermediate velocity, the fabric deforms extensively, and the primary yarns no longer sustain tension at the time of failure. Because the gradients of tension dissipate, the yarn slippage cannot occur to relieve the yarn tension at the point of impact.

2.5.1.2 Energy absorption forms

Duan et al.\cite{12,13} established a 3D solid continuum model to shed light on the effects of inter-yarn friction during the phase prior the yarn failure. They modelled a process of a spherical projectile impacting a square fabric with the length of 32.7 mm at a velocity of 800m/s. Three boundary conditions including four edges clamped, two parallel edges clamped and four edges free as well as two frictional conditions($\mu=0.5$ and $\mu=0$) were taken into consideration. The comparative results showed that the projectile at the higher frictional level loses energy more quickly than the fabric with no friction as shown in
Figure 2-19. In the conditions of two or four edges clamped, FDE only accounts for a small portion. However, the friction contributed to the increase of both SE and KE as shown in Figure 2-20(a) and (b). In the circumstance of four edges free, higher friction leading to increasing energy absorption are mainly through the mechanism of FDE, as shown in Figure 2-20(c). They also claimed that friction can dramatically hinder the lateral mobility of the primary yarns at the impact centre in the local fabric structure, requiring the projectile to resist and rupture more yarns.

Figure 2-19 The projectile energy loss in two frictional cases for three different boundary conditions$^{[12]}$

Figure 2-20 Effect of inter-yarn friction on the energy absorption mechanisms (a) with four edges clamped, (b) with two edges clamped and two edges free and (c) with four edges free$^{[12]}$
Zeng et al.\textsuperscript{[14]} claimed that in the range of the coefficient of friction from 0 to 0.20, the ballistic responses of aramid fabric are susceptible to the increase of friction and the energy absorption increases with the increase of inter-yarn friction in this range as shown in Figure 2-21. Their investigation was based on the FE results from a pin-jointed model for a woven fabric comprised of Twaron\textsuperscript{®} CT716 fibres. They found that the friction contributes to both KE and SE of the fabric as shown in Figure 2-22. In addition, according to the simulation results from Zeng et al.\textsuperscript{[14]}, the KE is the dominant energy absorption mechanism.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2_21}
\caption{Variation of energy absorbed by fabric with impact velocity for different yarn friction coefficients\textsuperscript{[14]}}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2_22}
\caption{Kinetic energy and strain energy histories for impact at 260m/s on fabric with different inter-yarn friction coefficients\textsuperscript{[14]}}
\end{figure}

\subsection*{2.5.2 Ballistic limit}

Nilakantan et al.\textsuperscript{[16]} investigated the effects of inter-yarn friction on $V_{50}$ at two different boundary conditions, four sides clamped and two sides clamped. They used the 3D
model for a square Kevlar® S706 fabric with the length of 50.8 mm impacted by a spherical projectile. Similar to Duan et al.\cite{12}, they found that the effects of inter-yarn friction are related to the clamp conditions. Under four sides clamped conditions, a low level of inter-yarn friction, somewhere between fully lubricated and 0.10, shows the highest $V_{50}$ and then a sharp drop witnesses in ballistic performance between 0.10 and 0.30, after which it flattens out, as illustrated in Figure 2-23(a). One possible reason they thought was that with low level of friction, the primary yarns can move easily at the impact site and take positions of lower stress levels, consequently prolonging their failure and contributing to overall internal and kinetic energies. On the contrary, in the circumstance that four sides clamped, $V_{50}$ Somewhat linearly increases with increasing friction levels, as shown in Figure 2-23(b). Increasing inter-yarn friction would increase the pulling-out energy because they observed that pulling the weft yarns is the primary mechanism of energy absorption in this case.

![Figure 2-23 Vx for fabrics (a) 4-sided clamped and (b) 2-sided clamped\cite{16}](image)

In addition, Zeng et al.\cite{14} found that the ballistic limit increases with frictional coefficient increasing from 0 to 0.20. Further increasing the frictional coefficient yields little difference in the ballistic limit. Parsons et al.\cite{161} found that the ballistic limit decreases from 182 m/s to 169 m/s with more slippage between yarns in the simulations. The explanations from Parsons et al. are as follows. When the impact velocity is near the ballistic limit, the majority area of the fabric deforms before the fabric fails. Near the time of failure, the clamped warp yarn could not slip to relieve the tensions at the point of impact due to small stress gradients. On the other hand, the unclamped weft yarns can
still move at this time, causing more portion of the load transmit to the warp yarns in the absence of yarn slip. Rao et al.\textsuperscript{[20]} compared the ballistic limits of the fabric without friction to that with inter-yarn friction. The inter-yarn friction can give approximately 9\% increase in the ballistic limit for KM\textsuperscript{®} baseline fabric and 63\% increase for the material with two times of stiffness of KM\textsuperscript{®} baseline fabric. They attributed this to the friction aiding in localising the damaged region and maintaining the integrity of the fabric. Oppositely, the absence of friction results in widespread damage and loss of fabric integrity.

2.5.3 Stress distribution

Some of the researchers noticed that the inter-yarn friction can affect the stress wave propagation. As pointed out by Hearle et al.\textsuperscript{[23]}, an increase in inter-yarn friction would cause an increase in the reflectance of the longitudinal wave at each crossover. Roylance\textsuperscript{[148]} built up a pin-jointed model for two intersection fibre and used a sliding factor from 0 to 1 representing the inter-yarn friction at the crossover points. He found that the inter-yarn friction not only influences the reflectance of the longitudinal wave but also the transmittance and diversion of it. As the inter-yarn friction decreases at the crossover, the stress wave transmitting along the fibre increases whilst the wave reflected and diverted is approaching zero.

2.5.4 Structure stability

Minh et al.\textsuperscript{[19]} attempted to reveal the effects of the individual inter-yarn friction and projectile-fabric friction in a three dimensional (3D) interlock fabric. Their work indicated that the inter-yarn friction and fabric/projectile frictions are beneficial to the ballistic performance of the 3D fabric. The inter-yarn friction assists in maintaining the structural integrity of the whole fabric during the impact event. The projectile/yarn friction can help to restrict yarn slipping out of the projectile surface and thus increase the number of yarns loading the projectile.
2.6 Empirical work on the effects of inter-yarn friction

2.6.1 The principles for changing inter-yarn friction

In the light of the better ballistic performance resulted from more inter-yarn friction during the ballistic impact, many researchers attempted to increase the inter-yarn friction\[^{10, 17, 21-23}\]. In a fabric, the variation of inter-yarn friction is usually evaluated by the yarn pull-out test\[^{162, 159}\]. The inter-yarn friction is generally calculated from the capstan equation\[^{17}\]. According to the equation, the inter-yarn friction $F_f$ between the orthogonal interlaced two yarns can be expressed in Equation 2-15\[^{160}\].

$$F_f = T \times e^{\mu \theta} \quad (2-15)$$

$T$ is the tension of the yarn within the fabric. $\mu$ is the frictional coefficient between the warp and weft yarns. $\theta$ is the wrap angle (in radians) of one yarn over the other yarn (or otherwise).

In the yarn pull-out test, input tension, loading speed and other testing conditions can cause effects to the results. At the same testing conditions, the expression of inter-yarn friction in the fabric indicates two ways of increasing inter-yarn friction in the fabric, one being increasing the coefficients of friction and the other one being increasing the wrapping angle. Increasing one of these two parameters would vary the inter-yarn friction in the fabric. The chemical surface coating methods can be used to increase the coefficients of friction since the coefficients of friction to a great degree rely on the surface morphology. With this consideration, finishing or coating yarns would be a feasible way to vary the inter-yarn friction because it would introduce some substances onto the surface and make the surface different. Change the wrapping angle can be achieved through weave based technology. Chen et al.\[^{160}\] tried to introduce more gripping in the woven structure since the wrap angle formed by two intersection yarns are positively related to the inter-yarn friction.
2.6.2 Gripping method

Zhou et al.\textsuperscript{[17]} attempted to introduce yarn gripping to the Dyneema\textsuperscript{®} woven plain fabric to increase the inter-yarn friction. They added double-weft insertion (PWL03DW), leno insertion (PWL03, PWL02) and cramming insertion (PWL02WC) to the plain fabric (PW) individually and obtained corresponding three types of fabric with yarn gripping as plotted in Figure 2-24. The quasi-static yarn pull-out test reveals that the fabrics with yarn gripping shows higher inter-yarn friction in the fabric. Contrary to their expectations, not significant difference in energy absorption was found among the fabrics with yarn gripping and the plain fabric although the inter-yarn friction are different, referring to Figure 2-25. Their explanation was that the increase of inter-yarn friction in the Dyneema\textsuperscript{®} fabric is not high enough to influence the ballistic performance. Sun et al.\textsuperscript{[21, 22]} introduced leno structure into the Kevlar\textsuperscript{®} woven fabric. However, the ballistic experimental results showed that gripping method is effective to increase the ballistic performance as described in Figure 2-26. All the fabrics with leno insertion present higher energy absorption compared to the plain fabric. In particular, the woven fabric with both warp and weft leno insertion at 6 cm intervals (WWG 06) absorbs about 5% more energy than the corresponding plain fabric.

(a) (b)

(c) (d)

Figure 2-24 fabric with gripping structures\textsuperscript{[52]}
2.6.3 General chemical finishing

Hearle et al.\textsuperscript{[23]} made an effort to use two chemical finishings Siligen E and Lurapret to vary the inter-yarn friction in Kevlar\textsuperscript{®} and Nylon\textsuperscript{®} fabrics and to investigate the ballistic performance of the two types of fabrics at different frictional levels. Siligen E was used to reduce the inter-yarn friction, and Lurapret was supposed to increase the inter-yarn friction. However, the inter-yarn friction for Kevlar\textsuperscript{®} fabrics treated by Siligen E also had been increased. Their experimental results about overall energy absorption in each treatment are listed in Table 2-3. High friction finish confers an improved overall energy absorption to the Nylon\textsuperscript{®} fabric compared to the low friction finish. However, the two finishings reduces the overall energy absorption of the Kevlar\textsuperscript{®} fabric.

Furthermore, they made another Kevlar\textsuperscript{®} fabrics with more open structure because they supposed that the inherent yarn freedom would give more space for changing the friction. Fabric treated with water was used as the control sample which experienced the same drying temperature to the samples with finishing additives. All the fabrics treated with finishings shows higher inter-yarn friction. The inter-yarn friction is represented by the
maximum yarn pull-out force, shown in Table 2-4. Larger yarn pull-out force indicates larger inter-yarn friction. A ballistic-performance indicator of energy absorption per density was applied. Nevertheless, they found that the control sample shows superior ballistic performance while all the fabrics treated give equal performance as shown in Table 2-4.

They concluded that the improvement in the ballistic performance of Nylon® fabric is owing to the reduction in lateral mobility of yarns at the impact zone. The higher friction reducing the ballistic performance of Kevlar® fabric was because the levels of friction they obtained have already exceeded the optimal level. They speculated that there would be a relative low friction, beyond which the ballistic resistance would decrease.

Table 2-3 V_{50} energy absorption at area density of 1000 g/m^2^{[23]}

<table>
<thead>
<tr>
<th>Type of fabric</th>
<th>Treatments</th>
<th>Calculated from single-layer (J)</th>
<th>Experimental results(J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kevlar® fabric</td>
<td>as received</td>
<td>62.4</td>
<td>62.8</td>
</tr>
<tr>
<td></td>
<td>Siligen E (high friction)</td>
<td>40.8</td>
<td>43.9</td>
</tr>
<tr>
<td></td>
<td>Lurapret (high friction)</td>
<td>48.3</td>
<td>44.4</td>
</tr>
<tr>
<td>Nylon fabric</td>
<td>Siligen E (low friction)</td>
<td>27.8</td>
<td>26.6</td>
</tr>
<tr>
<td></td>
<td>Lurapret (high friction)</td>
<td>37.5</td>
<td>35.6</td>
</tr>
</tbody>
</table>

Table 2-4 Results of yarn pull-out test and the ballistic performance indicator for a set of Kevlar® fabrics^{[23]}

<table>
<thead>
<tr>
<th>Fabric</th>
<th>Treatment</th>
<th>Maximum yarn pull-out force (Kgf)</th>
<th>Ballistic performance indicator(J/Kg/m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kevlar 49, 175g/m^2</td>
<td>water</td>
<td>0.125</td>
<td>29.5</td>
</tr>
<tr>
<td>Kevlar 49, 219g/m^2</td>
<td>Lurapret B30 (High friction)</td>
<td>0.590</td>
<td>17.5</td>
</tr>
<tr>
<td>Kevlar 49, 220g/m^2</td>
<td>Parapret HVN (Bonding agent) and Lurapret B30 (high friction)</td>
<td>6.14</td>
<td>16.6</td>
</tr>
<tr>
<td>Kevlar 29, 210g/m^2</td>
<td>Lurapret B30 (High friction)</td>
<td>0.406</td>
<td>18.7</td>
</tr>
</tbody>
</table>
Briscoe and Motamedi\cite{10} treated plain, satin and crowfoot fabrics with different chemicals. They achieved three levels of coefficient of friction: 0.22 for “as received”, 0.25 for Soxhlet extracted (scoured) fabric and 0.18 for fabric coated with 5% solution of poly-dimethysiloxane (PDMS). They conducted the ballistic impact on these fabrics in the velocity range of 50m/s to 200m/s. Their experimental work demonstrated that increasing inter-yarn friction is beneficial for improving ballistic performance of fabrics and they ascribed the better ballistic performance to the higher transverse stiffness of the fabric at higher inter-yarn friction.

### 2.6.4 Moisture lubricant

The moisture is regarded as a lubricant that can decrease the inter-yarn friction. Bazhenov\cite{125} has investigated the effect of moisture on the ballistic impact behaviours of 20-layer fabric subjected to 9-mm bullets. The wet fabric panel was perforated while the dry one was not. He speculated that the different performance might be ascribed to the different widths of the pull-out zones resulted from the ballistic impact. The width of the pull-out zone for each layer in the wet fabric panel was observed much smaller than that from corresponding layer in the dry one. Additionally, the first layer of the wet fabric panel was not broken but perforated by wedging through. In other words, the yarns were put aside and let the projectile go through without breaking. The larger pull-out zone implies larger pull-out force, namely the larger inter-yarn friction. He\cite{125} considered that the water serves as a lubricant at the interface of the yarn, which thus reduces the inter-yarn friction and weakens the ballistic performance. In addition, Karahan\textit{et al.}\cite{150} stated that 3.6% decrease in the trauma depth was measured in the wet condition compared to that in the dry state, and the amount of energy transmitted in the wet state was increased by 5%.

### 2.6.5 Natural rubber

Ahmad\textit{et al.}\cite{24} applied NR (nature rubber) to coat fabrics to increase the inter-yarn friction for better ballistic performance. They found that the ballistic limit and the energy absorption for the combined fabric system (the neat fabric and the coated fabric) are larger than those of the neat one, shown in Table 2-5. However, the specific energy
absorption is less for the fabric systems of No. 2, 5 and 8 because the add-on weight is significant. Also, the trauma depth of the combined fabric system is smaller compared with the corresponding neat fabric system, shown in Table 2-6. They proposed that the NR coating might have locked the yarn, in other words, reduced yarn movability, and thus the remaining energy can be distributed from the impact centre over a wider area in comparisons to all neat fabrics at the same position.

<table>
<thead>
<tr>
<th>No</th>
<th>Fabric system</th>
<th>Ballistic limit (m/sec)</th>
<th>Overall Energy absorption (J)</th>
<th>Fabric system density (g/m²)</th>
<th>Specific energy absorption (J/g/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2 Neat</td>
<td>149</td>
<td>12.2</td>
<td>404</td>
<td>302</td>
</tr>
<tr>
<td>2</td>
<td>2 Coated</td>
<td>190</td>
<td>19.9</td>
<td>676</td>
<td>295</td>
</tr>
<tr>
<td>3</td>
<td>4 Neat</td>
<td>200</td>
<td>22.0</td>
<td>808</td>
<td>272</td>
</tr>
<tr>
<td>4</td>
<td>2 Neat + 2 Coated</td>
<td>252</td>
<td>34.9</td>
<td>1078</td>
<td>324</td>
</tr>
<tr>
<td>5</td>
<td>6 Neat</td>
<td>241</td>
<td>31.9</td>
<td>1212</td>
<td>264</td>
</tr>
<tr>
<td>6</td>
<td>3 Neat + 3 Coated</td>
<td>261</td>
<td>37.5</td>
<td>1617</td>
<td>232</td>
</tr>
<tr>
<td>7</td>
<td>8 Neat</td>
<td>316</td>
<td>54.9</td>
<td>1616</td>
<td>340</td>
</tr>
<tr>
<td>8</td>
<td>4 Neat + 4 Coated</td>
<td>338</td>
<td>62.8</td>
<td>2160</td>
<td>291</td>
</tr>
</tbody>
</table>
Table 2-6 Blunt trauma results\cite{24}

<table>
<thead>
<tr>
<th>Fabric systems</th>
<th>Descriptions</th>
<th>No. of layers</th>
<th>Impact velocity (m/s)</th>
<th>Back-face deformation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Shot 1</td>
<td>Shot 2</td>
</tr>
<tr>
<td>A</td>
<td>All neat</td>
<td>18</td>
<td>359</td>
<td>361</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>21</td>
<td>360</td>
<td>357</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td>18</td>
<td>367</td>
<td>360</td>
</tr>
<tr>
<td>D</td>
<td></td>
<td>21</td>
<td>379</td>
<td>362</td>
</tr>
<tr>
<td>E</td>
<td></td>
<td>18</td>
<td>359</td>
<td>358</td>
</tr>
<tr>
<td>F</td>
<td></td>
<td>21</td>
<td>365</td>
<td>358</td>
</tr>
<tr>
<td>G</td>
<td></td>
<td>18</td>
<td>364</td>
<td>362</td>
</tr>
<tr>
<td>H</td>
<td></td>
<td>21</td>
<td>363</td>
<td>358</td>
</tr>
</tbody>
</table>

2.6.6 Shear thickening fluid (STF)

Some researchers\cite{25-29, 31-35} treated the fabric with shear thickening fluid (STF) to improve ballistic performance. The STF is a non-Newtonian fluid whose viscosity would increase with the increasing shear stress. It is usually prepared by dissolving SiO$_2$ nanoparticle into fluid ethylene glycol. The experiments of Lee et al.\cite{27} and Egres et al.\cite{34} demonstrated that the ballistic resistance of Kevlar® fabrics can be improved by the addition of colloidal STF. The explanation for the improvement varies. Wetzel et al.\cite{35} explained that the STF may provide coupling and load transfer effects on a filament-filament, yarn-yarn, or ply level. These interactions may alter the fabric’s response, and allow yarns to undertake the loads more efficiently than without STF. In addition, STF absorbs energy itself due to viscous dissipation in the fluid, which occurs as the fluid is sheared, either directly by the projectile or the relative motion of fabrics.

However, Tan et al.\cite{30} replaced the common carrier fluid ethylene glycol with water and named the new mixture as silica colloidal water suspension (SWS). He investigated
ballistic performance of the fabric impregnated with this suspension. Their results showed that both the yarn pull-out force and the specific energy absorption still increases with particle concentration of the SWS up to 40wt%. This investigation brought in focus the discussion between the role of shear thickening and the role of friction in improving ballistic performance of STF treated fabrics. Some of the researchers\cite{25,26,28-33} regarded it being simply due to increased frictional effects because the increased surface coverage of nanoparticles on the yarn could increase the friction in fabrics to various levels. The increased friction may restrain the inter-yarn mobility and lead to increased yarn pull-out energy\cite{34}, which enable fabric absorb more energy. Nevertheless, Majumdar et al.\cite{29} observed that the increase of inter-yarn friction increases the yarn pull-out energy but fails to enhance the ballistic performance in the STF treatment. Apparently, increase of inter-yarn friction is not the sole mechanism responsible for better ballistic resistance of STF treated fabric.

Srivastava et al.\cite{32} summarised that the mechanism of enhanced impact resistance of STF treated fabric is still not clearly understood. The probable mechanisms of improved energy absorption may include the following aspects: energy dissipation due to shear thickening behaviour, increased inter-yarn friction and better coupling and load transfer between fibre to fibre and yarn to yarn.

### 2.7 Surface modification methods for increasing inter-yarn friction

Through reviewing the previous surface modification methods to increase the inter-yarn friction for better ballistic performance, the inter-yarn friction may be increased over high or the weight of the fabric after treatment has been significantly increased. The purpose of surface modification in present research is to increase the inter-yarn friction without affecting other significant properties of the ballistic yarn materials, for example, tensile properties and weight. With these requirements in mind, two chemical treatment methods are proposed: sol-gel technology and the atmospheric pressure plasma enhanced chemical vapour deposition (APPCVD). These two methods can introduce some substances onto the surface of the fibre and roughen the surface. Meanwhile, these two methods only coat the upmost surface of the fibre with a very thin layer of scales or...
particles so as to achieve the aim of the present study.

2.7.1 Sol-gel method

The sol-gel technology is a general route for producing oxides by the “wet route”. It is a popular method to fabricate the nano-scale metal oxide. In the process, a sol is firstly gradually produced from the hydrolysis of appropriately selected precursors, mostly organometallic compounds, catalysed by a certain acid or alkaline\(^{163}\) and then a gel will be slowly formed by the poly-condensation of the hydrolysis product, generating an oxide skeleton in the solution. The sol-gel technology is, in nature, an inorganic polymerization process containing both hydrolysis and condensation reactions. The hydrolysis reaction (A) and poly-condensation reaction (B) and (C) are described as\(^{164}\):

\[
\text{M(OR)}_x + \text{H}_2\text{O} \rightarrow \text{M(OR)}_{x-1}\text{OH} + \text{ROH} \quad (A)
\]

\[
2\text{M(OR)}_{x-1}\text{OH} \rightarrow (\text{OR})_{x-1}\text{M-O-M(OR)}_{x-1} + \text{H}_2\text{O} \quad (B)
\]

\[
\text{M(OR)}_{x-1}\text{OH} + \text{ROH} \rightarrow (\text{OR})_{x-1}\text{M-OR} + \text{H}_2\text{O} \quad (C)
\]

where M is a metal species (Ti, Si, Al, Zr, etc.) and R is an alkyl group (methyl, butyl, ethyl, etc.)\(^{164}\).

The sol-gel technology contains several stages including sol stage, gel stage, ageing, drying and sintering. In textile industry applications, the textile are usually treated in the sol stage and then undergo drying and baking process to fix the metal oxide or other additives on the surface of the textiles. The sol-gel technology in textile application is usually to achieve the aims of ultra-violet property\(^{165,166}\), self-cleaning property\(^{167}\), antimicrobial activity\(^{167,168}\), hydrophobicity\(^{168,169}\), flame-retardance\(^{170,171}\), abrasion resistance\(^{172}\), photo-catalytic degradation property\(^{173}\), oil repellence\(^{174,175}\), increasing dyeing fastness\(^{176,177}\), wetting property\(^{178}\), improvement of strength\(^{164}\). Up till now, there is no attempt to enhance ballistic performance of woven fabrics by this method.
2.7.2 Atmospheric pressure plasma enhanced chemical vapour deposition (APPCVD) method

Plasma is regarded as the fourth state of substances in essence similar to other matter states such as gas, solid and liquid. It is constitutive of electrons, ions, radical groups, neutral particles and photon\(^{[179]}\). In the plasma, the positive particles electrically equal to negative particles. In other words, the overall charge of plasma is roughly zero. It is important to note that plasma is a collective behaviour. Though some particles in it are with charge, the plasma as a whole are not charged. The positive ions are equivalent to the negative electrons. In the plasma, the particles obtain substantial energy by collision with electrons\(^{[180]}\).

The chemical vapour deposition (CVD) is a process that a thin solid film is formed on a substrate material by means of a chemical reaction of a precursor in vapour phase. The CVD is distinguished from the physical vapour deposition (PVD) process including evaporation and reactive sputtering. In the CVD process, the substances deposited on the substrates are the products from the precursor through chemical reactions which occur both in the vapour phase and on the surface of the substrate. It can be promoted or initiated by heat (termed as thermal CVD), higher frequency radiation such as UV (termed as photo-assisted CVD) or plasma (termed as plasma-enhanced CVD)\(^{[181]}\).

Plasma-enhanced CVD is abbreviated as PCVD. It is a technique in which the homogeneous reactions for producing chemically active species are initiated by electrical energy rather than thermal energy. A major advantage of PCVD over thermal CVD processes is that the layer or film formation on the substrate can take place at very low temperatures, even at ambient temperature. The plasma used for textile treatment in PCVD is non-thermal plasma, where the plasma is not in thermodynamic equilibrium. In the non-thermal plasma, electron temperatures are orders of magnitude greater than for any accompanying neutrals, ions, and metastable but the actual heat content of the plasma is low because the electron accounts for much less, less than one millionth of the total mass of the plasma system. With the assistance of the plasma, the reactant species is broken down, which can subsequently lead to the creation of desirable solid products. It is a feasible method for chemical reactions to proceed near ambient temperatures\(^{[182]}\).
Thus, substrates sensitive to the temperature, for example, textiles, are allowed to be used\textsuperscript{[181]}.

The atmospheric pressure plasma enhanced chemical vapour deposition (APPCVD) is the CVD process initiated by the plasma under atmospheric pressure. The plasma is usually generated at low-pressure discharge because of the concentration and numbers of electrons are inversely proportional to the pressure\textsuperscript{[180]}. However, vacuum instrument is required to control the pressure below 1.3kpa, which is extremely expensive. The plasma source operating at atmospheric pressure is at an advantage as it does not need vacuum instrument.

Sun et al.\textsuperscript{[18]} firstly applied PCVD method to treat Kevlar\textsuperscript{®} fabric intended to increase inter-yarn friction for improving ballistic performance of the fabric. They used two processes to treat the fabric, N\textsubscript{2} plasma treatment and (CH\textsubscript{3})\textsubscript{2}Cl\textsubscript{2}Si plasma treatment. The change of inter-yarn friction was evaluated by the yarn pull-out force. They found that for fabric with (CH\textsubscript{3})\textsubscript{2}Cl\textsubscript{2}Si plasma treatment, the yarn pull-out force is significantly increased compared with the other two. The increase of the yarn pull-out force is attributed to the increased roughness surface of the yarn. Unfortunately, they did not carry out the ballistic performance tests for the treated fabrics. Instead, they conducted FE simulation analyses. Their simulation results showed that the energy absorption of the fabric would grow as the inter-yarn friction increases.

### 2.8 Discussions

The present study is trying to modify the fabric surface to increase the inter-yarn friction for better ballistic performance of the woven fabrics. Numerical study will be firstly carried out to provide the theoretical analyses and guidelines for increasing inter-yarn friction. According to the three approaches for modelling fabric structure, the yarn-level 3D continuum FE simulation method is better suited to capture the inter-yarn friction in the fabric because it involves the full yarn geometry information compared to the other two methods, pin-jointed modelling method and mesoscale unit-cell based one. As such, 3D continuum method will be chosen as the modelling method to establish the projectile-fabric system and based on the model, FE simulation will be completed.
According to previous numerical studies for the effects of inter-yarn friction, the ballistic performance will be analysed with regard to energy absorption, fabric response modes and forms of energy absorption.

According to the available evaluations of ballistic performance, both perforation and non-perforation tests will be adopted to assess the ballistic performance of the treated fabrics with respect to the energy absorption and the blunt trauma respectively.

Inter-yarn friction plays an important role in affecting ballistic performance, and the previous investigations have showed that increasing inter-yarn friction can obtain better ballistic performance. It is possible to employ surface modification methods to increase inter-yarn friction for improving ballistic performance. As far as the previous surface modification methods for increasing inter-yarn friction are concerned, the change of weight and tensile properties of yarns after treatments have not been paid attention to. However, these two parameters are of importance to the fabric used for soft ballistic body armour. In order to roughen the surface for increasing inter-yarn friction without affecting these two properties, two surface modification methods are proposed, sol-gel technology and APPCVD treatment. These two methods are proposed because the coating mainly occurs on the topmost of the yarn surface and the coating is in nano-scale or submicro-scale. It is anticipated that these two methods will not affect the tensile properties and weight of the yarns and fabrics and thus achieve the purpose of increasing inter-yarn friction and eventually superior ballistic performance with light weight.
Chapter 3 Research Methodologies

3.1 Introduction

This chapter is mainly about the introduction of the used methodologies. To establish the relation between the inter-yarn friction in quasi-static state and ballistic performance, both empirical approach and the numerical approach are employed in this research. The empirical approach is to conduct perforation and non-perforation test on the ballistic range while the numerical approach is to create FE model to simulate the process of a projectile impacting a piece of fabric. In addition, the methods for characterising coatings on the surface of fibres, measurements of coefficients of friction, tensile properties and weight add-on will also be described.

3.2 Empirical approach

The empirical approach is mainly associated with the ballistic impact test. Based on ballistic impact experiment, first-hand data can be obtained for evaluating the fabric performance during a ballistic impact event. In addition, the results from the ballistic test are frequently used to validate the results obtained from FE simulation. In the whole research, two types of ballistic impact experiments will be conducted for the fabrics untreated and treated. One is perforation test by which two velocities before and after impact are obtained and thus the energy absorption can be computed. The other one is non-perforation test, which is to evaluate the blunt trauma caused by the fabric panel deformation. The non-perforation test will be described in detail in Chapter 7 because the non-perforation performance of fabrics will be mainly studied in Chapter 7.

3.2.1 The ballistic range

Figure 3-1 shows the devices used for ballistic impact experiment in our laboratory. And Figure 3-2 schematically illustrates the detail of them. The infrared sensors are used to record the time needed for a projectile going through. The two infrared sensors in front
of a target is grouped as the first group of infrared sensors and the two at the back of the target is named as the second group of infrared sensors. From the time displayed on the chronograph connected with the first group of infrared sensors, the initial velocity of the projectile can be worked out. Similarly, the ending speed of the projectile can be computed from the time displayed on the chronograph connected with the second group of infrared sensors. Both perforation test and non-perforation test will be carried out on this ballistic range. In addition, the ballistic range is equipped with a high-speed camera connected to a computer, which makes it possible to record the whole impacting process.

Figure 3-1 The ballistic range

Figure 3-2 Schematic illustration of the top view of ballistic impact device
3.2.2 The projectile and the gun

Figure 3-3 shows how the projectile dimensions were measured. It is a cylinder with the diameter of 5.5mm and height of 5.5mm and the material is steel. The mass of it is around 1.00 g. The initial velocity of the projectile is around 475 m/s. The gun is a rifle with the geometry showing in Figure 3-4.

![Figure 3-3 The geometry of the projectile](image)

![Figure 3-4 The geometry of the gun (mm)](image)

3.2.3 The clamp condition

The clamp condition displayed in Figure 3-5 is the one used for perforation test, and that for non-perforation will be given in Chapter 7. A square sample with the size of 24 cm by 24 cm is placed on an underframe with an aperture, of which the diameter is 15 cm. The surface of the sample is covered with a square steel frame with an aperture the same as that in the underframe. The four sides of the sample are pressed under the four strip steel blocks. Each side is fixed by the press between the steel strip block and the steel square block. The steel square blocks with two distributed in each side are tightly
screwed to give enough force to fix the steel square block and the steel strip block. The four angles of the aperture are also tightly screwed. The effective area left in the sample is a circle with the diameter of 15 cm.

![Image of Clamp condition for the perforation test]

**Figure 3-5 Clamp condition for the perforation test**

### 3.3 Finite element modelling and validation

#### 3.3.1 Introduction to ABAQUS

In this research, Abaqus software, developed by ABAQUS Inc, is selected as the simulation code to do the theoretical analysis for the effects of inter-yarn friction in fabric during ballistic impact. It is a set of powerful engineering simulation software based on FE theory to carry out mechanical analysis, ranging from relatively simple linear analyses to the most challenging nonlinear simulations. Abaqus\(^{[183]}\) contains many methods, for example, the extrusion, sweep, revolution and so on to generate a model closely to the real one in geometry. In addition, it is also allowed to import geometry drawn by other software. It also contains a material library that can simulate the behaviour of most typical engineering materials such as metals, rubber and polymers.

Abaqus/CAE\(^{[184]}\) is one of the frequently used Abaqus products. It is an interactive interface to create models, submit and monitor jobs, and evaluate results, which are also
the three stages contained in a thorough FE analysis. In the process of model creation, the tasks are to generate the parts, assign the material properties, assemble the parts together, establish the analysis steps, define the interaction between contact, apply the loads and mesh the parts in corresponding module. After the model creation, a job can be produced from the model and submitted for FE analysis. The results from the job analysis will be presented in the visualization module. In this module, one can interpret the results.

3.3.2 Ballistic impact modelling

3.3.2.1 Fabric structure

The modelled fabric structure for TM fabric and DYM fabric, referring to Chapter 4 section 4.2, is constructed from yarns with the linear density of 93 tex. The warp density and weft density are designed identical, 7.8 ends/cm. The areal density is 153.61 g/cm². For the Dyneema® fabric model used in Chapter 7 section 7.4.2.2, the fabric is modelled from yarns of 174 tex. Both warp density and weft density are set as 6.75 ends/cm and the areal density is 231.74 g/cm².

3.3.2.2 The yarn cross-section and yarn path

The fabric are modelled in the yarn level without considering the single fibre geometry in the Abaqus because the yarn-level model is verified able to capture the ballistic impact behaviours of the fabric[12]. To create a 3D continuum yarn part in the Abaqus/CAE, the cross-section of the yarn and the wavelength are the basic information. The yarn can be generated by sweep method with this information.

The geometry of the yarn in woven fabric has been investigated for a considerably long time. In 1937, at first level research, Peirce[185] firstly considered that the yarn in a plain fabric had a circular cross-section. Later he put forward that the cross-section shape of the compressed yarn was elliptical due to the internal reactions between the warp yarn and weft yarn. Subsequently, a race-track cross-section shape was developed by Kemp[186] in 1958, which was constructed by rectangle enclosed by two semi-circular ends and considered the yarn flattening in the fabric. In 1978, Shanahan and Hearle[187]
proposed another version of the mathematical approximation of flattened yarn cross-sectional shape, the “lenticular” shape which is formed by two arcs. These three typical models are frequently applied for modelling the yarn geometry in fabric.

To get the actual yarn geometry in the fabric used for the ballistic impact simulation model, observation of the images of fabric cross-section is necessary. The sample preparation is described below. The fabric sample was cut into smaller pieces and placed vertically in a container. A mixture made from resin and hardener with the proportion of 10 to 1 was poured into the container to solidify the fabric piece. After the solidification process, the mould was taken out and polished by the sandpaper fastened to the grinding machine to get a smooth, flat, and legible surface for observation. Figure 3-6 and 3-7 depict micro-images of the yarn cross-section and the wave in the TM and DYM fabric based structure respectively by using an optical microscope. Based on the micro-image in Figure 3-6, the yarn cross-section can be realistically represented by lenticular model. From Figure 3-7, the wave can be considered as constructed by two lenticular arcs. Similarly, the yarn cross-section in Dyneema® fabric is modelled using lenticular model and the wave in it is regarded as constructed by two lenticular arcs as well.

The width of the cross-section and wavelength measured from Figure 3-6 and 3-7 was approximate because the fabric subjected to a little pressure from the resin. Due to this pressure, the structure of the fabric become much tighter than the actual one. Therefore, the width of the cross-section and the wavelength of the yarn are based on the
measurements from the SEM image of the fabric. In this case, the fabric is free from pressure. Figure 3-8 shows the way to measure the width of the cross-section and the wavelength. Based on data in Tables 1 and 2 in the Appendix, the average width of the cross-section of the yarn in both TM and DYM models is 1.134 mm and the average wavelength of the yarn is 2.556 mm. The average thickness of the fabric is measured as 0.210 mm by using the vernier caliper. The geometry parameters for the generated yarn part by sweep method are shown in Figure 3-9. In the same way, for Dyneema® fabric model, the measurements for the width of yarn cross-section, the average wavelength and the thickness are 1.745mm, 3.735mm and 0.488mm, respectively.

Figure 3-8 Image of the fabric structure for TM and DYM fabric

Figure 3-9 Yarn geometrical parameters in the model for TM and DYM fabric
3.3.2.3 Fabric assembly and boundary conditions

In order to be the same as the circular shape of the sample shown in Figure 3-5 in the experimental setup, each yarn is modelled with different lengths. The yarns generated in part module are then positioned according to the weave pattern in the assemble module in the Abaqus/CAE to form a fabric panel. Since the projectile-fabric system is symmetric, only a quarter of the fabric area is needed to be simulated, as shown in Figure 3-10. This would save 75% amount of computation. The fabric size is the same as the actual size for the ballistic impact test, with a radius of 7.5 cm. The warp yarn is positioned along X direction and the weft yarn along Z direction. The projectile is generated with the same geometry parameters as in the ballistic impact experiment.

All the freedoms for the projectile movement are restricted but it is allowed move along the negative direction of Y axis. For the fabric, the arc edge away from the impact area is fixed, and the remaining two sides are given symmetric boundary condition. The fabric is placed in the X-Z plane, impacted by the projectile in the negative Y direction.

![Figure 3-10 The fabric assembly](image)

3.3.2.4 Contact definition

The contact in the projectile-fabric system comprises yarn/yarn contact and projectile/fabric contact. The projectile/fabric contact is defined as surface to surface contact, and yarn/yarn contact is given a global contact algorithm. The commonly used
friction formulations in Abaqus are penalty and static-kinetic exponential decay. In the case of penalty, only one coefficient of friction is required to be prescribed but in the case of static-kinetic exponential decay, both coefficients of static and kinetic friction need to be given. Since the friction normally contains both static and kinetic one, the friction formulation of static-kinetic exponential decay is adopted in this research. The effective coefficient of friction between two contact surfaces is modelled using an exponential formulation as in Equation 3-1 below\[^{[20,188]}\]. \( \mu_k \) is the coefficient of kinetic friction (CSF). \( \mu_s \) is the coefficient of static friction (CKF). \( |v_{rel}| \) is the relative velocity between two surfaces in contact and \( \alpha \) is an exponential decay coefficient describing the transition from static friction to stable kinetic friction. According to Rao et al.\[^{[20]}\], the exponential decay coefficient is set equal to \( 10^8 \).

\[
\mu = \mu_k + (\mu_s - \mu_k) \cdot e^{-\alpha|v_{rel}|} \quad (3-1)
\]

3.3.2.5 Mesh algorithm

In the mesh step, the yarn is meshed by C3D8R, meaning an solid element type of 8-node linear brick, reduced integration, hourglass control. The cross-section of the yarn is meshed with ten elements, which is determined from the computational accuracy of the model and mesh sensitivity\[^{[12,13]}\]. Mesh sensitivity studies indicated that the chosen mesh density was able to capture both longitudinal and transverse wave responses in the impact event. The projectile is also meshed with C3D8R method. The fabric and projectile meshes are depicted in Figure 3-11(a) and (b), respectively.

![Figure 3-11 The mesh for the fabric (a) and the projectile (b)](image)
### 3.3.2.6 Solution algorithm

Abaqus/Standard and Abaqus/Explicit are the two commonly used solution algorithms in Abaqus analysis. Abaqus/standard needs to solve each equations implicitly at each time increment and it prefers fewer increment analyses. Abaqus/Explicit adopts the kinematic state in one increment to compute mechanical state in the next and the equations governing the motion are integrated explicitly through time using a central difference rule \(^\text{[189]}\). It is widely applied to analyse the instant dynamic problems, such as impact and blast problems. Thus, the analysis used in this research is Abaqus/Explicit. The algorithm of Abaqus/explicit is summarised below\(^\text{[189]}\):

(1) Nodal calculations

At the beginning of the increment, a dynamic equilibrium should be solved by the program. The dynamic equilibrium states that the nodal mass matrix, \(M\), multiplying the nodal acceleration, \(\ddot{u}\), equals the total forces acting on the node. The total force is computed from the external applied forces, \(P\), and internal element forces, \(I\):

\[
M\ddot{u} = P - I
\]

\((3-2)\)

a. Calculating the acceleration.

Through the dynamic equilibrium, the acceleration \(\ddot{u}\) at the beginning of the current time \(t\) is calculated as:

\[
\ddot{u}|(t) = (M)^{-1} \cdot (P - I)|_t
\]

\((3-3)\)

b. Integrate explicitly through time.

Provided that the acceleration is constant, it can be integrated through time with the central difference rule to compute the change in velocity. This change adds to the velocity \(\dot{u}\) from the middle of the former increment, in turn equalling to the velocity at the middle of the present increment:

\[
\dot{u}|_{(t+\Delta t/2)} = \dot{u}|_{(t-\Delta t/2)} + \frac{(\Delta t|_{(t+\Delta t)} + \Delta t|_{(t)})}{2} \ddot{u}|_(t)
\]

\((3-4)\)
The displacements $u$ at the end of the increment is the sum of the displacements at the beginning of the increment adding the integration of velocities through time:

$$u|_{(t+\Delta t)} = u|_{(t)} + \Delta t |_{(t+\Delta t)} \dot{u}|_{(t+\frac{\Delta t}{2})} \tag{3-5}$$

(2) Element calculations.

a. Compute element strain increments, $d\varepsilon$, from the strain rate, $\dot{\varepsilon}$.

b. Compute stresses, from constitutive equations below.

$$\sigma|_{(t+\Delta t)} = f(\sigma|_{(t)}, d\varepsilon) \tag{3-6}$$

c. Assemble nodal internal forces, $I|_{(t+\Delta t)}$.

(3) Set $t + \Delta t$ to $t$ and return to step (1).

### 3.3.2.7 Material properties

The material constants for the yarns are dominated by the longitudinal tensile properties although the real yarns are made of bundled fibres with orthotropic properties. As such, the model for the yarns is assumed to be homogeneous and isotropic $^{12, 13, 20, 53}$. Previous researchers have shown that the homogeneity and isotropy assumptions of the yarn lead to acceptable results with inaccuracy approximately 2.4% in energy absorption $^{190, 191}$.

A progressive damage model which reflects the material property degradation is implemented in ABAQUS/ Explicit to allow the fracture of the material $^{192}$. The simulation of material failure consists of three stages: (i) establishment of the damage initiation criterion, (ii) determination of the damage evolution law and (iii) element removal upon reaching a completely damaged state. The failure of the material is usually divided into brittle failure or ductile failure. The stress-based ductile damage criterion is used to detect the failure mode in the fabric and yarn. Sun et al.$^{191}$ and Wang et al.$^{193}$
used this damage criterion in their simulation analysis. The damage initiates when the condition in Equation 3-7 is satisfied:

\[ w_D = \int \frac{d\varepsilon^{pl}}{\varepsilon^D_0(\gamma, \dot{\varepsilon}^{pl})} = 1 \quad (3-7) \]

\[ \gamma = -\frac{p}{q} \quad (3-8) \]

Where \( w_D \) is the state variable, \( \varepsilon^{pl} \) is equivalent plastic strain. \( \varepsilon^D_0 \) is a function of stress triaxiality \( \gamma \) and strain rate. The method for computing triaxiality \( \gamma \) is shown in Equation 3-8\(^{192} \). \( p \) is the pressure stress, \( q \) is the Mises equivalent stress. \( \dot{\varepsilon}^{pl} \) is the equivalent of plastic strain rate.

When the material damage occurs, the stress–strain relationship no longer accurately represents the material’s behaviour. Hillerborg et al.’s fracture energy proposal is then used to reduce mesh dependency by creating a stress-energy response after damage initiation to define the damage evolution. Hillerborg et al.\(^{194} \) defined the energy, \( G_f \), as a material parameter. It indicates the required energy to open a unit area of a crack and is given in Equation 3-9. Removal of a solid element is set by default, when maximum degradation is reached at any one integration point.

\[ G_f = \int_{\varepsilon^0}^{\varepsilon^{pl}} L \sigma_y \, d\varepsilon^{pl} = \int_0^{\bar{u}^{pl}} \sigma_y d\bar{u}^{pl} \quad (3-9) \]

Where \( L \) is the characteristic length of the mesh; \( \bar{u}^{pl} \) is the equivalent plastic displacement, equalling to the product of \( L \) and \( \dot{\varepsilon}^{pl} \); \( \sigma_y \) is the yield stress.

### 3.3.3 Model validation

The comparison between the results from experiment and FE simulation was carried out in terms of the residual velocity and the transverse wave propagation to verify if the established model is valid. Since the fabric in the ballistic impact experiment for validating the FE simulation is based on Twaron® fabric, the material properties for the yarns in the model is according to Twaron® yarns. The tensile properties of Twaron® yarn are set at high strain rate because of the difference in tensile properties of Twaron®.
yarns between high strain rate and low strain rate\textsuperscript{143, 195}. The strain rate is found through FE simulation between 800/s to 1200/s as the impact velocity increases from 248 m/s to 550 m/s\textsuperscript{97}. Therefore, it is reasonable to assume the strain rate is around 1000/s for the impact velocity of 475 m/s. Based on the investigation from Zeng \textit{et al.}\textsuperscript{14}, the Young’s modulus is configured as 72 GPa and the failure strain 4.28% in the model at the strain rate of 1000/s for Twaron\textsuperscript{®} yarn. The coefficient of static friction (CSF) and the coefficient of static friction (CKF) of the original Twaron\textsuperscript{®} yarns are obtained from actual experimental test and are computed as 0.16 and 0.15 respectively using capstan method with yarn-yarn angle 90°. They are smaller than the values reported by Brisco \textit{et al.}\textsuperscript{10} and Rao \textit{et al.}\textsuperscript{20}. This is because the Twaron\textsuperscript{®} yarn surface has already been treated with some finishing of organic silicon, which may be a lubricant causing the coefficients of friction to become smaller. The coefficients of friction are averaged from 30 tests.

### 3.3.3.1 Determination of the impact velocity and residual velocity

In FE simulation, the impact velocity $V_i$ needs to be given. It is the velocity that the projectile impacting upon the surface of the fabric because the projectile is positioned on the surface of the fabric in FE model. However, the initial velocity $V_0$ measured from the experiment is not the impact velocity because of the distance left between the first group of sensors and the fabric, shown in Figure 3-12. Analogously, the velocity obtained at the end of impact in experiment, named as the end velocity $V_e$, is not the residual velocity $V_r$ from FE simulation, either. The residual velocity is the velocity at the moment when the projectile gets through the fabric. Due to the air resistance in the test, the impact velocity is lower than the initial velocity and the residual velocity is larger than the end velocity. Therefore, it needs to do some modifications to the velocities acquired from the measurements. Those velocities are annotated in Figure 3-12. The impact velocity $V_i$ and the residual velocity $V_r$ can be calculated from the initial velocity $V_0$ and the end velocity $V_e$ respectively according to the equations of linear motion of constant deceleration.
In the shooting process without fabric, $V_0$ is computed out as 482.29 m/s and $V_i$ 479.39 m/s. They are averaged from the data in Table 3 in the Appendix. From Figure 3-12, the distance between the centre of the two group of infrared sensors is 1.035m. Given that the process is a linear motion with constant deceleration, one can obtain that the acceleration $a$ and the total time $t$ based on Equations 3-10 and 3-11. The total time $t$ is divided into two time parts $t_1$ and $t_2$, where $t_1$ represents the time needed for the projectile to get through from the centre of the first group of infrared sensors to the target and $t_2$ means the time for the projectile to get through from the target to the centre of the second group of infrared sensors. The deceleration is computed out as 1347.28m/s$^2$ and the obtained total time $t$ is about 2.152E10-3 s, in which $t_1$ takes up 1.501E10-3 s and $t_2$ accounts 6.510E10-4 s. Therefore, $V_i$ and $V_r$ for corresponding initial velocity and end velocity are obtained and shown in Table 3-1.

\[ V_i = V_s + at \quad (3-10) \]
\[ S = V_s t + \frac{1}{2} at^2 \quad (3-11) \]

Where, $V_i$ and $V_s$ represent the larger velocity and the smaller velocity in the two pairs of velocities, $V_0$ and $V_i$, and $V_r$ and $V_s$, respectively. $a$ is the acceleration and $t$ is the total time.
Table 3-1 Vi and Vr for different original single-layer Twaron® samples

<table>
<thead>
<tr>
<th></th>
<th>$V_0$ (m/s)</th>
<th>$V_t$ (m/s)</th>
<th>$V_i$ (m/s)</th>
<th>$V_r$ (m/s)</th>
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<td>460.12</td>
<td>448.90</td>
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<td>454.20</td>
<td>468.45</td>
<td>455.08</td>
</tr>
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<td>455.92</td>
<td>473.21</td>
<td>456.80</td>
</tr>
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<td>457.95</td>
</tr>
<tr>
<td>7</td>
<td>478.13</td>
<td>462.92</td>
<td>476.11</td>
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</tr>
</tbody>
</table>

### 3.3.3.2 Validation of the model

#### 3.3.3.2.1 Residual velocity

Figure 3-13 compares the residual velocities from FE simulation to those from experimental test when the projectile impacts a single-layer Twaron® fabric. In Figure 3-14, the horizontal axis and the vertical axis represent the experimental residual velocity and the corresponding residual velocity from the FE simulation, respectively. From the equation of linear regression added to the scatter points, the correlation coefficient $R^2$ is close to 1, manifesting that the residual velocities from FE simulation linearly relate to those from ballistic test. From the equation displayed in Figure 3-13, the slope value is around 1, indicating that the difference between the residual velocities from FE and experiment is minimal. Thus, the results from the FE simulation model have a good consistency with the experimental results with respect to the residual velocity.
3.3.3.2.2 Transverse wave velocity

Wave propagation is one of the essential characteristics of the ballistic behaviours of the fabric. Figure 3-14 compares the transverse wave propagation in the fabric from FE simulation to that recorded from the high-speed camera. The resolution is configured as 250000 frame/second because higher resolution will lead to much smaller area taken into the visual field of camera. Therefore, the picture is recorded every 4 µs. For the FE simulation, the transverse wave propagates to the 4.5th yarn at 4 µs counted from the impact centre and the 6.5th yarn at 8 µs and the 8.5th at 12 µs. In order to clearly observe where the transverse wave propagates at a certain time on the images taken from the high-speed camera, the area involved is circled out by the red line, as shown in Figures 3-14 (a’),(b’) and (c’). The images are recorded in the case of the impact velocity of 473.21 m/s. These images show that at 4 µs, the transverse wave travels to approximately 3-3.5th yarn, and to 6th yarn at 8µs and to 8th yarn at 12 µs, respectively. Based on the above comparison, the transverse wave propagates almost at the same speed in the two methods. Therefore, the results from the FE model can capture the transverse wave propagation correctly.
Figure 3-14 Comparison of the transverse wave propagation between the FE(a),(b),(c) and the recorded photographs from high speed camera (a')(b')(c').

3.4 Methods of coating characterisation and tests

3.4.1 Coating characterisation

Fourier transform infrared (FTIR) spectra and Energy-dispersive X-ray (EDX) are used to identify the coated substance on the surface of the fibre. Scanning electron microscopy (SEM) is used to characterise the morphology of fibres.

3.4.1.1 FTIR characterisation

Since the material surface can be modified after deposition at the micron level, infrared is found to be an appropriate technique to characterise the induced chemical changes. The FTIR spectra are taken using the NICOLET5700 FT-IR by Thermo Electron Corporation. The spectra are recorded at room temperature within the range of 4000 to 500 cm\(^{-1}\) with 32 scans and a resolution of 4 cm\(^{-1}\). Each scan is made on a yarn specimen involving thousands of filaments, and this is repeated three times per specimen.

3.4.1.2 SEM characterisation

In order to examine the surface changes of the treated yarns, the yarn morphology after treatment is identified by scanning electron microscopy (SEM). Both Twaron\(^\text{®}\) and Dyneema\(^\text{®}\) yarns are insulators and therefore are likely to be charged by the electron beam. An ultra-thin layer of gold is used to coat each specimen to make it more electrically conductive for SEM observation.

3.4.1.3 EDX characterisation

EDX is employed to analyse the chemical component deposited on the surface of the fibre. The electron probe for EDX measurement is mounted on the SEM EVO 60 Model. The measurement is based on the principle that the X-rays produced from any specific element are characteristic of that element.
3.4.2 Evaluation of inter-yarn friction

3.4.2.1 Evaluation methods

Coefficients of inter-yarn friction are used to indicate the friction between yarns, namely the inter-yarn friction. According to ASTM standard D3412-01, the coefficients of inter-yarn friction are usually expressed in the following two equations, Equation 3-12 for the twisted strand method and Equation 3-13 for the capstan method. Figure 3-15 illustrates the twist strand method and Figure 3-16 shows the capstan methods measured at yarn angles of 0° and 90° respectively. During the impact process, the inter-yarn friction is mainly caused by the rubbing between warp and weft yarns, which is the same as that in the case of the yarn-yarn angle of 90°. Hence, the inter-yarn friction is evaluated by the capstan method with yarn–yarn angle of 90° in the present research.

![Figure 3-15](image1.png)

**Figure 3-15** Twist strand method for testing coefficients of friction

![Figure 3-16](image2.png)

(a) Yarn wrap angle α at 0°  
(b) Yarn wrap angle α at 90°

**Figure 3-16** Capstan method for testing coefficients of friction
For twisted strand method:

\[
\mu = \frac{\ln\frac{T_2 - \Delta T}{T_1 + \Delta T}}{\frac{1}{2} \pi n \theta}
\]  

(3-12)

For capstan method:

\[
\mu = \frac{1}{2\alpha} \ln\frac{T_2}{T_1}
\]  

(3-13)

Where \(\mu\) means coefficients of inter-yarn friction; \(T_1\) means input tension; \(T_2\) means output tension; \(\Delta T\) means zero twist tension; \(n\) means the number of wraps; \(\alpha\) means wrap angle; \(\theta\) means apex angle.

3.4.2.2 Device for coefficients of friction test

The coefficient of inter-yarn friction test were carried out using a device on an Instron tensile tester as shown in Figure 3-17. The method applied here is the capstan method in the case of yarn-yarn angle at 90°. In the setup, two rods with diameters of 13 mm are fixed horizontally on a frame, mounted on the tensile machine. The yarn wraps the rods in the axial direction. The displacement of the crosshead is limited to 20 mm. All the tests were carried out on Instron 5500 at room temperature of 23°C and humidity of 50%.

The test speed has effects on the coefficients of friction between yarns\cite{196}. In the ballistic impact, the speed of the yarn motion is around \(10^6\) mm/min\cite{9}. It is impossible to test the coefficients of friction at such high loading speed because of the limitation of equipment. Thus, it is essential to build the relationship between inter-yarn friction in quasi-static state and the ballistic performance. Coefficient of friction in quasi-static state was found relatively stable when the test speed is between 0.1 yard/min to 1 yard/min\cite{196}, approximately 90 mm/min to 900 mm/min and so that the crosshead speed was set as the intermedia value of 500 mm/min. According to the standard, the free-hanging weight was adjusted to provide an input tension of 10.0±0.5 mN/tex. In this way, the input weight used was set to be 99.36 g for the Twaron® yarn and 171.89 g for
Dyneema® yarn to control the individual input tension $T_1$. The output tension $T_2$ was measured by the load sensor of the Instron machine. The wrapping angle of the yarn over the rods in the device is 90°. Consequently, the equation to compute the coefficients of inter-yarn friction can be written as in Equation 3-14:

$$\mu = \frac{1}{\pi} \ln \frac{T_2}{T_1} \quad (3-14)$$

Figure 3-17 A device used for coefficients of friction test (Instron based)

3.4.2.3 Coefficient of static friction and coefficient of kinetic friction

Figure 3-18 shows the typical output tension curve obtained from the coefficients of friction test. The peak force in each output tension curve corresponds to the coefficient of static friction (CSF), and the average of the data in range A is used to compute coefficient of kinetic friction (CKF). Within this range, the acceleration of yarn motion is almost 0 mm/min. From the Equation 3-14, the coefficient of friction is in positive correlation to the output tension. Namely, the larger output tension indicates the larger coefficient of friction. With known of both output and input tensions, the coefficients of friction (CSF and CKF) can be figured out according to Equation 3-14.
3.4.3 Tensile property test

The tensile property test refers to ASTM D2256 test criterion. It was carried out using Instron-44. The special gauge length was set to be 250 mm. A pre-tension of 0.5 cN was employed in the tensile property test to make the filament straight and parallel. The test was carried out at the temperature of 20°C and humidity of 60%. The yarn was stretched at a speed of 250 mm/min and all the tests at this speed is used to evaluate the changes of tensile properties after treatments. It should be mentioned that the tensile properties of yarns in FE simulation model are those at high strain rate.

3.4.4 Weight add-on test

Since the requirement of weight for soft body armour at the same protective level is as light as possible, the weight changes after the treatments needs to be tested. The weight change percentage P% is calculated from the dry net weight before treatment \( W_0 \) and that after treatment \( W_d \) for each sample, as shown in Equation 3-15. For the weight test, the sample would absorb some moisture in the air. As such, before tests, all the samples were placed in the condition of temperature of 20°C and relative humidity of 65% for 4 hours because 4 hours is enough for the moisture regain to arrive a relatively constant value.
\[ P \% = \frac{W_d-W_0}{W_0} \times 100\% \quad (3-15) \]

3.5 Summary

The main methodologies for completing the ballistic impact investigation have been introduced in this chapter, including the empirical approach and the FE simulation. In addition, coating characterisation methods, inter-yarn friction test, tensile properties test and weight add-on test are also introduced. In the FE simulation model, the projectile-fabric system is built up by 3D continuum method. In the model, it has been found that the yarn cross-section can be realistically represented by lenticular shape and the yarn waviness can be constructed by two lenticular arcs. The validation of the model has been done by comparing the transverse wave propagation and the residual velocity between the FE simulation and the experiment. The results showed that the transverse wave velocity and the residual velocity from FE simulation are consistent with those from the experiment, indicating that the model established is valid.
Chapter 4 Numerical Study of Effects of Inter-yarn Friction on Ballistic Performance

4.1 Introduction

Finite element (FE) method has been frequently used to theoretically study ballistic impact problems\cite{12-20}. With this method, previous researchers provided some insights into the effects of inter-yarn friction in quasi-static state during the ballistic impact. In these investigations, different levels of coefficients of friction were selected to indicate the levels of inter-yarn friction in the fabric. However, the level of inter-yarn friction was either set over large or not exist\cite{12, 13, 19}. Due to the power limitation of the computer, the targets modelled in the previous investigations were smaller than the actual size, which may lead to incorrect understanding because the sample size also has effects on ballistic performance\cite{12-16, 18-20}. In addition, some investigations did not consider the actual tensile properties of materials available for body armour\cite{12, 13}. Thus, the role of inter-yarn friction needs to be further investigated considering the above issues. In addition, in order to give some guidelines for the surface modification, theoretical and thorough understanding of the effects of inter-yarn friction is also necessary.

In this chapter, the effects of inter-yarn friction in quasi-static state on a single-layer fabric subjected to ballistic impact will be theoretically analysed through FE simulation based on the model established in Chapter 3. The effects of inter-yarn friction on ballistic performance will be comprehensively elucidated from the perspectives of energy absorption, the fabric response mode and the forms of energy absorption. It is anticipated that through FE analyses, the effects of inter-yarn friction will be uncovered and the direction for improving the ballistic performance through increasing inter-yarn friction will be acquired.
4.2 Materials and impact conditions

The effects of inter-yarn friction will be investigated under two Young’s moduli conditions, one being 72 GPa and the other being 112 GPa. The 72 GPa is set according to the Young’s modulus of Twaron® yarns. Based on previous investigations\textsuperscript{[14]}, the Young’s modulus of Twaron® yarns is 72 GPa at the strain rate of 1000 /s. The 112 GPa is set according to the Young’s modulus of Dyneema® yarns. In the research from Koh et al.\textsuperscript{[197]} and Huang et al.\textsuperscript{[198]}, the Young’s modulus of Dyneema® yarn is around 80 GPa at the strain rate around 1000 m/s while from the tests carried out by Russell et al.\textsuperscript{[199]}, the Young’s modulus of Dyneema® is around 130 GPa at the same strain rate range. Russell et al. explained that the discrepancy is associated with the measurement method and the slip between specimen and grips\textsuperscript{[199]}. Form other references\textsuperscript{[200-202]}, the Young’s modulus of Dyneema® yarns it is around 107-115 GPa. Thus, the Young’s modulus of Dyneema® yarns is set as 112 GPa at the high strain rate of 1000/s. The other material properties in the two moduli cases are kept same and are set according to Twaron® yarns. The fracture strain and the yield stress are estimated as 4.28% and 2.9 GPa individually. The density of the yarn is set as 1268 kg/m$^3$ according to packing density of fibres in yarns with a value of approximately 0.89. The Poisson ratio of the yarn is set as 0.3\textsuperscript{[15]}. These two moduli cases are named Twaron® fabric model (TM) and Dyneema® yarn based model (DYM), respectively.

The projectile is steel with the density of 7687g/cm$^3$. Compared with the fabric, the projectile is much stiffer. As such, the projectile is defined as a rigid body, which means that it is not deformable in the whole process. The Poisson ratio is set as 0.3\textsuperscript{[93]}.

A pair of coefficients of friction including coefficient of static friction (CSF) and coefficient of kinetic friction (CKF) is set to indicate the variations of inter-yarn friction in the fabric. The CSF varies from 0 to 1 and CKF from 0.05 to 0.95 with 0.1 intervals. The impact velocity of the projectile in the FE simulation is set as 475 m/s since it is averaged around 475 m/s in the ballistic experiment. The energy absorption computed in the following analyses is based on the entire fabric although the model in FE simulation is a quarter based.
4.3 Effects of inter-yarn friction on energy absorption

4.3.1 Overall energy absorption

The overall energy absorption is the total energy absorbed by the fabric ultimately, which equals to the total projectile energy loss. The changing trend of overall energy absorption with the increase of inter-yarn friction is plotted in Figure 4-1. There are some similarities in the two moduli cases. The overall energy absorption presents an increasing trend as the level of the inter-yarn friction increases from CSF of 0.30 and CKF of 0.25 to CSF of 0.80 and CKF of 0.75 in case of TM and to CSF of 0.60 and CKF of 0.55 in case of DYM and it slightly decreases at much higher inter-yarn friction. The difference between the two cases lies in the levels of the inter-yarn friction from zero to CSF of 0.30 and CKF of 0.25. In this range, the overall energy absorption in the DYM 112 GPa case gradually grows with the increase of inter-yarn friction but it shows an opposite trend in the TM 72 GPa case. It should be noted that the overall energy absorption in DYM case is larger than that in TM case because larger modulus is more efficient in dissipating the impact energy, leading to more energy absorption.

Figure 4-1 Overall energy absorption with increase of inter-yarn friction
The trend of the overall energy absorption with the increase of inter-yarn friction in DYM 112 GPa case agrees with the previous work carried out by Zhou et al.\cite{17}, Sun et al.\cite{18}, Duan et al.\cite{12} and Briscoe and Motamedi\cite{10}. However, the trend of overall energy absorption decreasing as the inter-yarn friction grows from zero to CSF of 0.30 and CKF of 0.25 has never been found in any previous investigations. It is assumed that the Young’s modulus plays a role. Thus, the Young’s modulus is extended to a larger range and the trends of overall energy absorption with the increase of inter-yarn friction at those Young’s modulus conditions are plotted in Figure 4-2. When the Young’s modulus is relative lower, for instance, 72 GPa and 52 GPa, the trends of the overall energy absorption with the increase of inter-yarn friction are almost similar, which indicates that it is possible that the near zero inter-yarn friction gives rise to higher energy absorption. Since the overall energy absorption is related to the energy absorption rate and the failure time, the effects of inter-yarn friction on these two aspects will be discussed.

Figure 4-2 Overall energy absorption at different Young’s modulus cases

### 4.3.2 Energy absorption rate

#### 4.3.2.1 Results

Although the ballistic impact is almost a transient process, the energy absorption is still a time dependent parameter. The energy absorption rate is a parameter computed from the
overall energy absorption divided by time. Thus, the energy absorption rate denotes the average energy absorbed in a unit time, or termed as average energy absorption rate which reflects how fast the fabric can dissipate the impact energy. In fact, the energy absorption in the whole time history is not an uniform process. It may be due to the non-homogenous nature of the fabric structure and the asynchronism of the failure of each yarn. Despite the non-uniformity of the energy absorption, the average energy absorption rate can still reflect the efficiency of the energy absorption at different frictional levels.

The energy absorption rates in TM 72 GPa and DYM 112 GPa cases are plotted as a bar chart in Figure 4-3. The energy absorption rates with the increase of the inter-yarn friction in the two different moduli cases display a similar pattern, where it increases monotonously with the increase of inter-yarn friction. Comparing the effect of inter-yarn friction on the overall energy absorption with that on the energy absorption rate, it is clear the parameter that the inter-yarn friction can make increase monotonously is the energy absorption rate rather than the overall energy absorption. The following is to analyse the underlying reasons.

![Figure 4-3](image)

Figure 4-3 The average energy absorption rate with the increase of the inter-yarn friction

**4.3.2.2 Analyses and discussions**

Figure 4-3 indicates that higher inter-yarn friction will result in higher energy absorption.
rate in the two moduli cases. It may be attributed to the increased resistant forces acting on the projectile from the fabrics with higher friction levels. The higher resistant force from the fabric would accelerate the loss of the projectile velocity and in turn make the energy transfer to the fabric more efficiently. The resistant force can be calculated based on the impulse principle as shown in Equation 4-1. Figure 4-4 plots the resistant forces acting on the projectile in different frictional levels in TM 72 GPa case and DYM 112 GPa case, respectively. The resistant force calculated is the average force resisting the projectile during the whole time history. As the process proceeds, the resistant force to the projectile becomes less and less because the fabric structure begins to fail. Despite the resistant force attenuating with time, the average resistant force is still an useful indicator that can assist in reflecting the difference among the resistant forces acting on the projectile. In the two moduli cases, the resistant force on the projectile is higher with higher levels of inter-yarn friction. The reason may be that higher inter-yarn friction makes yarn-yarn joint force at the crossover within the fabric become stronger, and thus enables the yarns in the entire fabric function more efficiently to obstruct the projectile.

\[ f t = m v_i - m v_r \]  

(4-1)

where \( f \) is resistant force; \( t \) is failure time; \( m \) is the mass of the projectile; \( v_i \) and \( v_r \) are the impact velocity and the residual velocity of the projectile.

Figure 4-4 The average resistant force acting on the projectile from the fabric
4.3.3 Failure time of the fabric

4.3.3.1 Results

The trend of the failure time for the fabric with the increase of inter-yarn friction is shown in Figure 4-5. The failure time is the total time from the beginning of the impact to the fabric failure, which is the moment when the energy absorbed by the fabric keeps unchanged. In the TM 72 GPa case, the time significantly shortens with the increase of the friction while it becomes a little longer as the CSF grows starting from 0.40 to 0.80 and CKF from 0.35 to 0.75. When the friction is higher than CSF of 0.80 and CKF of 0.75, the time becomes shorter once more. As DYM 112 GPa is concerned, the time firstly decreases as the inter-yarn friction increases by CSF of 0.20 and CKF of 0.15 and then gradually increases as the inter-yarn friction increases. When the inter-yarn friction reaches a much higher level of CSF of 0.80 and CKF of 0.75, the time decreases again. The trend of the failure time with inter-yarn friction in the two cases is similar. The difference between the maximum failure time and minimum is around 2 µs in DYM 112 GPa case whilst that for TM is approximate 6 µs. The failure mechanism will be further explored.

Figure 4-5 The trends of failure time of fabrics with the increase of the inter-yarn friction
4.3.3.2 Failure mechanism

Based on the trend of the failure time with the increase of inter-yarn friction, it is assumed that there should be some negative effects and positive effects caused by inter-yarn friction. The distribution of tensile stress and shear stress on primary yarns, the involvement of secondary yarns and the structure stability at the impact centre would be responsible for the failure of the fabric. In this way, the understanding of the effects of inter-yarn friction on the failure mechanism will be explained with respect to the mentioned items.

4.3.3.2.1 Tensile failure

In a ballistic impact event, the broken of primary yarns is responsible for the failure of a fabric. Since the modelled impact velocity is around 475 m/s which is in the critical velocity range (referring to section 2.4.1.2), the broken of primary yarns is the combination of tensile failure and shear failure. To explore the effects of inter-yarn friction on the tensile failure mode, the tensile stress loaded on primary yarns are firstly studied. The effects of inter-yarn friction on the shear failure mode will be discussed in the next section. Tensile stress is a stress component along the axis of the yarns and is hoped to be uniformly distributed on a larger area and propagate fast far from the impact point. Figure 4-6 and 4-7 plot the tensile stress distributions on the selected two primary yarns in TM case and DYM case, respectively. The positions of the selected primary yarns (warp yarn 2 and weft yarn 2) are shown in Figure 4-8. The horizontal axis is the distance from the impact centre. The time point for each case is selected every 3 µs. The end time points for the two cases are selected as 6 µs and 12 µs because after those time points the primary yarns in each case begin to fail.

The speeds of the tensile stress propagation at different frictional levels are the same but the inter-yarn friction affects the distribution of tensile stress on the primary yarns. It is noticeable that the tensile stress in the case of higher frictional level near the impact centre is higher than that in the case of a lower friction level. Conversely, the tensile stress at the stress wave front far from the impact centre in the case of lower friction is higher than that in the case of higher inter-yarn friction. This type of stress distribution indicates that the tensile stress concentrates more at higher levels of inter-yarn friction.
Specially, focusing in the area 3-5mm from the impact centre where the break takes place for the used projectile, the tensile stress taken by the primary yarns at higher level of inter-yarn friction is always higher than that at lower one. Due to the limitation of the space, the tensile stress distributions on other primary yarns are not presented here but the distribution trend is similar to these in the representative yarns. With the increase of inter-yarn friction, the yarns are more likely to be hindered at the interlacing points, and less tensile stress can pass over the crossovers and transmit out. The tensile stress concentration is harmful because it will lead to the earlier tensile failure of the fabric. For this reason, the primary yarns would fail a little earlier at higher inter-yarn friction.

Figure 4-6 The distribution of tensile stress on the primary yarns in TM 72 GPa case
(a) warp yarn 2 at 3 $\mu$s

(a') weft yarn 2 at 3 $\mu$s

(b) warp yarn 2 at 6 $\mu$s

(b') weft yarn 2 at 6 $\mu$s

(C) warp yarn 2 at 9 $\mu$s

(C') weft yarn 2 at 9 $\mu$s
Apart from tensile stress acting on the yarns during ballistic impact, the yarns also subjected to the shear action. The shear stress mainly refers to the stress acting on the cross-section of a yarn. To clarify the effects of inter-yarn friction on the shear action, the shear stress distribution on the primary yarns is also investigated. Warp yarn 2 and weft yarn 2 in Figure 4-8 are still selected as the representatives of the primary yarns. The distributions of the shear stress on these two yarns for TM 72 GPa case and DYM 112 GPa case during the impact event at different frictional levels are presented in
Figure 4-9 and Figure 4-10 below, respectively. The time points selected are similar to those in Figure 4-6 and 4-7.

At 3 µs, the shear stress on the primary yarns in the narrow region 3-4 mm away from the impact centre which is right around the edge area of the cylindrical projectile is larger in higher frictional level. In other parts of the primary yarns, the shear stress fluctuates on a small scale, and the inter-yarn friction has no effects. As the time goes on, the area is enlarged. The shear stress keeps higher value at higher level of the inter-yarn friction until 6 µs for TM case and 12 µs for DYM case near the edge of the projectile. It should be mentioned here that the shear stress distribution on the other primary yarns also shows such trends although they are not presented here because of limitation of space. All in all, during the whole process, the primary yarns near the projectile edge at higher level of inter-yarn friction continuously load the higher shear stress. This may be that higher inter-yarn friction can increase the transverse modulus of the fabric\textsuperscript{[10]}, and the fabric cannot transversely deform more, which will be verified in the section of 4.4.2, and thus the projectile has to break the primary yarns by more shear action. In turn, it will increase the possibility that the primary yarn fail earlier due to the shear action.
Figure 4-9 The distribution of shear stress on the primary yarns in TM 72 GPa case
4.3.3.2.3 Involvement of secondary yarns

In the impact process, due to the small contact area between the projectile and the fabric, the number of primary yarns is very few. In the current model, there are five primary yarns directly resisting the projectile. It is anticipated that the involvement of secondary could be more. Therefore, the involvement of secondary yarns in ballistic impact with the increase of inter-yarn friction are investigated. It can be understood from the stress taken by them and the involved area occupied by them. The area occupied by secondary yarns indicates the area that the impact energy can distribute onto and the stress taken by them indicates the amount of stress transferred out from the impact centre.

(1) Enhanced stress taken by secondary yarns near the impact centre

The stress taken by secondary yarns discussed is the total stress on them because the total stress is the reflection of their full ability to share the impact energy. To investigate
the total stress shared by the secondary yarns, the von Mises stress $\sigma$ is used as the indicator, which is a combination of three primary stresses $\sigma_x$, $\sigma_y$, $\sigma_z$ and three shear stresses $\tau_{xy}$, $\tau_{yz}$, $\tau_{xz}$ and is expressed in Equation 4-2. The von Mises stress at a material point approximately equals to the total stress in the fibre\(^{[13]}\). It is usually used to represent the total stress in the yarns in Abaqus\(^{[52,53]}\). The yield stress is set as 2.9 GPa. Figure 4-11 and 4-12 show the von Mises stress distribution on the selected secondary yarns in TM 72 GPa case and DYM 112 GPa case individually. The positions of the selected two representative secondary yarns are described in Figure 4-13. The maximum time is set as 9 $\mu$s for TM 72 GPa case and 12 $\mu$s for DYM 112 GPa because the fabric structures begins to be significantly damaged after the time points. It should be mentioned here that the stress distributions on other secondary yarns near the impact centre follow the same rule. At a given time, the stress taken by the secondary yarns near the impact centre is always larger at higher levels of inter-yarn friction. In addition, the area that the secondary yarns take more stress at higher level of inter-yarn friction is enlarged with advance of time. There is a smaller area near the wave front where the secondary yarns take lower stress for larger inter-yarn friction. The stress distribution on the selected secondary yarns in DYM case is similar to that in TM case. This type of stress distribution indicates that the stress taken by the primary yarns is more likely to disperse to the neighbouring secondary yarns with higher levels of inter-yarn friction. The higher inter-yarn friction can enable secondary yarns to engage more in alleviating the stress that primary yarns take because of the increased stress wave diversion\(^{[39,148]}\).

$$\sigma = \frac{1}{\sqrt{2}} \left[ (\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{xz}^2) \right]^{1/2} \quad (4-2)$$

(a) warp yarn 5 at 3 $\mu$s

(a’) weft yarn 5 at 3 $\mu$s
Figure 4-11 The von Mises stress distribution on the secondary yarns in TM 72 Gpa

(a) warp yarn 5 at 3 µs
(b) warp yarn 5 at 6 µs
(c) warp yarn 5 at 9 µs

(a') weft yarn 5 at 3 µs
(b') weft yarn 5 at 6 µs
(c') weft yarn 5 at 9 µs
(b) warp yarn 5 at 6 µs

(b') weft yarn 5 at 6 µs

(c) warp yarn 5 at 9 µs

(c') weft yarn 5 at 9 µs

(d) warp yarn 5 at 12 µs

(d') weft yarn 5 at 12 µs
Figure 4-12: The von Mises stress distribution on the selected secondary yarns in DYM 112 GPa case

Figure 4-13: The position of the selected secondary yarns in red colour: warp yarn 5 along the x axis and weft yarn 5 along the z axis

(2) More involved area occupied by secondary yarns

Figure 4-14 and 4-15 display the profile of the involved area in the transverse wave from the FE simulation near the failure of the fabric in the two moduli cases, and the elements with green colour is the involved area. Based on the profiles, the shape of the involved area slightly changes from triangle-like to more circular-like at higher levels of inter-yarn friction. The more circular-like shape indicates that the transverse wave spreads to more secondary yarns. The reason that the involved area becomes more circle-like may be that the higher inter-yarn friction makes the whole structure more isotropic and more
homogenous structure enables the transverse wave propagate uniformly in all directions.

Figure 4-14 The profile of area involved in TM 72 Gpa case at 9µs

Figure 4-15 The profile of area involved in DYM 112 GPa case at 12 µs

To observe the changing process of the involved area, the involved areas in the transverse wave in the two moduli cases every 3 µs at the selected four frictional levels are described in Figure 4-16 and 4-17 respectively. The horizontal and vertical axis indicate the involved area along the warp direction and the weft direction respectively. In these figures, the area formed by the two axes and the points are the involved area. At 3 µs, the involved area at different frictional levels are almost the same. In the latter stage, the involved area is enlarged by a slight increase of inter-yarn friction (from zero friction to CSF of 0.30 and CKF of 0.25). Much higher inter-yarn friction has little effects. Most of the enlarged areas is the area occupied by secondary yarns according to the position of secondary yarns in Figure 4-15. Increasing inter-yarn friction will increase the involved area in the transverse wave and thus increase the involvement of the secondary yarns because higher inter-yarn friction increases the diversion of the stress propagation [39, 148].
Figure 4-16 The propagation of area covered by transverse wave in TM 72 GPa case

(a) 3 µs

(b) 6 µs

(c) 9 µs
(3) Analyses and discussion

From analyses of the stress distribution on secondary yarns and the involved area, increasing inter-yarn friction can enable secondary yarns to share more stress near the impact centre and more secondary yarns involve in. These two effects lead to more involvement of secondary yarns. The more involvement of secondary yarns leads to more energy absorbed by them, which indicates the load undertaken by primary yarns can be largely alleviated and efficiently transferred to secondary yarns. Figure 4-18 shows the energy absorbed by the secondary yarns and the primary yarns occupied in the overall energy absorption with the increase of inter-yarn friction, respectively. Here the energy absorbed only includes KE and SE. The FDE is not in calculation because it is infeasible to distinguish the FDE between primary yarns and secondary yarns in FE simulation. In the case of zero friction, the energy dissipated by the secondary yarns is the smallest one, accounting for 65.09% and 67.74% respectively for each modulus case. With the increase of inter-yarn friction, the secondary yarns dissipate more energy until the friction is beyond CSF of 0.60 and CKF of 0.55 in TM case and CSF of 0.40 and CKF of 0.35 in DYM case. On the contrary, the amount of energy absorbed by the primary yarns as the function of inter-yarn friction presents an opposite trend. It is confirmed that secondary yarns can be engaged more in energy absorption to avoid the energy concentration on the primary yarns. This is a beneficial action that can keep the primary yarns sustain longer and thus postpone the failure. The current finding confirmed the investigation form Roylance\cite{39,148} that increasing inter-yarn friction will
increase the diversion part of the stress wave propagation, making the impact energy loaded on primary yarns more transfer to secondary yarns. Further increasing inter-yarn friction no longer affects the percentages of energy absorbed by secondary yarns and primary yarns. This indicates that an optimal inter-yarn friction exists for the most involvement of secondary yarns. That may be that the proportion of stress diversion at the crossover is not increased with the increase of inter-yarn friction beyond certain level of inter-yarn friction.

4.3.3.2.4 Structure stability

Figure 4-19 and 4-20 compare the stability of the fabric structure among selected three levels of inter-yarn friction in the impact area during the whole impact process in TM case and DYM case, respectively. In the TM case, there are always two and half yarns contacting with the nose face of the projectile until 10 µs in the two higher friction conditions in each direction. However, only one and half yarns left contact in each direction in zero friction level from 5 µs onwards. In the DYM case, at 3 µs, two and half primary yarns in each direction come into contact with the flat nose face of the projectile at each frictional condition. From 6 µs onwards, two of the primary yarns at the edge of the cylinder begin to slide away from the projectile face in the zero friction level and only one and half yarn left until 9 µs. For the other two frictional conditions, two and half yarns in each direction are always kept contact with the face of projectile.
until 15 µs. More inter-yarn friction holding the structure more stable at impact centre has also been observed in the investigation carried out by Ha-Minh\textsuperscript{19} and Rao\textsuperscript{20}. Greater structure stability can make more yarns directly resist the projectile, which would prolong the time to perforate the fabric. However, there is no difference between the structure stability at those higher inter-yarn frictional levels, CSF of 0.70 and CKF of 0.65, and CSF of 1.00 and CKF of 0.95. The reason may be that the mobility of yarns at those levels of inter-yarn friction might be restricted to the same level.
Figure 4-19 Structure stability at the impact area in TM 72 GPa case

(a) CSF=0, CKF=0
(b) CSF=0.7, CKF=0.65
(c) CSF=1.0, CKF=0.95

10µs

3 µs

6 µs

(a) CSF=0, CKF=0
(b) CSF=0.7, CKF=0.65
(c) CSF=1.0, CKF=0.95
Figure 4-20 Structure stability at the impact area in DYM 112 GPa case

4.3.3.3 Discussion of the failure mechanism in different frictional levels

On one hand, increasing inter-yarn friction leads to more involvement of secondary yarns and hold the structure more stable. On the other hand, it produces more tensile and shear stress concentration and less transverse deflection ability. The effects of inter-yarn
fication on the transverse deflection ability will be discussed in the section 4.4.2. It is speculated that the failure of the fabric results from these positive and negative effects caused by increasing inter-yarn friction.

Without inter-yarn friction, the fabric can transversely deform more to form a stress gradient and alleviate the yarn tension in the impact centre, resulting in the primary yarn surviving longer\textsuperscript{[161]}. This can be evidenced by the largest transverse deflection ability of the fabric at zero inter-yarn friction. With the increase of inter-yarn friction ranging from CSF and CKF (0, 0) to (0.40, 0.35) in TM case and from CSF and CKF (0, 0) to (0.20, 0.15) in DYM case, the failure time decreases. This may be because negative effects are much more pronounced, leading to the earlier fabric failure. However, beyond the aforementioned levels, CSF and CKF (0.40, 0.35) for TM and CSF and CKF (0.20, 0.15) for DYM, the failure time becomes a little longer. The explanation may be that the positive effects caused by increasing the inter-yarn friction cover the negative effects that it brings, and the transverse deflection ability no longer decreases, thus prolonging the fabric failure. As the frictional level is in excess of CSF of 0.80 and CKF of 0.75, the advantages caused by increasing inter-yarn friction diminish. In turn, the stress concentration becomes more dominant and results in the decline of the failure time again.

Thus, it can be concluded that in the whole applied inter-yarn friction range, the positive effects and negative effects compete with each other, leading to the fluctuation of the failure time. Comparing the TM fabric to DYM fabric, the decrease in the failure time with an initial increase of inter-yarn friction is more significant. This is because the transverse deflection ability of the TM fabric is more significantly decreased. The reasons can refer to section 4.4.2. If the fabric has the comparative advantage in the transverse deflection ability, the fabric can transversely deflect more to sustain longer.

\textbf{4.3.4 Analyses and discussion on the mechanism of energy absorption}

The overall energy absorption depends on two parameters, one being the energy absorption rate and the other being the total failure time. However, in the previous investigations, researchers only observed the effects of inter-yarn friction on either
energy absorption rate or failure time \cite{12-15, 17, 18}. Increasing overall energy absorption can be achieved in two manners, absorbing energy much more efficiently and prolonging the failure of the fabric. However, slightly increasing the inter-yarn friction will on one hand result in higher energy absorption rate owing to the higher resistance force. On the other hand, it would aggravate the stress concentration from tension stress and shear stress acting on the primary yarns near the impact area and decrease the transverse deformation ability, leading to less failure time.

The time history of energy absorption curves at different levels of inter-yarn friction are plotted below in Figure 4-21 and 4-22. The slope of the curve represents the energy absorption rate and the moment that the curve flattening indicates the failure of the fabric. It is not difficult to discover that the overall energy absorption with the increase of inter-yarn friction in the TM case is more dependent on the failure time in the frictional range from zero friction to CSF of 0.30 and CKF of 0.25; while from CSF of 0.30 and CKF of 0.25 to CKF of 0.80 and CSF of 0.75, it is more dependent on the energy absorption rate. In DYM case, the overall energy absorption more relies on the energy absorption rate from zero friction to frictional level of CKF of 0.80 and CSF of 0.75. With higher levels of the inter-yarn friction, the overall energy absorption in both moduli cases begins to decrease because of the significant decrease of the failure time, referring to Figure 4-1.
Figure 4-21 Time history of energy absorption in TM 72 GPa case

Figure 4-22 Time history of energy absorption in DY M 112 GPa case
4.4 The effects of inter-yarn friction on fabric response modes

4.4.1 The fabric response modes

In the ballistic impact, it is more anticipated that the fabric give a globalised response rather than a localised one because the localised response would cause more serious trauma. A globalised response indicate the energy absorbed spread through a larger area of the fabric. To investigate the effect of inter-yarn friction on the response mode, the effects of inter-yarn friction on the transverse deflection velocity and the transverse wave velocity should be taken into account because the transverse wave velocity and transverse deflection velocity indicate the rate of energy distribution in horizontal and vertical direction respectively. The two velocity are obtained from the base radius and the depth of the back-face signature (BFS) divided by the failure time respectively. The BFS is the pyramid-like shape formed by the fabric transverse deflection at the end of impact. Those parameters are annotated in Figure 4-23.

![Figure 4-23 The back-face signature of the fabric](image)

Figures 4-24 and 4-25 shows the transverse deflection velocity and transverse wave velocity as function of inter-yarn friction. It can be seen that increasing inter-yarn friction to the level of CSF of 0.5 and CKF of 0.45 is better for decreasing the transverse deflection velocity and accelerating the transverse wave velocity. In other words, increasing inter-yarn friction will cause the response of the fabric transfer from a more localised one to lobalised one, as shown in Figure 4-26. Increasing inter-yarn friction
Aiding fabric response globally may be because the transverse deflection ability of the fabric decreases with higher inter-yarn friction. The effect of inter-yarn friction on the transverse deflection ability of the fabric will be discussed in the next section. It is thus clear that although the TM fabric absorbs more energy at zero friction, the energy absorption mode is not desirable because it is a localised energy absorption mode.

Figure 4-24 The effects of inter-yarn friction on the transverse deflection velocity

Figure 4-25 The effects of inter-yarn friction on the transverse wave velocity
4.4.2 Transverse deflection ability

To indicate transverse deflection ability of a fabric, an angle $\beta$ is developed. The angle $\beta$ is formed between the deformed fabric and the undeformed one, as shown in Figure 4-27. It equals to the arc tangent value of the ratio between BFS depth $D$ and BFS base radius $R$, as expressed in Equation 4-3. A smaller angle $\beta$ is desirable because smaller angle means that the fabric is less prone to deflect transversely upon the ballistic impact and thus cause less trauma.

$$\beta = \tan^{-1} \frac{D}{R} \quad (4-3)$$

Figure 4-27 The illustration of the angle $\beta$

Figure 4-28 shows the trend of $\beta$ with the increase of inter-yarn friction. It shows that the angle $\beta$ decreases with the inter-yarn friction increasing from zero friction to CSF of 0.40 and CKF of 0.35. This has also been found in the investigation carried out by Briscoe and Motamedi\[10\]. It is assumed that more inter-yarn friction at crossover may
restrain the bending of the yarn and thus the fabric transversely deflect less. After a certain level of inter-yarn friction, the transverse deflection ability is no longer affected by the inter-yarn friction and the materials, which may be explanation that the constrain from the friction at the crossover reaches the maximum and over high inter-yarn friction cannot take any effect.

Comparing the transverse deflection ability of the fabric in the low frictional range from zero friction to the level of CSF of 0.30 and CKF of 0.25 with that in the high frictional range, fabrics at the low frictional range have the comparative advantage of the transverse deflection ability. This advantage is a way to alleviate the stress in the impact centre by manner of transversely deflecting more, thus the fabric can sustain longer. In this frictional range, increasing inter-yarn friction will weaken the transverse deflection ability, in other words, reduce the failure time. This is one of the reasons for that in this range, increasing inter-yarn friction will significantly decrease the failure time.

In addition, in the low frictional range, increasing inter-yarn friction will more significantly decrease the transverse deflection ability of the TM fabric than that of the DYM fabric. The explanations are as follows. The transverse deflection ability of the fabric is related to the transverse modulus of the yarn in it. For the transverse modulus, it is positively dependent on the Young’s modulus of the yarn and thus the transverse modulus of Dyneema® yarn is larger than that of Twaron® yarn. Since the transverse
deflection ability of the fabric is related to the transverse modulus of the yarn, where the larger transverse modulus of the yarn means the corresponding fabric is less likely to deflect transversely, the transverse deflection ability of the DYM fabric is smaller than that of the TM fabric and consequently the room for decreasing the transverse deflection ability of the DYM fabric is less. Hence, the transverse deflection ability of the TM fabric will be more significantly affected with the initial increase of inter-yarn friction than that of the DYM fabric. The descending degree of the transverse deflection ability with increasing inter-yarn friction corresponds to the descending degree of the failure time. Therefore, the failure time of the DYM fabric decreases more than that of the TM fabric.

4.5 Effects of inter-yarn friction on forms of energy absorption
4.5.1 The energy transfer between the projectile and the fabric

When a projectile impacts a fabric, strain is generated in the yarns and part of the energy carried by the projectile is dissipated as strain energy (SE) in the fabric. Meanwhile, the fabric at the impact area would move because of the pulling force of the projectile, leading to energy being absorbed by the fabric in the form of kinetic energy (KE). Apart from these two routes for dissipation of the projectile energy, inter-yarn friction also plays a role by frictional sliding, which is named as frictional dissipation energy (FDE). During the impact, KE, SE and FDE are regarded as the three main forms of energy absorption to dissipate the projectile energy\[13, 14\].

Figures 4-29 and 4-30 describe the percentage of KE, SE and FDE occupied in the overall energy absorption in the two moduli cases. Basically, KE is the dominant energy absorption mechanism and SE and FDE rank the second and third place through the whole process. However, in the friction levels of zero friction and CSF of 0.10 and CKF of 0.05 for DYM case, and zero friction for TM case, SE can outperform KE. Because SE is related to the transverse deflection ability of the fabric in the process, the transverse deflection ability of the fabric at those extremely low levels of the inter-yarn friction is the largest. Thus, the SE at these situations would be the dominant energy absorption form. More energy being absorbed in the form of SE is not desirable because more SE means more transverse deflection of the fabric.
Figure 4.29 The ultimate percentage of KE, SE and FDE in TM 72GPa case

Figure 4.30 The ultimate percentage of KE, SE and FDE in DYM 112 GPa case

4.5.2 The forms of energy absorption

Figure 4.31 describes the proportion of KE as function of inter-yarn friction in the two moduli cases. In both moduli cases, the percentage of KE shows a slight increasing tendency with the increase of inter-yarn friction. Figures 4.32 and 4.33 plot the time history of the KE at different frictional levels in the two moduli cases, respectively.
From the two figures, it is found that the final KE depends more on the KE absorption rate, which is the slope of the curve in Figures 4-32 and 4-33. The KE absorption rate also increases with the increase of inter-yarn friction. Higher inter-yarn friction leading to higher KE absorption rate may be related to the larger transverse wave velocity at higher levels of inter-yarn friction, referring to Figure 4-25. Larger transverse wave velocity will enable the impact energy to be distributed onto a larger area efficiently. Since the KE absorption rate is associated with the involved area at each moment, the higher inter-yarn friction would give a higher KE absorption rate, thus higher KE percentage.

![Figure 4-31 The effects of inter-yarn friction on KE](image-url)
Figure 4-32 Time history of KE in TM 72 GPa case

Figure 4-33 Time history of KE in DYM 112 GPa case
Figure 4-34 shows the effect of inter-yarn friction on the SE percentage in the two moduli cases. The trends of SE percentage as the function of inter-yarn friction in two moduli cases are a little different. In DYM case, the amount of SE fluctuates with the increase of inter-yarn friction. The fluctuation is in a small range, around 5%. Differently, in TM case, the SE percentage dramatically decreases from 35% to 15% from zero friction to CSF of 0.30 and CKF of 0.25. It is kept almost at that level in the remain frictional levels. It can be concluded that increasing inter-yarn friction to the level of CSF of 0.30 and CKF of 0.25 will significantly decrease the SE percentage of the TM fabric than that of the DYM fabric. This may be associated with the difference of transverse deflection ability between the two fabric. It is observed that slightly increasing inter-yarn friction more significantly decreases the transverse deflection ability of the TM fabric but the transverse deflection ability of the DYM fabric decreases less.

The FDE proportion as function of inter-yarn friction is depicted in Figure 4-35. The proportion of FDE firstly dramatically reaches a peak and then decreases with the increase of inter-yarn friction. It is reasonable that with a small increase of inter-yarn friction, the FDE increases dramatically because the work done by friction is linear to the magnitude of frictional force. However, much higher inter-yarn friction would restrain the motion of the yarns, leading to a much lower FDE. The amount of FDE is
not only related to the coefficients of friction but also to the relative motion between yarns. An optimum level of inter-yarn friction exists for each fabric for achieving the highest amount of FDE.

![Figure 4-35 The effects of inter-yarn friction on FDE](image)

### 4.6 Summary

In this chapter, the effects of inter-yarn friction in quasi-static state on ballistic performance have been analysed using FE simulation in the two Young's moduli cases of 72 GPa and 112 GPa. The relationships between the inter-yarn friction in quasi-static state and the overall energy absorption, the fabric response mode and the forms of energy absorption during the ballistic impact have been established. The main results from the FE theoretical analyses are given below:

1. The overall energy absorption increases with the increase of inter-yarn friction. The reasons are given below:
   1. The fabric with higher inter-yarn friction presents higher resistance to the projectile, thus increasing the energy absorption rate and enabling the fabric to dissipate the impact energy much more efficiently;
   2. At higher levels of inter-yarn friction, the structure of fabric can be kept much more stable, leading to more yarns involved into directly resisting the projectile;
   3. More inter-yarn friction leads to more involvement of secondary yarns to participate into loading the impact energy thus alleviating the loads in primary
yarns and prolonging the failure of primary yarns.

(d) Increasing inter-yarn friction can increase the KE percentage and FDE percentage.

It should be noted that much higher inter-yarn friction is counterproductive because it will cause the stress to be more concentrated on primary yarns, resulting in earlier failure of a fabric. In addition, it is not the desirable energy absorption mode that the TM fabric near zero friction absorbs more energy because the mode is a localised response.

(2) The transverse deflection ability of the fabric relates to Young’s modulus of the yarn. Larger Young’s modulus gives rise to lower transverse deflection ability, and vice versa.

(3) Increasing inter-yarn friction decreases the transverse deflection abilities of fabrics. The response of fabric will transfer from a localised response to a globalised one with the increase of inter-yarn friction. This effect is more pronounced for the fabric with the yarn of lower Young’s modulus.

(4) Increasing inter-yarn friction can affect the forms of energy absorption. Near zero friction, SE is the dominant mechanism of a fabric. With the increase of inter-yarn friction, KE becomes the dominant one. Moreover, increasing inter-yarn friction can increase the KE percentage. Slightly increasing inter-yarn friction will significantly decrease the SE percentage of the fabric with yarns of lower Young’s modulus but affect that of the fabric with yarns of higher Young’s modulus little. An maximum inter-yarn friction exists for FDE absorption.

Through the theoretical analyses, increasing inter-yarn friction is feasible for improving ballistic performance of body armour constructed by woven fabrics. Based on results in this chapter, a small increase of inter-yarn friction in quasi-static state is advantageous to increase the overall energy absorption of the fabric with yarns of Young’s modulus of 112 GPa and reduce the transverse deflection for the fabric with yarns of Young’s modulus of 72 GPa. The following chapters will investigate the surface modification of the corresponding yarns and fabrics to increase the inter-yarn friction, eventually improve the ballistic performance.
Chapter 5 Yarn Surface Modification by Atmospheric Pressure Plasma Enhanced Vapour Deposition (APPCVD)

5.1 Introduction

Owing to the benefits of a small increasing in inter-yarn friction for improving ballistic performance of fabrics, this chapter aims to increase inter-yarn friction practically. The method for modification of inter-yarn friction will be through plasma enhanced vapour deposition (PCVD) treatment. In our previous work\cite{18}, woven Kevlar® fabrics were treated with PCVD method using low-pressure plasma, which demonstrated obvious modification to the fibre surface and increase of friction between yarns\cite{18}. In order to simplify the surface modification, the current research focuses on coating the aramid yarns with PCVD technology at atmospheric pressure (APPCVD). The application of this method will be extended to other aramid yarns and UHMWPE yarns. One of the organic silicon compounds, (CH3)2Cl2Si, is selected as the precursor substance. The following sections will explore the effects of APPCVD treatment time on surface morphology, surface chemical groups, inter-yarn friction and tensile properties for the treated yarns. SEM observation will be performed to characterise the morphology of the untreated and treated yarns. Both FTIR and EDX analyses are going to be used to confirm the products on the surface of fibres. The inter-yarn friction and the tensile properties after treatments will be assessed by the method introduced in Chapter 3 section 3.4.2 and 3.4.3 respectively.

5.2 APPCVD treatment principles

When a chemical is carried into the reactor in the APPCVD equipment, it can gain energy through inelastic collision with high-energy species especially with the electrons in the plasma. The bonds of the chemicals will be broken up and a new substance would
be deposited on the surface of a substrate. The substance and the substrate would be constantly subjected to the plasma until the process is finished. Since high-performance fibre is somewhat inert to normal chemical reactions, APPCVD treatment would be an choice to make chemical or physical changes to these fibres.

APPCVD is one of popular approaches to treating textiles\textsuperscript{[203, 204]}. Compared to other treatments such as the traditional chemical methods, this treatment is less material consuming, easier operating, much more environmental friendly\textsuperscript{[205, 206]} and it generate less effluents. It is also a good way to deposit non-polymerisable substance at normal condition on the surface of a substrate. In addition, the APPCVD process would only affect a few topmost atomic layers of the substrate surface, ensuring that the bulk of the substrate is not affected, thus allowing a decoupling of the surface properties from the bulk properties of the material and giving the product designer considerable new degree of freedom\textsuperscript{[207]}.

### 5.3 Materials and treatment process

#### 5.3.1 Materials

The chemical \((\text{CH}_3)_2\text{Cl}_2\text{Si}\) is used as the precursor, and it falls into the group of organosilicon compounds, which are widely used as the precursor. Previous research has shown that the yarn pull-out property of the fabric, one of the important factors for energy absorption, increased significantly with this treatment\textsuperscript{[18]}. For the reasons given above, \((\text{CH}_3)_2\text{Cl}_2\text{Si}\) is employed for the current research. Yarns for treatment are aramid yarn, Twaron\textsuperscript{®} 93 tex, produced by Teijin Aramid and UHMWPE yarn, Dyneema\textsuperscript{®} 174 tex, offered by DSM.

#### 5.3.2 Treatment process

Figure 5-1 schematically illustrates the chemical vapour deposition on yarns under air plasma glow discharge (APGD), similar to the facilities used by Sun and Chen\textsuperscript{[18]}, but under the air atmospheric pressure. Figure 5-2 depicts the APPCVD reactor used in the experiment for the production of plasma, which is established in Salford University. The base of the chamber in the APPCVD reactor is designed to be rectangular with the size
of 10cm×5cm. The gap between the two electrodes is set to be 3 mm in the APPCVD reactor. The two types of yarns to be processed are positioned in the sample holder statically after being wrapped in a thin and smooth paper tape. The precursor chemical \((\text{CH}_3)_2\text{Cl}_2\text{Si}\) is thermostable outside the APPCVD reactor and then carried into the reactor by nitrogen gas. The precursor container has the pressure higher than that in the nitrogen gas lines. When the valves are pulsed open, the precursor vapour is simply drawn into the nitrogen gas and carried to the reaction chamber.

The APPCVD treatment includes two steps, which are (i) surface activation of yarns by nitrogen gas plasma and (ii) precursor disassociation and deposition on the activated yarns using precursor. The working gas is nitrogen and the chemical undergoing reaction is \((\text{CH}_3)_2\text{Cl}_2\text{Si}\). The plasma source is alternate current (AC) with the specified input voltage of 21.90 KV and the frequency of 3.25 kHz. The flow rate of nitrogen gas is set to be 5 L/min and the chemical flow rate is set to be 0.20 L/min.

![Figure 5-1](image1.png)

Figure 5-1 The schematic diagram for the set-up of APPCVD used

![Figure 5-2](image2.png)

Figure 5-2 Photograph of the APPCVD reactor
5.4 Twaron® yarns

5.4.1 SEM analysis

Figure 5-3 shows the morphology changes of the Twaron® yarns after APPCVD treatment. From the images, it can be seen that the treatment time has significant effects on the vapour deposition process. Polymeric fibres such as Twaron® fibres would be sized with a finish in order to improve their durability, performance and processability\cite{208}. Because of this reason, the surface of the original fibre is not smooth and some impurities are present on the fibre surface, as shown in Figure 5-3(a). This is also supported by the FTIR and EDX analyses where silicon was identified on the original fibre. In the whole APPCVD process, the chemical reactions are quite complicated, but basically the substances that the high energetic species in the plasma would interact with are (i) the neutral gases (e.g. O\textsubscript{2} and N\textsubscript{2}) present in the reactor, (ii) the chemical (CH\textsubscript{3})\textsubscript{2}Cl\textsubscript{2}Si carried into the reactor, and (iii) the aramid polymer and the original finishes on the surface of the fibre. During this process, dissociation and ionisation will take place. The interaction between the neutral gas and the plasma would produce new high energetic species. The possible collision between (CH\textsubscript{3})\textsubscript{2}Cl\textsubscript{2}Si and the plasma would lead to some particles containing silicon to be deposited on the surface of the fibre. In addition, the surface of the fibre and the finishes on the original fibre surface exposed to the plasma would be inevitably bombarded by the highly energetic species, which would cause some etch of the original finish or the topmost fibre molecular. The latter two interactions with the plasma play significant roles to the change of the morphology of the fibre. It can be seen from (b), (c), and (d) in Figure 5-3 that with a longer treatment time, the granules formed from (CH\textsubscript{3})\textsubscript{2}Cl\textsubscript{2}Si are continuously accumulated on the surface of the fibre. However, the area etched by the plasma does not show significant increase with the treatment time because the surfaces of fibres have already been covered with granular materials. The frictional behaviour of a fibre is affected by the roughness of the fibre surface, and therefore the APPCVD treatment on the fibre surface is expected to play an important role in influencing the inter-yarn coefficients of friction.
**5.4.2 FTIR analysis**

FTIR measurements were performed on both the original Twaron® yarns and the treated yarns with the treatment time being 21 seconds, 2 minutes and 4 minutes. The original Twaron® yarn was selected to be the control sample for this study. For all Twaron® yarns, the FTIR spectra in the range of 500–4000 cm⁻¹ were depicted in Figure 5-4.

Table 5-1 lists the typical assignments for the absorbance bands from FTIR microscopy. The peak at 3299 cm⁻¹ is ascribed to the stretching vibration in an amide in trans with a bonded hydrogen. The wave numbers at 1637 cm⁻¹, 1534 cm⁻¹ and 1300 cm⁻¹ are assigned to amide I (C=O) in an amide stretching vibration for hydrogen-bonded amide group, amide II (N-H deformation and C-N stretching coupled modes) and amide III (the C-N and N-H combined vibrations). 1508 cm⁻¹ is C=C stretching vibration of
aromatic ring; 1016 cm\(^{-1}\) is assigned to in-plane C-H vibration, characteristic of para-substituted aromatic compounds, particularly poly-aramids\[^{[213]}\]; 820 cm\(^{-1}\) is ascribed to be out-of-plane C-H vibration of two adjacent hydrogens in an aromatic ring (para substitution of the aromatic). 524, 726, and 862 cm\(^{-1}\) are assigned to out-of-plane N-H deformation modes. These spectra are typical of those obtained from FTIR microscopy for the original Twaron\(^{\text{®}}\) yarns, which are in agreement with the results published in the literature\[^{[214]}\].

![Figure 5-4 The FTIR spectra profile of the Twaron\(^{\text{®}}\) fibres by APPCVD treatments](image)

For the Twaron\(^{\text{®}}\) yarns with 21 seconds, 2 minutes and 4 minutes treatment, the FTIR spectra profiles of these fibres are not significantly different from these of the original. A weak difference is noticed at the absorption peak located around 1225 cm\(^{-1}\) that is assumed to be the C-N stretching and N-H deformation combined vibration in associated state. The peak at 3299 cm\(^{-1}\) becomes weaker in the circumstance of 4-minute treatment because the hydrogen bonds are destroyed by the plasma itching. The peak located at 1106 cm\(^{-1}\) has been attributed to the original finishing agent on the fibre done by the manufacturer as in Derombise et al.’s investigation\[^{[208]}\], but in Zou et al.\[^{[215]}\], the wave number is assigned to Si-O-Si anti-symmetric stretching vibrations. Therefore, the original finishing agent may be a substance containing silicon element. In this research, the chemical used for APPCVD treatment is organic silicon. During the process, the
bond in the chemical organic silicon is highly possible to be broken through collision with energetic plasma particles, leading to the formation of ion Si$^+$. The positive Si$^+$ would be combined with the oxygen particles and their products are inclined to deposit on the fibre surfaces located on the cathode. In this case, the peak of Si-O-Si vibration resulting from APPCVD treatment would be overlapping with that of the original finish agent.

Table 5-1 Assignments for the absorbance bands for the original Twaron® yarn

<table>
<thead>
<tr>
<th>Peak(cm$^{-1}$)</th>
<th>Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>3299</td>
<td>N-H stretching vibration</td>
</tr>
<tr>
<td>1637</td>
<td>Amide I, C=O stretching vibration</td>
</tr>
<tr>
<td>1534</td>
<td>Amide II, N-H deformation and C-N stretching coupled modes</td>
</tr>
<tr>
<td>1508</td>
<td>C=C stretching vibration</td>
</tr>
<tr>
<td>1300</td>
<td>Amide III, C-N stretching and N-H deformation combined vibrations</td>
</tr>
<tr>
<td>1106</td>
<td>Si-O-Si anti-symmetric stretching</td>
</tr>
<tr>
<td>1016</td>
<td>In-plane C-H vibration</td>
</tr>
<tr>
<td>862 , 726 ,524</td>
<td>Out-of-plane N-H deformation modes</td>
</tr>
<tr>
<td>820</td>
<td>Out-of-plane C-H vibration of two adjacent hydrogens in an aromatic ring</td>
</tr>
</tbody>
</table>

5.4.3 EDX analysis

To further ascertain the deposition of (CH$_3$)$_2$Cl$_2$Si on the surface of the fibre, EDX analysis was carried out and the results are shown in Table 5-2, where the data indicate the atomic percentage of the elements. Since the chemical reactions in APPCVD are quite sophisticated, the compounds formed in the reaction are usually random. However, in general, a dominant reaction is presented in the whole system. In our case, the dominant reaction is the dissociation of the element of Si from the precursor (CH$_3$)$_2$Cl$_2$Si and form Si$^+$ to compound with the other particles present at cathode, where the sample is placed. This can be seen from the deposition on the surface of the fibre. Therefore, the amount of the element of Si would increase with the increase of treatment time while the weight of other elements would possibly be irregular. It can be seen that for the original
Twaron® fibre, a small quantity of silicon is presented on the surface of the fibre, which confirms the FTIR result. However, the atomic percentage of silicon increases from 0.07% for 21-second treatment to 0.99% for 4-minute treatment. This is a strong indication of deposition of the chemical compound (CH$_3$)$_2$Cl$_2$Si. It is also worth mentioning that chlorine element starts to show on the surface of the fibre after 4 minutes of treatment as a result of the compound deposition.

Table 5-2 The components of the elements on the Twaron® fibres by APPCVD treatments

<table>
<thead>
<tr>
<th>Treatment time</th>
<th>C</th>
<th>N</th>
<th>O</th>
<th>Si</th>
<th>Cl</th>
</tr>
</thead>
<tbody>
<tr>
<td>original</td>
<td>83.24</td>
<td>2.04</td>
<td>11.48</td>
<td>0.02</td>
<td>-</td>
</tr>
<tr>
<td>21 seconds</td>
<td>81.24</td>
<td>6.00</td>
<td>9.54</td>
<td>0.07</td>
<td>-</td>
</tr>
<tr>
<td>2 minutes</td>
<td>72.26</td>
<td>14.69</td>
<td>9.41</td>
<td>0.34</td>
<td>-</td>
</tr>
<tr>
<td>4 minutes</td>
<td>82.07</td>
<td>-</td>
<td>12.39</td>
<td>0.99</td>
<td>0.52</td>
</tr>
</tbody>
</table>

5.4.4 Coefficients of friction

Figure 5-5 displays the changes of the coefficients of both static and kinetic friction of yarns before and after the treatments. The method for computing the two coefficients of friction from the output tensions can refer to Chapter 3 section 3.4.2. In Figure 5-5, CSF stands for coefficient of static friction and CKF refers to the coefficient of kinetic friction. With a longer treatment time, both CSF and CKF increase. The CKF is increased from 0.18, for which the treatment time is 21 seconds, to 0.24 when the treatment time is prolonged to 4 minutes. Similarly, the CSF undergoes an increase from 0.21 to 0.30 when the treatment time changes from 21 seconds to 4 minutes. Compared with the CSF and CKF of the original Twaron® yarn, those with 4-minute treatment are increased by 56.74% and 83.68% respectively.

From the SEM images in Figure 5-3, it is evident that all the fibre surfaces become much rougher after APPCVD treatments. The increase of coefficients of friction may be attributed to the morphology changes of fibres, since the roughness of the surface is one of the most important factors affecting the friction. It demonstrates that making fibre surface rougher is an effective way to increase the coefficient of friction among yarns.
5.4.5 Tensile properties

For body armour materials, the mechanical properties of the constituent yarns contribute to ballistic performance significantly. The purpose of the treatment for Twaron® yarns is to improve inter-yarn friction without reducing the mechanical properties of the yarns, especially the tensile properties. Figure 5-6 shows the tenacities, strains and Young’s moduli of yarns with different levels of APPCVD treatments from the tensile property test.

The APPCVD treatment is a coating process to a yarn and in this process foreign matters are added onto fibre surfaces. Thus the weight change should be considered when the changes of tensile properties of the treated yarns need to be identified. However, based on the current reactive chamber, the length of yarn that can be treated is less than one metre. The increase of the yarn weight is impossible to be detected because it is found that the change of the weight in the length fewer than one metre after treatment is too weak to be detected. Based on images in Figure 5-3, the depositions on fibre surface are in nano-scale. Therefore, it is reasonable to believe that the treatment has little effect on the weights of the treated yarns.
Table 5-3 lists the change percentages of the tensile properties for different treatment conditions. To investigate whether the changes of yarn properties are significant or not, the statistical significance test at 95% confidential interval was carried out and the results are shown in Table 5-4. Basically, it can be concluded that the deposition of the chemical compound does not cause any change to the fibre tensile properties as all the P values are larger than 0.05 except the Young’s modulus of the yarn after 4-minute treatment. The Young’s modulus of the yarn after 4-minute treatment increases 1.44%, which may be attributed to the much more roughening-up of fibre surfaces. This result suggests that the APPCVD treatment with (CH$_3$)$_2$Cl$_2$Si is feasible and valid for modifying the Twaron® fibres for ballistic applications.

![Graph](image-url)  
(a) Tenacity
Figure 5-6 Tensile properties of Twaron® yarns by APPCVD treatments: (a) Tenacity; (b) Modulus; (c) Strain

Table 5-3 The increase percentages of tensile properties for Twaron® yarns by APPCVD treatments

<table>
<thead>
<tr>
<th>Treatment time</th>
<th>Increase of tenacity (%)</th>
<th>Increase of modulus (%)</th>
<th>Increase of strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21 seconds</td>
<td>6.38</td>
<td>0.07</td>
<td>9.03</td>
</tr>
<tr>
<td>2 minutes</td>
<td>3.03</td>
<td>0.75</td>
<td>6.54</td>
</tr>
<tr>
<td>4 minutes</td>
<td>4.98</td>
<td>1.44</td>
<td>8.19</td>
</tr>
</tbody>
</table>
Table 5-4 The change singificance of tensile properties of Twaron® yarns after APPCVD treatments

<table>
<thead>
<tr>
<th>Treatments</th>
<th>P-value</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tenacity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21 seconds</td>
<td>0.28</td>
<td>No</td>
</tr>
<tr>
<td>2 minutes</td>
<td>0.70</td>
<td>No</td>
</tr>
<tr>
<td>4 minutes</td>
<td>0.71</td>
<td>No</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21 seconds</td>
<td>0.15</td>
<td>No</td>
</tr>
<tr>
<td>2 minutes</td>
<td>0.06</td>
<td>No</td>
</tr>
<tr>
<td>4 minutes</td>
<td>0.00</td>
<td>Yes</td>
</tr>
<tr>
<td>Strain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21 seconds</td>
<td>0.06</td>
<td>No</td>
</tr>
<tr>
<td>2 minutes</td>
<td>0.44</td>
<td>No</td>
</tr>
<tr>
<td>4 minutes</td>
<td>0.16</td>
<td>No</td>
</tr>
</tbody>
</table>

5.5 Dyneema® yarn

5.5.1 SEM analysis

Figure 5-7 characterises the morphology of Dyneema® yarns before and after treatments. Based on Figure 5-7(a), it reveals that the surface of the original Dyneema® fibre is not as smooth as other synthetic fibres. The shape of the ridges and bulges on the fibre surfaces is more clearly distinguished and the fibrillar nature of UHMWPE fibres is discernible. The visible lines running parallel to the fibre axis are more highly defined on the original fibre surface [216]. In addition, a few impurities are scattered on the surface of the fibre. With 21 seconds treatment, the surface of the filament is observed not to be significantly affected. When the treatment time prolongs to 2 minutes, even to 4 minutes, the surface of the fibre is still covered with limited substance. The striation nature of the surface is not subjected to seriously damage even when the treatment time prolongs to 4 minutes. It is reported that the plasma would etch the surface of the fibre because of the highly energetic particle in the plasma system [217, 218]. The less damage for the Dyneema® fibre may be attributed to its inherently much more inert property compared to Twaron® fibre. Consequently, the same treatment conditions are not enough to give rise to etch effect to the Dyneema® yarn. Overall, as the time increases to 4 minutes, the surface of the Dyneema® yarn would be deposited with limited granular-like substances by APPCVD treatment.
5.5.2 FTIR analysis

The FTIR spectra for original Dyneema® yarns and the ones treated for different times are shown in Figure 5-8. For the original Dyneema® yarn, the strong absorptions at 2911 cm\(^{-1}\) and 2844 cm\(^{-1}\) are ascribed to C-H asymmetric and C-H symmetric vibrations in \(-\text{CH}_2-\), respectively. The troughs at wave length of 1461 cm\(^{-1}\) and 1471 cm\(^{-1}\) are assigned to methylene and methyl bending vibration, respectively. The wave numbers at 729 cm\(^{-1}\) and 717 cm\(^{-1}\) are ascribed to C-H rocking vibration in structure \(-\text{CH}_2)n\[^{219}\]. The weak absorption at 1138 cm\(^{-1}\) corresponds to the C-O absorption due to the impurities\[^{206}\]. These absorption assignments are shown in Table 5-5.

A weak absorption peak at 1740 cm\(^{-1}\) is discernible in the FTIR spectrum of the yarn treated for 21 seconds compared to the original yarn, indicating a creation of carbonyl,
and mainly in forms of carboxyl functional groups on the surface of modified polyethylene fibre due to oxidation. Also, the faintly visible broad absorption range from 3600 cm\(^{-1}\) to 3100 cm\(^{-1}\) is the typical absorption of hydroxyl. In addition, the absorption at wave number of 1138 cm\(^{-1}\) shifts to the low wave number because of the formation of Si-O bond generated through the action between free radicals of silicon and the oxygen in the system. Although the surface morphology of the yarn for 21-second treatment shows little change from the SEM observation, there are still some chemical reactions taking place during the period. The free radicals in the plasma produced at or near the yarn surface can interact to form the cross-links and unsaturated groups with the chain scission. At the same time, some of the groups on the surface of the yarn would be oxidised by the highly energetic particles. These two possible reactions are corresponding to the new absorption peaks on the spectra of the yarns treated for 21 seconds.

When the treatment time becomes longer, to 2 minutes and 4 minutes, the absorption at wave number 1138 cm\(^{-1}\) shifts to 1090 cm\(^{-1}\) due to the strong Si-O-Si stretching absorption\(^{[220]}\) and this absorption peak becomes stronger because of more silicon oxidation are formed on the surface of the fibre. The absorption peak at frequency of 1740 cm\(^{-1}\) and the wide band ranging from 3100 cm\(^{-1}\) to 3500 cm\(^{-1}\) for the hydroxyl are more noticeable. Except the absorption at the above wave numbers, FTIR results for the treated fibres for 2 minutes and 4 minutes show other new weak discernible absorptions. 3080 cm\(^{-1}\) and 3180 cm\(^{-1}\) may be caused by the amine group. 1405 cm\(^{-1}\) and 1270 cm\(^{-1}\) may be assigned to the asymmetric and symmetric vibration of methylene directly link with silicon\(^{[221]}\). The weak absorptions at 802 cm\(^{-1}\) and 929 cm\(^{-1}\) might be ascribed to Si-O bending vibration and Si-OH stretching vibration\(^{[222]}\). In general, some polar groups appear on the surface of the yarn, including carboxyl, carbonyl, hydroxyl and amine groups and compounds containing silicon.
Figure 5.5.3 The FTIR spectra of Dyneema® yarns by APPCVD treatments

Table 5-5 Assignments for absorbance bands of original Dyneema® yarn

<table>
<thead>
<tr>
<th>Peak(cm⁻¹)</th>
<th>assignments</th>
</tr>
</thead>
<tbody>
<tr>
<td>3153,3052</td>
<td>O-H stretching vibration</td>
</tr>
<tr>
<td>2911</td>
<td>C-H asymmetric vibration in -CH₂-</td>
</tr>
<tr>
<td>2844</td>
<td>C-H symmetric vibrations in -CH₂-</td>
</tr>
<tr>
<td>1461</td>
<td>methylene bending vibration</td>
</tr>
<tr>
<td>1471</td>
<td>methyl bending vibration</td>
</tr>
<tr>
<td>729</td>
<td>C-H rocking vibration in structure -(CH₂)n-</td>
</tr>
<tr>
<td>717</td>
<td>C-H rocking vibration in structure -(CH₂)n-</td>
</tr>
</tbody>
</table>

5.5.3 Coefficients of friction

Figure 5-9 displays the coefficients of friction of original and treated Dyneema® yarns. Based on the tests, the coefficients of friction of the original Dyneema® yarn are 0.12 for CSF and 0.11 for CKF. The obtained coefficients of friction are in agreement with the measurement in Zhou et al.\textsuperscript{[98]} The coefficients of friction are also sensitive to the applied APPCVD treatments. Just after 21 seconds, the CSF and CKF go up to 0.17 and 0.15 respectively. When the treatment time increases to 2 minutes, CSF and CKF can be
increased by 90.61% and 69.90% respectively. However, for the yarn treated for 4 minutes, the coefficients of friction are almost the same as those of the yarn treated for 2 minutes.

Based on SEM observations, the surface roughness of all the treated Dyneema® yarns has not been significantly affected. The increase in inter-yarn friction after APPCVD treatments may be owing to the increase of adhesion between the increased polar groups on the yarn surface. It is believed that there are two components of friction, deformation and adhesion [223, 224]. Increasing either components will increase the final friction. For the original Dyneema® yarn, the surface of the yarn is solely covered with non-polar C-H group. The surfaces of two original Dyneema® yarns are repulsive because of the same electrical charge carried by the hydrogen atom. After treatments, the FTIR spectra confirmed that the surfaces of the yarns have been introduced a certain amount of polar groups, including hydroxyl bond, carbonyl and carboxyl groups. Hydrogen bond can develop at very short distance in polymers with the groups of -OH, -COOH, -NHCO- and others, in which the hydrogen atom is linked with an electronegative atom. Under favourable conditions, two approaching atoms are linked together by a common proton providing a strong and stable compound [223]. Based on this theory, more hydrogen bonds may be produced when the two surfaces of the treated Dyneema® yarns come into contact, which can give rise to more junctions and interfacial bonds in turn. Formation and rupture of the junctions controls the adhesion component of friction [224]. Therefore, the treated Dyneema® yarns would have larger inter-yarn friction. When the treatment
prolongs to 4 minutes, the polar groups are not significantly increased as evidenced by FTIR analysis. Thus, the inter-yarn friction from 4-minute treatment equals that from 2-minute treatment.

5.5.4 Tensile properties

The averaged values of the tensile properties of Dyneema® yarns are shown in Figure 5-10. Table 5-6 lists the change percentages of the tensile properties after treatments. Normally, the changes of the yarn weight after treatments should be taken into account. However, as mentioned in the section of Twaron® tensile properties, the difficulty of measuring the changes of the yarn weights also exists in the case of Dyneema® yarns. Moreover, based on the SEM observations, the surfaces of the treated yarns are deposited with limited substances, even if the time prolongs to 4 minutes. Consequently, it is reasonable to study tensile properties assuming that the weights of the treated Dyneema® yarns have not been affected.

Using significance test in statistical analyses at 95% confidence interval, all P-values in each treatment condition are larger than 0.05, shown in Table 5-7, indicating no significant difference between the tensile properties of yarns before and after treatments. These results demonstrate that the APPCVD treatment just acts on the outermost layer of the fibre, and the bulk property of the yarn remains unaffected.
Figure 5-10 The tensile properties of Dyneema® yarns by APPCVD treatments: (a) tenacity; (b) Modulus; (c) Strain

Table 5-6 Changes of tensile properties of Dyneema® yarns by APPCVD treatments

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Increase of tenacity (%)</th>
<th>Increase of modulus (%)</th>
<th>Increase of strain(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21 seconds</td>
<td>-1.85</td>
<td>-0.62</td>
<td>1.21</td>
</tr>
<tr>
<td>2 minutes</td>
<td>-4.42</td>
<td>-1.91</td>
<td>1.53</td>
</tr>
<tr>
<td>4 minutes</td>
<td>-1.49</td>
<td>-0.31</td>
<td>-1.34</td>
</tr>
</tbody>
</table>
Table 5-7 The change significance of tensile properties of Dyneema® yarns after APPCVD treatments

<table>
<thead>
<tr>
<th>Treatments</th>
<th>P-value</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tenacity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21 seconds</td>
<td>0.63</td>
<td>No</td>
</tr>
<tr>
<td>2 minutes</td>
<td>0.21</td>
<td>No</td>
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<tr>
<td>4 minutes</td>
<td>0.69</td>
<td>No</td>
</tr>
<tr>
<td><strong>Young’s modulus</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21 seconds</td>
<td>0.27</td>
<td>No</td>
</tr>
<tr>
<td>2 minutes</td>
<td>0.24</td>
<td>No</td>
</tr>
<tr>
<td>4 minutes</td>
<td>0.32</td>
<td>No</td>
</tr>
<tr>
<td><strong>Strain</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21 seconds</td>
<td>0.41</td>
<td>No</td>
</tr>
<tr>
<td>2 minutes</td>
<td>0.25</td>
<td>No</td>
</tr>
<tr>
<td>4 minutes</td>
<td>0.44</td>
<td>No</td>
</tr>
</tbody>
</table>

5.6 Discussions on APPCVD treatment for increasing inter-yarn friction

The inter-yarn friction has approximated to CSF of 0.30 and CKF of 0.24 for Twaron® yarns and CSF of 0.23 and CKF of 0.19 for Dyneema® yarns by APPCVD treatment. There is still large space left for increasing inter-yarn friction because the FE simulation shows that the maximum of inter-yarn friction can be increased by the level of CSF of 0.80 and CKF of 0.75 for the largest overall energy absorption. It is suggested to change other parameters including so-called ‘external’ parameters such as the gas, the precursor, the gas flow and the input power to lead to different ‘internal’ plasma characteristics, particularly the electron density, to achieve the maximum inter-yarn friction.

Overall, the APPCVD method has demonstrated as an efficient way to modify the inter-yarn friction without sacrificing the tensile properties and the weight. It has led to the establishment of a feasible and valid method to increase inter-yarn friction within ballistic fabrics in order to achieve enhanced ballistic energy absorption and to provide better protection against high-velocity projectile impact. Nevertheless, the device used is not suitable to treat a fabric specimen due to the small reaction chamber. The APPCVD equipment is constrained by some plasma physical principles. The breakdown voltage of gas is a function of the gas pressure and the electrode spacing. When the gas
pressure rises towards atmospheric pressure, the electrode spacing must decrease. For instance, the inter electrode gap is only 5 mm when the voltage is 2.5 kV at atmospheric pressure, which makes it technologically interesting for textile processing with plasma\textsuperscript{[207]}. The electrode spacing determines whether the process can be used with the fabric or not. In addition, the APPCVD equipment is expensive. For industry applications, a new method is required to be put into practice to increase the inter-yarn friction with yarn tensile properties and weight unaffected and should be capable of treating fabric samples.

### 5.7 Summary

This chapter is concerned with the surface modifications of Twaron\textsuperscript{®} and Dyneema\textsuperscript{®} yarns in order to increase inter-yarn friction for efficiency improvement of ballistic performance. These two types of yarns have been treated by the plasma enhanced chemical vapour depositions with \((\text{CH}_3)_2\text{Cl}_2\text{Si}\) under the atmospheric pressure. The inter-yarn friction has been evaluated by capstan method in quasi-static state. The achievements can be summarised as follows:

For Twaron\textsuperscript{®} yarns, SEM photography provided evidence of the surface change after treatments. FTIR spectra and EDX analysis confirmed the deposition of the product from the precursor. It has been discovered that the effects of APPCVD treatments towards Twaron\textsuperscript{®} yarn are the two coupled modes of etching and deposition. The obvious increases in both the frictional coefficients (static and kinetic) result from the much rougher surfaces. The CSF shows an increase from 0.16 to 0.30 and the CKF an increase from 0.15 to 0.24 as the treatment time rises up to 4 minutes. In addition, almost all the treatment cause little effect on the tensile properties of the Twaron\textsuperscript{®} yarns only when the treatment time prolongs to 4 minutes, where the increase of Young’s modulus is 1.44%.

For the treated Dyneema\textsuperscript{®} yarns, compared with the original yarns, the CSF has been improved from 0.12 to 0.23 and CKF increased from 0.11 to 0.19, as exposure that increases from 21 seconds to 2 minutes. Further increasing treatment time has no effect on the inter-yarn friction. The surface roughness is not greatly changed based on the
SEM observation. The FTIR confirmed that the APPCVD treatment can introduce polar groups including carbonyl, carboxyl, hydroxyl and amine groups onto the surface of the yarn. The increase of inter-yarn friction for the treated Dyneema® yarn may be attributed to the change of chemical group on yarn surfaces. These groups can form hydrogen bonds when the two yarn surfaces come into contact and consequently may increase the adhesion between the yarns, hence increasing inter-yarn friction. In addition the tensile properties of treated Dyneema® yarns are unaffected.
Chapter 6 Yarn Surface Modification of by Sol-gel Treatment

6.1 Introduction

Due to the limitation of sample size in AAPCVD treatment, the fabric sample cannot be treated. As such, another surface modification method has to be developed. In this chapter, sol-gel technology would be attempted to treat the yarns with the aim of increasing the inter-yarn friction at the same time affecting the tensile properties and weight as little as possible. The sol-gel technology is supposed feasible to increase inter-yarn friction because the substrate can be coated with some oxidations and thus achieve the purpose of modifying the surface morphology. The Twaron® and Dyneema® yarns are the target substrates. The coefficients of inter-yarn friction after treatment would be measured by capstan method. The morphology changes on the yarn surfaces will be characterised by SEM and the substances introduced onto the yarn surfaces will be analysed by FTIR and EDX. The weight addition and the tensile properties of yarns after treatments will be investigated as well.

6.2 Principle of sol-gel treatment

The sol-gel technology is based on colloidal suspensions, popularly known as sols, which are made from the hydrolysis of appropriately selected precursors, mostly organometallic compounds and catalysed by certain acids or alkalines\(^{163, 164}\). A gel is gradually formed by the poly-condensation of the hydrolysis product, generating an oxide skeleton in the solution. The sol-gel coating process involves firstly, coating the yarn or fabric with the sol, and then drying the coated material at elevated temperature to remove the excessive liquid phase, which creates a thin porous layer covering the fibre surface. A further treatment at elevated temperature is necessary to perform the poly-condensation where the gel layer is converted to a cross-linked gel physically and possibly chemically combined with the fibre surface\(^{172, 176}\).
The sol-gel technology is a frequently used method for surface treatment and it is able to introduce coatings to modify the surface morphology\cite{226,227}. This method is convenient in operation and suitable for batch processes. Additionally, it can easily introduce the metallic oxide with higher coefficients of friction to the surface of the fibre\cite{163}. For the sol-gel technology, most of the sol is alcosol, and a large amount of ethanol is needed to use as dispersant, whereas in our work, the alcosol was replaced by hydrosol, reducing the amount of ethanol in the process and making the process more environmentally friendly.

6.3 Preparation, characterisation and treatment process

6.3.1 Preparation of hydrosols

6.3.1.1 Chemicals

The chemicals including titanium (IV) butoxide Ti(OC\textsubscript{4}H\textsubscript{9})\textsubscript{4}, ethanol, ethanolamine and zinc acetate dehydrate were all supplied by Sigma-Aldrich, and the acetic acid by Fisher Scientific. Deionized water was used for the hydrolysis of titanium (IV) butoxide and preparation of sol-gel solution. All the chemical regents were used as received.

6.3.1.2 Preparation of TiO\textsubscript{2}/ZnO hydrosol

The preparation of TiO\textsubscript{2}/ZnO hydrosols started from creating ZnO hydrosol using the peptisation method. Zinc acetate dehydrates dissolved in a solution of deionized water with ethanol and ethanolamine was used as the reaction initiating materials. The mole ratio between zinc acetate dehydrate and ethanolamine was 1:1. Acetic acid was used as the peptiser for producing ZnO hydrosol. The second step in this process was to create the mixture of titanium (IV) butioxide and dehydrate alcohol with an optimal amount of glacial acetic acid. This product was then dropped into ZnO hydrosol. After a 2-hour vigorous stirring, the compound TiO\textsubscript{2}/ZnO hydrosol was obtained\cite{226,227}. By controlling the reaction temperature, TiO\textsubscript{2}/ZnO hydrosols with two different particle sizes were prepared. The possible reactions are shown below:
1) Reaction between zinc acetate dehydrate and ethanolamine

(i) $\text{C}_4\text{H}_6\text{O}_4\text{Zn} \cdot 2\text{H}_2\text{O} \rightarrow \text{CH}_3\text{COOZn}^+ + \text{CH}_3\text{COO}^- + 2\text{H}^+ + 2\text{OH}^-$

(ii) $\text{CH}_3\text{COOZn}^+ + \text{CH}_3\text{COO}^- + 2\text{H}^+ + 2\text{OH}^- + \text{NH}_2\text{CH}_2\text{CH}_2\text{OH} \rightarrow \text{Zn(OH)}_2 + \text{CH}_3\text{COONH}_2 + \text{CH}_3\text{CH}_2\text{COOCH}_3 + \text{H}_2\text{O}$

(2) Hydrolysis reaction

(i) $\text{Ti(OC}_4\text{H}_9)_4 + \text{CH}_3\text{COOH} \leftrightarrow (\text{Ti(OC}_4\text{H}_9)_4(\text{CH}_3\text{COO})\text{H}) \leftrightarrow \text{Ti(OC}_4\text{H}_9)_3(\text{CH}_3\text{COO}) + \text{HOC}_4\text{H}_9$

(ii) $\text{Ti(OC}_4\text{H}_9)_4(\text{CH}_3\text{COO})\text{H} + \text{H}_2\text{O} \rightarrow \text{Ti(OC}_4\text{H}_9)_2(\text{CH}_3\text{COO})\text{-OH} + 2\text{HOC}_4\text{H}_9$

(3) Condensation reaction

(i) $\text{Ti(OC}_4\text{H}_9)_2(\text{CH}_3\text{COO})\text{-OH} + \text{HO-(CH}_3\text{COO})(\text{OC}_4\text{H}_9)_2\text{Ti} \rightarrow \text{(OC}_4\text{H}_9)_2(\text{CH}_3\text{COO})\text{Ti-O-Ti(CH}_3\text{COO})(\text{OC}_4\text{H}_9)_2 + \text{H}_2\text{O}$

(ii) $\text{Ti(OC}_4\text{H}_9)_2(\text{CH}_3\text{COO})\text{-OH} + \text{HO-Zn-OH} \rightarrow \text{Ti(OC}_4\text{H}_9)_2(\text{CH}_3\text{COO})\text{-O-Zn-OH} + \text{H}_2\text{O}$

(iii) $\text{HO-Zn-OH} + \text{HO-Zn-OH} \rightarrow \text{HO-Zn-O-Zn-OH} + \text{H}_2\text{O}$

6.3.1.3 TiO$_2$ hydrosol

The process for preparing TiO$_2$ hydrosol was to dip the mixture of titanium (IV) butoxide and dehydrate alcohol with an optimal amount of glacial acetic acid to a certain amount of water. Similarly, TiO$_2$ hydrosols with two different particle sizes were also prepared by control of the temperature.
6.3.2 Characterisation of the hydrosols

6.3.2.1 The particle size

The particle size in hydrosols was measured with the instrument of Zetasizer Nano particle analyser series Nano ZS ZEN3600 produced by Malvern. The measurement is based on the dynamic light scattering theory. The dispersant was ethanol. The test temperature in the chamber was set to be 25°C.

The diameter of a particle is used to represent the size of it and the diameter is a statistical value, which is described by the normal distribution curve, as shown in Figure 6-1. The size of the particle in the hydrosol made at the low temperature (5°C) is in the nano-scale and that made at the temperature (60°C) is in the submicro-scale. The smaller particle size at the low reaction temperature may be attributed to the reason that the hydrolysis rate of the titanium butoxide is likely to be suppressed at lower temperature. The appearances of the two types of TiO$_2$/ZnO hydrosols are shown in Figure 6-2. It can be seen that the nano-sized hydrosol displays a transparent appearance while the submicro-sized hydrosol shows a white colour. The particle size in the nano-sized hydrosol is small and thus let light go through it and gives rise to a transparent appearance.
Figure 6-1 The size distribution in hydrosols, (a) nano-sized TiO$_2$/ZnO hydrosol; (b) submicro-sized TiO$_2$/ZnO hydrosol; (C) nano-sized TiO$_2$ hydrosol; (d) submicro-sized TiO$_2$ hydrosol

Figure 6-2 Images of different hydrosols (a) TiO$_2$/ZnO nano-sized hydrosol; (b) TiO$_2$/ZnO submicro-sized hydrosol; (c) TiO$_2$ nano-sized hydrosol; (d) TiO$_2$ submicro-sized hydrosol

6.3.2.2 PH values of hydrosols

Table 6-1 is the PH values of the different sols measured at the temperature of 22°C. Generally, the hydrosol is acidic. The PH values of TiO$_2$/ZnO hydrosols are larger than those of TiO$_2$ hydrosols. That is because ethanolamine is used in preparing TiO$_2$/ZnO sol and it is alkaline in nature. It neutralized some acid used in the sol. The PH value of the
submicro-sized hydrosol is a little lower than that of the non-sized one because the liquid in the submicro-sized hydrosol evaporates more due to the higher reaction temperature.

<table>
<thead>
<tr>
<th>Types of hydrosol</th>
<th>PH</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiO$_2$/ZnO nano-sized hydrosol</td>
<td>4.12</td>
</tr>
<tr>
<td>TiO$_2$/ZnO submicro-sized hydrosol</td>
<td>4.07</td>
</tr>
<tr>
<td>TiO$_2$ nano-sized hydrosol</td>
<td>2.83</td>
</tr>
<tr>
<td>TiO$_2$ submicro-sized hydrosol</td>
<td>2.74</td>
</tr>
</tbody>
</table>

6.3.3 Treatment process to yarns

6.3.3.1 Treatment conditions

The yarns for sol-gel treatment were Twaron$^\circledR$ 93 tex produced by Teijin Aramid and Dyneema$^\circledR$ yarn 174 tex offered by DSM. Dip-Pad-Dry process was used to treat these yarns. The yarns were impregnated with the corresponding sol solution, and were squeezed by applying a two-roll laboratory padder (CH-8155 Mathis AG, Switzerland; air pressure 3 bar, rotatory speed 2 m/min) before being cured on a curing machine (CH-8156 Mathis AG, Switzerland). The same padding conditions were used because similar wet pick-up was anticipated in each type of the yarn. In order to guarantee an even pick-up of the sol, the yarns went through the impregnation and padding processes twice.

In the treatment process, the concentration for the TiO$_2$/ZnO hydrosol and TiO$_2$ hydrosol used for the yarn treatment was 0.2 mol/L, and the drying temperature was set to be 70 °C with the drying time being set at 1 minute. The curing temperature for the yarn was set to be 110 °C and the curing time was set to be 1.5 minutes.

6.3.3.3 Settings for the yarn treatments

Six treatments are set for the present investigation for the two types of yarns, as described in Table 6-2. TiO$_2$/ZnO and TiO$_2$ hydrosols are applied to treat the yarns with curing process and without curing process. In the treatment labels, TiZn- represents the TiO$_2$/ZnO hydrosol and Ti- represents the TiO$_2$ hydrosol. T and W stand for transparent
and white, representing the nano-sized hydrosol and the submicro-sized one, respectively. Letters D and C in the sequence correspondingly means drying and curing.

<table>
<thead>
<tr>
<th>Treatment labels</th>
<th>Types of hydrosols</th>
<th>Treatment process</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiZn-WD</td>
<td>TiO₂/ZnO submicro-sized</td>
<td>Dip-Pad-Dry</td>
</tr>
<tr>
<td>TiZn-WDC</td>
<td>TiO₂/ZnO hydrosol</td>
<td>Dip-Pad-Dry–Cure</td>
</tr>
<tr>
<td>TiZn-TD</td>
<td>TiO₂/ZnO</td>
<td>Dip-Pad-Dry</td>
</tr>
<tr>
<td>TiZn-TDC</td>
<td>nano-sized hydrosol</td>
<td>Dip-Pad-Dry–Cure</td>
</tr>
<tr>
<td>Ti-WDC</td>
<td>TiO₂ submicro-sized hydrosol</td>
<td>Dip-Pad-Dry–Cure</td>
</tr>
<tr>
<td>Ti-TDC</td>
<td>TiO₂ nano-sized hydrosol</td>
<td>Dip-Pad-Dry–Cure</td>
</tr>
</tbody>
</table>

### 6.3.3.2 Wet pick-up of yarns

The wet pick-up of the yarn indicates the amount of liquid that the fabric can take up and it can be calculated from Equation 6-1. The weight test is conducted at temperature of 17°C and relative humidity of 23% in the laboratory. The dry net weight and the weight after padding for each case are averaged from 10 tests. Table 6-3 lists the average wet pick-ups for each yarn category towards different hydrosols. Due to the difference in viscosity among the four hydrosols, as shown in Figure 6-3, there are some fluctuations about the wet pick-up among the four hydrosols for each yarn category. Nevertheless, the difference is not pronounced. On the whole, the wet pick-up of the Dyneema® yarn after two-time dip-pad processes towards different sols are around 50% while that for the Twaron® yarn is lower, around 30%. The difference between wet pick-up of Dyneema® yarn and Twaron® yarn is initially assumed to be associated with the moisture regain. However, it is illogical because the moisture regain of Dyneema® yarn is zero and that of Twaron® yarn is around 3%. Therefore, the difference is not caused by their moisture regain property. It may be related to the rate of amorphous area for different types of fibre, which can be explored in future study.

\[
W\% = \frac{w_w - w_0}{w_0} \times 100\% \tag{6-1}
\]

Where, \(w_w\) is the wet weight of the sample after padding and \(w_0\) is the dry weight of the original sample.
Table 6-3 The wet pick-up for different hydrosols

<table>
<thead>
<tr>
<th>Materials</th>
<th>Types of hydrosol</th>
<th>Wet pick-up (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Twaron® yarn</td>
<td>TiO$_2$/ZnO submicro-sized hydrosol</td>
<td>33.4</td>
</tr>
<tr>
<td></td>
<td>TiO$_2$/ZnO nano-sized hydrosol</td>
<td>25.6</td>
</tr>
<tr>
<td></td>
<td>TiO$_2$ submicro-sized hydrosol</td>
<td>34.2</td>
</tr>
<tr>
<td></td>
<td>TiO$_2$ nano-sized hydrosol</td>
<td>29.9</td>
</tr>
<tr>
<td>Dyneema® yarn</td>
<td>TiO$_2$/ZnO submicro-sized hydrosol</td>
<td>51.5</td>
</tr>
<tr>
<td></td>
<td>TiO$_2$/ZnO nano-sized hydrosol</td>
<td>49.1</td>
</tr>
<tr>
<td></td>
<td>TiO$_2$ submicro-sized hydrosol</td>
<td>48.1</td>
</tr>
<tr>
<td></td>
<td>TiO$_2$ nano-sized hydrosol</td>
<td>44.6</td>
</tr>
</tbody>
</table>

**Figure 6-3** Viscosities of different hydrosols

### 6.4 Identification of coating substances using FTIR and EDX

Since the coating substance is prepared through the hydrolysis of the precursor and polycondensation of the hydrolysed product, it is necessary to identify whether the main substance introduced onto the surface of the fibre is the desired metal oxide polymer. To achieve this aim, FTIR and EDX are employed to obtain such information.
6.4.1 Coating on Twaron® yarn

6.4.1.1 TiO$_2$/ZnO hydrosol treatment

The FTIR spectra of the treated Twaron® yarns are presented in the range of wave numbers from 4000 to 400 cm$^{-1}$, and this is shown in Figure 6-4. The absorption peak assignments in the FTIR spectrum for the original Twaron® yarn are shown in Table 5-1 in Chapter 5. The FTIR spectra of yarns treated by different TiO$_2$/ZnO hydrosols are almost the same, indicating that the substances introduced onto the surfaces of yarns are similar for each case.

Compared with the spectrum of the original yarn, new peaks appeared on the spectra of the treated yarns. The peak at 640 cm$^{-1}$ is split into two peaks. The new absorption peak at wave number 620cm$^{-1}$ is assigned to Ti-O-Zn bond$^{[228]}$. The absorption at the peak around 470cm$^{-1}$ is enhanced after all the treatments and is ascribed to the Ti-O-Ti bond in a configuration where every Ti atom is bound to four atoms of oxygen dioxide$^{[229-232]}$. This confirmed that the TiO$_2$/ZnO compounds have been formed on the surface of the fibre through the poly-condensation reaction from the hydrolysis and peptisation products. In addition, the element analysis by means of EDX also supports the above results. Table 6-4 lists the elements and their atomic percentages of the original yarn and treated yarns. It can be seen that titanium and zinc turn up on all treated Twaron® yarns with TiO$_2$/ZnO hydrosol treatment.

In addition, the spectra of the treated yarns show a broad band at 3100-3600 cm$^{-1}$ that is attributed to -OH stretching vibrations, and this band overlaps with the -NH band of amine and amide. Compared with the corresponding absorption peak on the original yarn spectrum, it tends to move to the lower wave number and becomes wider after treatment, which is believed to be caused by the formation of hydrogen bond$^{[233]}$. It is reported that TiO$_2$ or ZnO would absorb water in the air and form hydrogen bond between the water molecular$^{[234-236]}$. Therefore, this band may be due to the hydrogen bond formed between TiO$_2$/ZnO and water molecular.

There are weak absorption peaks at the wave numbers of 2920cm$^{-1}$ and 2855 cm$^{-1}$ in the spectra of the yarns with TiO$_2$/ZnO hydrosol treatment. These are due to CH$_2$- asymmetric and symmetric vibration. These bands constitute the presence of methyl
groups from the unreacted organic precursor\textsuperscript{[237]}.

Figure 6-4 The FTIR spectra of the Twaron\textsuperscript{®} yarns treated by TiO\textsubscript{2}/ZnO hydrosols

Table 6-4 The components of the elements (atomic %) on Twaron\textsuperscript{®} yarns treated by TiO\textsubscript{2}/ZnO hydrosols

<table>
<thead>
<tr>
<th>Element</th>
<th>Original (%)</th>
<th>TiZn-WD (%)</th>
<th>TiZn-WDC (%)</th>
<th>TiZn-TD (%)</th>
<th>TiZn-TDC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>83.24</td>
<td>62.62</td>
<td>72.33</td>
<td>73.83</td>
<td>69.45</td>
</tr>
<tr>
<td>N</td>
<td>2.04</td>
<td>18.48</td>
<td>16.09</td>
<td>9.26</td>
<td>15.56</td>
</tr>
<tr>
<td>O</td>
<td>11.48</td>
<td>15.47</td>
<td>10.27</td>
<td>13.71</td>
<td>13.03</td>
</tr>
<tr>
<td>Ti</td>
<td>-</td>
<td>1.37</td>
<td>0.24</td>
<td>1.02</td>
<td>0.75</td>
</tr>
<tr>
<td>Zn</td>
<td>-</td>
<td>1.51</td>
<td>0.42</td>
<td>1.17</td>
<td>0.55</td>
</tr>
</tbody>
</table>

6.4.1.2 TiO\textsubscript{2} hydrosol treatment

Figure 6-5 displays spectra of Twaron\textsuperscript{®} yarns treated by TiO\textsubscript{2} hydrosols. It can be seen that the two spectra of the treated yarns share the same characteristic, indicating that the substances on the surface of the Twaron\textsuperscript{®} yarn are the same. Compared with the spectra
of the original yarn, the absorption at wave number of 470 cm\(^{-1}\) turns up on the spectra of the treated yarns, which is ascribed to the absorption peak of the Ti-O-Ti bond. The EDX element analysis also captures Ti element on the surface of the treated yarns, shown in Table 6-5. All in all, the hydrolysed product titanium dioxide from the precursor titanium (IV) butoxide have been confirmed on the surface of the Twaron\(^{\circledR}\) yarns by TiO\(_2\) hydrosol treatments.

![Figure 6-5 The FTIR spectra of Twaron\(^{\circledR}\) yarns treated by TiO\(_2\) hydrosols](image)

Table 6-5 The components of the elements (atomic %) on Twaron\(^{\circledR}\) yarns treated by TiO\(_2\) hydrosols

<table>
<thead>
<tr>
<th>Element</th>
<th>Ti-WDC (%)</th>
<th>Ti-TDC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>72.86</td>
<td>74.98</td>
</tr>
<tr>
<td>N</td>
<td>13.62</td>
<td>11.76</td>
</tr>
<tr>
<td>O</td>
<td>10.99</td>
<td>10.10</td>
</tr>
<tr>
<td>Ti</td>
<td>0.41</td>
<td>0.55</td>
</tr>
</tbody>
</table>

6.4.2 Coating on Dyneema\(^{\circledR}\) yarn

6.4.2.1 TiO\(_2\)/ZnO hydrosol treatment

The FTIR spectra for the original Dyneema\(^{\circledR}\) yarn and those treated with TiO\(_2\)/ZnO hydrosols are shown in Figure 6-6. The typical absorption peaks for the original Dyneema\(^{\circledR}\) yarn have been classified in Table 5-4 in Chapter 5. All the spectra of the Dyneema\(^{\circledR}\) yarns treated by TiO\(_2\)/ZnO hydrosols share the same characteristic in Figure 6-6. After treatments, several new absorption peaks appear on the spectra. In the high
wave number spectral range, a broad band between wave frequency 3600 and 3100 cm\(^{-1}\) is assigned to fundamental stretching vibrations of different hydroxyl groups (free or bounded)\(^{[238]}\). The peak at 1400 cm\(^{-1}\) is attributed to the vibration mode of Ti–O bond\(^{[239]}\). The band at 620 cm\(^{-1}\) is assigned to Ti-O-Zn bond\(^{[228]}\) and the band at 470 cm\(^{-1}\) is ascribed to Ti-O-Ti bond by condensation reaction\(^{[229-232]}\). As such, the substances coated on the Dyneema\(^{®}\) yarns with different particle sizes of TiO\(_2\)/ZnO hydrosols are similar and they are TiO\(_2\)/ZnO compounds. Table 6-6 lists the elements on the surfaces of the Dyneema\(^{®}\) yarns treated by TiO\(_2\)/ZnO hydrosols and it corroborates that the surfaces of those yarns have been covered with element Ti and Zn. The existence of oxygen in the original Dyneema\(^{®}\) yarn is probably formed during the production of UHMWPE fibre\(^{[240, 241]}\).

It should be pointed out that the peaks around 1114 cm\(^{-1}\), 955 cm\(^{-1}\), 930 cm\(^{-1}\) are attributed to the precursors or species derived from them\(^{[238]}\). It is known that the absorption bands in the range 1100–1000 cm\(^{-1}\) are attributed to the OR groups linked to Ti such as OC\(_2\)H\(_5\), OC\(_3\)H\(_7\) and OC\(_4\)H\(_7\). The characteristic absorption peak of (OR) group of titanium isopropoxide, which is the structure contained in the precursors of the sols, is in the range of 1085–1050 cm\(^{-1}\)\(^{[242]}\). 1560 cm\(^{-1}\) and 1339 cm\(^{-1}\) may be caused by the reaction substance containing N-H and C-N deformation couple modes. These absorption peaks are not detected on the Twaron\(^{®}\) yarns because they may be overlapped with absorption peaks of some groups built in the Twaron\(^{®}\) chemical structure.
The FTIR spectra of Dyneema® yarns treated by TiO$_2$/ZnO hydrosols

Figure 6-7 shows the spectra of the Dyneema® yarns treated by TiO$_2$ hydrosols.

Generally, the characteristics of the two spectra are almost the same, implying the same substance coated onto the Dyneema® yarns. Compared with the spectrum of the original yarn, there are some new peaks on the spectra of the treated yarns. The Ti-O-Ti bond absorption peak at wave number of 470 cm$^{-1}$ is noticeable, and it is further evidenced by the element analyses, shown in Table 6-7. After treatments, the element of titanium appears on the surface of the Dyneema® yarns with the TiO$_2$ hydrosols. In addition, there

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Table 6-6 The components of the elements (atomic %) on Dyneema® yarns with TiO$_2$/ZnO hydrosols

<table>
<thead>
<tr>
<th>Element</th>
<th>Original (%)</th>
<th>TiZn-WD (%)</th>
<th>TiZn-WDC (%)</th>
<th>TiZn-TD (%)</th>
<th>TiZn-TDC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>88.7</td>
<td>75.53</td>
<td>80.63</td>
<td>87.1</td>
<td>85.79</td>
</tr>
<tr>
<td>O</td>
<td>3.48</td>
<td>10.70</td>
<td>5.59</td>
<td>5.2</td>
<td>3.56</td>
</tr>
<tr>
<td>Ti</td>
<td>-</td>
<td>3.28</td>
<td>2.13</td>
<td>2.32</td>
<td>1.56</td>
</tr>
<tr>
<td>Zn</td>
<td>-</td>
<td>2.82</td>
<td>1.68</td>
<td>0.87</td>
<td>0.67</td>
</tr>
</tbody>
</table>
is a weak broad band between 3600 and 3100 cm$^{-1}$, indicating that the hydrogen bond formed between the titanium dioxide and water molecular. It thus confirms that the surface of the Dyneema® yarn is coated with titanium dioxide from TiO$_2$ hydrosol treatments.

![FTIR spectra](image)

Figure 6-7 The FTIR spectra of the Dyneema® yarn treated by TiO$_2$ hydrosols

<table>
<thead>
<tr>
<th>Element</th>
<th>Ti-WDC (%)</th>
<th>Ti-TDC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>77.77</td>
<td>83.78</td>
</tr>
<tr>
<td>O</td>
<td>7.96</td>
<td>5.52</td>
</tr>
<tr>
<td>Ti</td>
<td>6.00</td>
<td>5.16</td>
</tr>
</tbody>
</table>

**Table 6-7 The components of the elements (atomic %) on Dyneema® yarns with TiO$_2$ hydrosols**

**6.5 The morphology analyses**

**6.5.1 Morphology of Twaron® yarn**

**6.5.1.1 The TiO$_2$/ZnO hydrosol treatment**

Figure 6-8 is the surface information of Twaron® original yarn and treated yarns obtained from the SEM images. Because of the initial finish, the surface of the original fibre is not smooth but with some impurities. Based on the observation of the images of the treated yarns, it can be seen that the surfaces of these yarns are coated with some
solid substance through the sol-gel process. The sol-gel process is a process for shaping molecules into materials. It is a very complex process consisting of several transformations of very different natures and involving three states of matter: solution, colloid and solid\[^{237}\]. The precursors used give rise to nanometric linear and cyclic oligomers of the titanium dioxide and zinc oxide and these oligomers gradually become intermingled to yield cross-linked titanium dioxide and zinc oxide polymers by poly-condensation. The particle of titanium dioxide and zinc oxide in the sol would grow further by aggregation, forming gel. At this stage, it can be used as a covering by dip coating. Drying is a process corresponding to a solid phase development of the gel on the substrate. During the drying, gelation, rapid cross-linking and syneresis are occurring\[^{163}\]. The gel gradually becomes a solid as the liquid continues to evaporate. It is believed that the particle size, drying temperature would take effect on the final texture of the solid substance\[^{163}\].

From the SEM images in Figure 6-8, the submicro-sized TiO\(_2\)/ZnO hydrosol tends to form lump-like substance attached to the surface of the yarn whilst in the case of nano-sized TiO\(_2\)/ZnO hydrosol, surfaces of yarns are covered by a layer of laminar scale-like substance. It is reported that the larger particle size in the sol easily results in uneven appearance and forms larger cluster on the surface whereas the smaller particle size in the sol is likely to give rise to a relative smooth scale surface\[^{243}\]. The surfaces of the yarns treated by submicro-sized TiO\(_2\)/ZnO hydrosol are much more non-uniform and rougher than these treated by nano-sized hydrosols.

The size of the lump or the scale is not independent of the curing process, as the treatment without curing is more likely to form bigger pieces while the treatment with curing is inclined to produce smaller pieces. The curing process is likely to destroy the continuity of the scale. During the treatment where higher temperatures are involved, further shrinkage and densification as a result of increased capillary stress due to solvent loss tend to occur. The remaining surface hydroxyl or alkoxy groups would be removed by condensation with associated liberation of water or alcohol\[^{163}\]. Thus, further crack of the gel would occur.
Figure 6-8 The morphology images of Twaron® yarns by sol-gel treatments (a) Original; (b) TiZn-WD; (c) TiZn-WDC; (d) TiZn-TD; (e) TiZn-TDC

6.5.1.2. The TiO₂ hydrosol treatment

Figure 6-9 shows morphologies of Twaron® yarns treated by submicro-sized TiO₂ hydrosol and nano-sized one. Through the whole treatment process, the TiO₂ gels resulted from the hydrolysis of the precursor and poly-condensation of the
corresponding oligomer, are adhered onto yarn surfaces. The surfaces are covered with the mixture shapes of non-continuous scale-like and granular-like TiO$_2$ polymer. However, the coating formed from larger particle size hydrosol is more irregular and thicker than that corresponding smaller one.

![Figure 6-9](image)

(a) Ti-WDC  
(b) Ti-TDC

Figure 6-9 The morphology images of Twaron® yarns by sol-gel treatments: (a) Ti-WDC; (b) Ti-TDC

### 6.5.2 Morphology of Dyneema® yarn

#### 6.5.2.1 The TiO$_2$/ZnO hydrosol treatment

The morphologies of the treated and the untreated Dyneema® yarns are shown in Figure 6-10. The surface of the original Dyneema® yarn is not as smooth as other synthetic fibres. The striations are clearly revealed on fibre surface$^{[230]}$. In addition, along the longitudinal direction, bamboo-like joint is shown in the micrograph of the original Dyneema® yarn. Compared to the original Dyneema® yarn, the coating morphologies of the yarns treated by the two TiO$_2$/ZnO hydrosols are different. Generally, the larger size particle in the sol would form more granular-like coating and the smaller size particle sol would give rise to a scale-like appearance. The texture of the coating through gelification of larger particle size sol is larger, thicker, more irregular while the smaller size particles sol form a layer of thin and even scale coating. This illustrates that the final texture of the coating is highly relative to the initial particle size in the sol stage.

Regarding the coating morphology of the Dyneema® yarns subjected to different thermal treatment histories in the same hydrosol group, further higher temperature heating plays
a role in the continuity of the coating texture. The higher temperature causes more
gelification to take place and more liquid entrapped in the gel to evaporate, which make
the previous coating crack. Consequently, the fibres treated by the hydrosols with curing
process are less covered by the corresponding gels. The weight add-on results of the
corresponding yarns by different treatments give the evidence, referring to Table 6-9.

Figure 6-10 The morphology images of Dyneema® yarns by sol-gel treatments (a) Original; (b) TiZn-WD;
(c) TiZn-WDC; (d) TiZn-TD; (e) TiZn-TDC
6.5.2.2 The TiO$_2$ hydrosol treatment

Figure 6-11 shows the surface morphology characteristics of the Dyneema® yarns treated by the two different particle sizes of the TiO$_2$ hydrosols. In the case of treatment with submicro-sized TiO$_2$ hydrosol, some of the lump-like TiO$_2$ substance are scattered between fibres or in the interspaces between the striations and some are attached to the fibres. The surface of Dyneema® yarn treated with the nano-sized one are covered with TiO$_2$ substance more in the form a layer of scale. Some of the scales are cracked because of the curing process.

6.6 Effects on coefficients of friction

The coefficients of friction for Twaron® yarns and Dyneema® yarns after sol-gel treatments are shown in Figure 6-12 and Figure 6-13. The coefficients of friction test are according to the method described in Chapter 3 section 3.4.2. The CSF and CKF values of the treated Twaron® and Dyneema® yarns given below display different degrees of increase compared with the values of the original yarn. From the significance test at 95% confidence interval, the increases of inter-yarn friction by all sol-gel treatments are significant because the P values in all treatment in Tables 6-8 and 6-9 are smaller than 0.05 but the CKF of Twaron® yarns by TiZn-TDC treatment is an exception. The increase percentage for each case is shown in Tables 6-8 and 6-9. On the whole, the coefficients of friction for Twaron® yarns can be increased by approximately 68.43% for
CSF and 39.82% for CKF through the sol-gel treatment. For the Dyneema® yarns, the CSF and CKF can be increased by 89.61% and 74.03%, respectively. A possible reason may be attributed to the morphology changes. As shown in SEM images, the surfaces of the treated yarns become much rougher. It has been proved that the sol-gel treatment is an effective way to increase the coefficients of friction for the two types of yarns.

Figure 6-12 The coefficients of friction for Twaron® yarn at different sol-gel treatment conditions

Figure 6-13 The coefficients of friction for Dyneema® yarn at different sol-gel treatment conditions
Table 6-8 The increasing percentages of CKF and CSF of Twaron® yarns after sol-gel treatments

<table>
<thead>
<tr>
<th>Treatments</th>
<th>CSF (%)</th>
<th>P value</th>
<th>Significance</th>
<th>CKF (%)</th>
<th>P value</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiZn-WD</td>
<td>52.10</td>
<td>4.67E-19</td>
<td>Yes</td>
<td>44.49</td>
<td>1.28E-15</td>
<td>Yes</td>
</tr>
<tr>
<td>TiZn-WDC</td>
<td>54.10</td>
<td>1.32E-18</td>
<td>Yes</td>
<td>45.02</td>
<td>4.56E-16</td>
<td>Yes</td>
</tr>
<tr>
<td>TiZn-TD</td>
<td>8.99</td>
<td>7.51E-09</td>
<td>Yes</td>
<td>2.84</td>
<td>3.55E-03</td>
<td>Yes</td>
</tr>
<tr>
<td>TiZn-TDC</td>
<td>9.57</td>
<td>2.17E-09</td>
<td>Yes</td>
<td>1.06</td>
<td>2.84E-01</td>
<td>No</td>
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<tr>
<td>Ti-WDC</td>
<td>68.43</td>
<td>1.62E-32</td>
<td>Yes</td>
<td>39.82</td>
<td>1.06E-32</td>
<td>Yes</td>
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<tr>
<td>Ti-TDC</td>
<td>52.49</td>
<td>6.57E-31</td>
<td>Yes</td>
<td>33.34</td>
<td>8.59E-26</td>
<td>Yes</td>
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</tbody>
</table>

Table 6-9 The increasing percentages of CKF and CSF of Dyneema® yarns after sol-gel treatments

<table>
<thead>
<tr>
<th>Treatments</th>
<th>CSF (%)</th>
<th>P value</th>
<th>Significance</th>
<th>CKF (%)</th>
<th>P value</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiZn-WD</td>
<td>43.35</td>
<td>2.65E-15</td>
<td>Yes</td>
<td>29.30</td>
<td>5.85E-15</td>
<td>Yes</td>
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<tr>
<td>TiZn-WDC</td>
<td>44.32</td>
<td>6.87E-26</td>
<td>Yes</td>
<td>29.15</td>
<td>6.35E-25</td>
<td>Yes</td>
</tr>
<tr>
<td>TiZn-TD</td>
<td>18.40</td>
<td>9.44E-15</td>
<td>Yes</td>
<td>11.35</td>
<td>3.01E-12</td>
<td>Yes</td>
</tr>
<tr>
<td>TiZn-TDC</td>
<td>40.10</td>
<td>6.09E-27</td>
<td>Yes</td>
<td>36.51</td>
<td>1.05E-22</td>
<td>Yes</td>
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<td>Ti-WDC</td>
<td>89.61</td>
<td>2.99E-28</td>
<td>Yes</td>
<td>74.03</td>
<td>2.21E-26</td>
<td>Yes</td>
</tr>
<tr>
<td>Ti-TDC</td>
<td>61.21</td>
<td>2.94E-35</td>
<td>Yes</td>
<td>58.83</td>
<td>3.45E-30</td>
<td>Yes</td>
</tr>
</tbody>
</table>

6.6.1 The particle size in the sol

Figure 6-14 shows the coefficients of friction for Twaron® and Dyneema® yarns treated by submicro-sized hydrosol and nano-sized hydrosol. Irrespective of the curing process, or the coating substance on the yarn surfaces, all the CSF and CKF values of the two types of yarns treated by the submicro-sized hydrosol are larger than those treated by the nano-sized hydrosol. That is because the coating formed from submicro-sized hydrosol is more irregular, and much harder, producing much rougher surface while the coating resulted from the nano-sized hydrosol treatment is relatively flat. It can be deduced that the surface covered by lump-like or granular-like substance is endowed with much higher coefficients of friction compared with the surface roughened by laminar scale-like substance.
6.6.2 The curing process

The effects of curing process on the coefficients of friction are described in Figure 6-15. For Twaron® yarns, the curing process plays little role in the coefficients of friction either at the conditions of micro-sized hydrosol or nano-sized one. However, for Dyneema® yarns, the curing process has increased the coefficients of friction more significantly in the case of treatment with the nano-sized hydrosol. It is believed that
further gelification would occur during the post-curing process, which may cause more cracking of the coating, referring to Figures 6-8 and 6-10. This is thought to be a way to introduce more roughness to the surface. However, at the same time, due to the further densification or shrink of the coating, the coated area would become less. Therefore, there is a competition between these two effects with respect to the curing process.

![Figure 6-15 The effects of curing process on coefficients of friction](image)

### 6.6.3 The coated substance

Based on the FTIR analyses, the surfaces of the Twaron® yarn and Dyneema® yarn has been coated with two types of materials, TiO₂/ZnO compounds and pure TiO₂ substance. Figure 6-16 shows the effects of coated substance on the coefficients of friction. Generally, for the two types of ballistic yarns, the yarns coated with TiO₂ substance give higher coefficients of friction than the ones covered with TiO₂/ZnO compounds. The reasons are not clear but may be associated with the oxide material itself because each oxide material has its own coefficients of friction in a certain physical form. Changing the final oxide material obtained through the sol-gel technology is a way to increase the
inter-yarn friction to a higher level.

![Graphs showing coefficient of friction for different treatments](image)

Figure 6-16 The effects of coated substance on coefficients of friction

6.7 Effects on weight and tensile properties

6.7.1 Weight add-on

For ballistic applications, the weight of the body armour should be as light as possible because heavy weight would limit the flexibility of the motion of the wearer. Consequently, it is imperative to be aware of the weight changes of yarns after different types of treatment processes. The net dry weights before and after treatments are averaged from 10 tests. Table 6-10 displayed the results form significant test at 95% confidence interval. Since the P values is smaller than 0.05 in each treatment, the change of the weight before and after each treatment is significant. The increasing percentages for all cases are given below in Table 6-11.

Normally, yarn weight would be increased after the treatment because new materials have been introduced onto the yarn surface. However, it is interesting to discover that some of the treatments reduce the weights of the Twaron® yarns. The reason to explain the weight loss after the treatment in the case of Twaron® yarn is that the final weight
add-on comprises two parts: one is the increase quantity owing to the coating and the other is the loss of the fibre body due to acid and higher temperature environment in the processing. For the Twaron® yarn, acid hydrolysis is observed because of the amide linkage in the chemical structure. Park et al.\cite{210} found that chemical treatment with acidic solution may lead to micro-etch formation on the surface of aramid fibres. Lin et al.\cite{244} discovered that chlorosulfonic acid may penetrate inside the aramid fibre, destroying the structure of the fibre. Therefore, It is possible that the yarn would lose some weight because of the microetch, caused by the acid environment, shown in Figure 6-17, and the final weight of the Twaron® yarn treated would be less than the original one. For the Dyneema® yarns, the surface of it is inert owing to the less functional groups in its structure\cite{245}. Therefore, there is no weight loss due to the acid and relatively higher temperature action.

In addition, in Table 6-11, it is also found that the treatments with curing process results in less weight increase of the yarn than the corresponding treatment without curing process. As mentioned before, the curing process is a process to further densify the gel, causing the liquid in the gel to further evaporate and leading to less increase of weight. Therefore, curing process is necessary when light weight of treated yarn for ballistic application is required.

<table>
<thead>
<tr>
<th>Types of yarns</th>
<th>Treatments</th>
<th>P-value</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Twaron® yarn</td>
<td>TiZn-WD</td>
<td>1.73E-09</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>TiZn-WDC</td>
<td>9.04E-17</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>TiZn-TD</td>
<td>5.87E-11</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>TiZn-TDC</td>
<td>1.91E-10</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Ti-WDC</td>
<td>8.69E-10</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Ti-TDC</td>
<td>1.51E-18</td>
<td>Yes</td>
</tr>
<tr>
<td>Dyneema® yarn</td>
<td>TiZn-WD</td>
<td>3.16E -05</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>TiZn-WDC</td>
<td>9.42E-03</td>
<td>Yes</td>
</tr>
<tr>
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<td>TiZn-TD</td>
<td>8.43E-05</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>TiZn-TDC</td>
<td>7.23E-06</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Ti-WDC</td>
<td>6.61E-09</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Ti-TDC</td>
<td>6.05E-04</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Table 6-11 Weight changes of yarns in different sol-gel treatment conditions

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Twaron® yarn</th>
<th>Dyneema® yarn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Increasing percentage(%)</td>
<td>Increasing percentage(%)</td>
</tr>
<tr>
<td>TiZn-WD</td>
<td>3.91</td>
<td>4.01</td>
</tr>
<tr>
<td>TiZn-WDC</td>
<td>-1.21</td>
<td>1.55</td>
</tr>
<tr>
<td>TiZn-TD</td>
<td>3.92</td>
<td>8.79</td>
</tr>
<tr>
<td>TiZn-TDC</td>
<td>1.07</td>
<td>6.61</td>
</tr>
<tr>
<td>Ti-WDC</td>
<td>0.52</td>
<td>4.89</td>
</tr>
<tr>
<td>Ti-TDC</td>
<td>-1.03</td>
<td>2.38</td>
</tr>
</tbody>
</table>

Figure 6-17 The microetch for Twaron® yarns caused by the sol-gel treatment

6.7.2 Tensile properties

6.7.2.1 Twaron® yarns

Mechanical properties of yarns, which are highly related to the energy absorption ability
of a fabric, are of importance to ballistic performance of the fabric. In this investigation, tensile properties of yarns treated by sol-gel technology are taken into account as an indicator to see variations in mechanical property. As mentioned above, there are some weight changes during the sol-gel treatment process. Therefore, both of the tensile properties with and without considering the weight change are shown in Figure 6-17. It should be pointed out here that the strain property of the yarn is not related to the weight change.
To verify the change significance, significance test at 95% confidence interval was conducted on the data and the results are presented in Table 6-12. It can be seen that all the sol-gel treatment introduce significant change to the yarn tenacity because the P value is smaller than 0.05 in each treatment. Table 6-13 lists the change percentage for each case. The tenacities in the two treatments TiZn-WD and TiZn-TD are the smallest, where the decrease percentages in these two cases without considering the weight change is around 3% and the percentages with considering the weight change are around 6%. With the significance test, the Young’s moduli treated by TiZn-WD and TiZn-TD and the strains treated by TiZn-WD and TiZn-TDC are little affected. In addition, the loss for the tensile properties of yarns treated without curing process was found mainly due to the weight change of the yarns because the tensile properties of the yarns treated without curing process show further noticeable reductions when considering weight change and this is not the case for the yarn treated with curing process. According to the above analyses and through the comparison of the changes of tensile properties after each treatment, the two treatment TiZn-WD and TiZn-TD take the least effect on the tensile properties.

For the decrease in the tenacity property of the treated Twaron® yarns, the higher temperature with the acidic environment may be the reason for the loss of tenacity. It was found that the tenacity of the Kevlar® fibre was reduced about 10% when treated by chlorosulfonic acid of 0.08% concentration at 10°C for 0.5 minutes[244]. In addition, 25%
loss in tensile strength was observed when the aramid fibres were immersed for 15 seconds in an sulfuric acid bath of 80% concentration, while at 85% acid concentration, the loss in strength was around 35% \textsuperscript{[246]}. Springer \textit{et al.}\textsuperscript{[247]} noticed that aramid fibre kept only 60% of its original strength value after being treated by 40% sulfuric acid for one day. The acid hydrolysis of aramid was also observed by other researchers \textsuperscript{[248-250]}. Uomoto \textit{et al.}\textsuperscript{[251]} noticed that the higher temperature would accelerate the degradation of aramid fibres. Although our treatment condition is not as harsh as those mentioned before, it is still reasonable to speculate that aramid fibre would degrade due to the acid-catalysed hydrolysis in acidic environment and at higher temperature. It should be noted that the tenacity property of the Twaron\textsuperscript{®} yarns treated by TiO\textsubscript{2}/ZnO hydrosol are less affected than those treated by TiO\textsubscript{2} hydrosol because the TiO\textsubscript{2}/ZnO hydrosol is less acidic than the TiO\textsubscript{2} hydrosol.

Table 6-12 The change significances of tensile properties of Twaron\textsuperscript{®} yarns after sol-gel treatments

<table>
<thead>
<tr>
<th>Yarn tensile properties</th>
<th>Treatments</th>
<th>P value</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tenacity</strong></td>
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<td></td>
<td></td>
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<tr>
<td></td>
<td>TiZn-WD</td>
<td>9.75E-03</td>
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<td>TiZn-WDC</td>
<td>7.41E-11</td>
<td>Yes</td>
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<td>TiZn-TD</td>
<td>8.92E-03</td>
<td>Yes</td>
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<tr>
<td></td>
<td>TiZn-TDC</td>
<td>4.96E-07</td>
<td>Yes</td>
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<td>Ti-WDC</td>
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<td>Ti-TDC</td>
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<tr>
<td><strong>Young’s Modulus</strong></td>
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<tr>
<td></td>
<td>TiZn-WD</td>
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<td>TiZn-WDC</td>
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<td></td>
<td>TiZn-TD</td>
<td>6.99E-02</td>
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<td>TiZn-TDC</td>
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<td>Ti-WDC</td>
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</tr>
<tr>
<td></td>
<td>Ti-TDC</td>
<td>3.02E-07</td>
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<tr>
<td><strong>Strain</strong></td>
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<td>TiZn-WDC</td>
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<td>Ti-TDC</td>
<td>4.12E-17</td>
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Table 6-13 The change of tensile properties for treated Twaron® yarns

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Tenacity(%)</th>
<th>Young’s Modulus (%)</th>
<th>Strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without considering the weight change</td>
<td>Considering the weight change</td>
<td>Without considering the weight change</td>
</tr>
<tr>
<td>TiZn-WD</td>
<td>-3.20</td>
<td>-6.84</td>
<td>-1.05</td>
</tr>
<tr>
<td>TiZn-WDC</td>
<td>-8.94</td>
<td>-7.83</td>
<td>0.12</td>
</tr>
<tr>
<td>TiZn-TD</td>
<td>-2.80</td>
<td>-6.47</td>
<td>1.67</td>
</tr>
<tr>
<td>TiZn-TDC</td>
<td>-6.89</td>
<td>-7.88</td>
<td>0.62</td>
</tr>
<tr>
<td>Ti-WDC</td>
<td>-14.09</td>
<td>-14.54</td>
<td>-2.36</td>
</tr>
</tbody>
</table>

6.7.2.2 Dyneema® yarns

The average tensile properties of the treated Dyneema® yarns are shown in Figure 6-18. The change significance of the tensile properties of Dyneema® yarns caused by sol-gel treatments are also evaluated by the statistical significance test at 95% confidence interval, as listed in Table 6-14. The change percentages after treatments are given in Table 6-15.

The tenacities have been changed for all treatments since in each case, the P value is smaller than 0.05. The tenacities present around 10% increase after all the treatments. When the effect of weight add-on is excluded, there are still some increases for the tenacities, this may be owing to the inert property of Dyneema® yarns and the increased friction between filaments. For the Young’s modulus, all the treatments except the two treatments of TiZn-TD and Ti-TDC present P values smaller than 0.05. Therefore, TiZn-WD, TiZn-WDC, TiZn-TDC and Ti-WDC treatments have little effect on the Young’s modulus of the Dyneema® yarns. The changes of the Young’s moduli in the two cases of TiZn-TD and Ti-TDC around 4% without considering the weight change. With considering the weight change, the Young’s moduli in all treatments cases show further decrease. Similarly, for the strain, the three treatments TiZn-TD, Ti-WDC and Ti-TDC
affect it little with the significance test. The strain in the other three treatments are decreased by around 5%. The decrease in Young’s modulus and strain may be associated with the poor heat resistance property of the Dyneema® yarns. Comparatively speaking, the four treatments TiZn-TD, TiZn-TDC, Ti-WDC and Ti-TDC influence the tensile properties the least.

(a) Tenacity

(b) Modulus
Figure 6-19 Tensile properties for Dyneema® yarns after sol-gel treatment

Table 6-14 The change significance of tensile properties of Dyneema® yarns after sol-gel treatments

<table>
<thead>
<tr>
<th>Yarn tensile properties</th>
<th>Treatments</th>
<th>P value</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tenacity</td>
<td>TiZn-WD</td>
<td>1.39E-09</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>TiZn-WDC</td>
<td>6.87E-06</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>TiZn-TD</td>
<td>3.17E-06</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>TiZn-TDC</td>
<td>3.30E-04</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Ti-WDC</td>
<td>1.03E-08</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Ti-TDC</td>
<td>2.81E-04</td>
<td>Yes</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>TiZn-WD</td>
<td>2.16E-01</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>TiZn-WDC</td>
<td>4.16E-01</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>TiZn-TD</td>
<td>2.99E-03</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>TiZn-TDC</td>
<td>7.04E-01</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Ti-WDC</td>
<td>9.63E-02</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Ti-TDC</td>
<td>3.61E-03</td>
<td>Yes</td>
</tr>
<tr>
<td>Strain</td>
<td>TiZn-WD</td>
<td>3.38E-03</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>TiZn-WDC</td>
<td>6.22E-03</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>TiZn-TD</td>
<td>1.13E-01</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>TiZn-TDC</td>
<td>1.28E-03</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Ti-WDC</td>
<td>3.25E-01</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Ti-TDC</td>
<td>1.62E-01</td>
<td>No</td>
</tr>
</tbody>
</table>
Table 6-15 The change of tensile properties for treated Dyneema® yarns

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Tenacity(%)</th>
<th>Young’s Modulus(%)</th>
<th>Strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without considering weight change</td>
<td>Considering weight change</td>
<td>Without considering weight change</td>
</tr>
<tr>
<td>TiZn-WD</td>
<td>12.38</td>
<td>8.05</td>
<td>2.17</td>
</tr>
<tr>
<td>TiZn-WDC</td>
<td>10.27</td>
<td>8.59</td>
<td>1.38</td>
</tr>
<tr>
<td>TiZn-TD</td>
<td>12.54</td>
<td>3.45</td>
<td>4.75</td>
</tr>
<tr>
<td>TiZn-TDC</td>
<td>7.87</td>
<td>1.18</td>
<td>-0.57</td>
</tr>
<tr>
<td>Ti-WDC</td>
<td>11.18</td>
<td>5.99</td>
<td>-2.53</td>
</tr>
<tr>
<td>Ti-TDC</td>
<td>7.97</td>
<td>5.46</td>
<td>-4.56</td>
</tr>
</tbody>
</table>

6.8 Discussions on the sol-gel treatment for increasing inter-yarn friction

For the sol-gel method, it is the first time to be used to increase the inter-yarn friction. It has been proved as a feasible way to achieve the increase of inter-yarn friction without significantly affecting the weight and tensile properties. The degree of the inter-yarn friction in the fabric has reached near the level of CSF of 0.25 and CKF of 0.20 for Dyneema® yarns and CSF of 0.30 and CKF of 0.25 for Twaron® yarns. It was found that changing the introduced oxide materials on the yarn surfaces can increase the inter-yarn friction, which suggests other precursors could be attempted for producing other oxidation materials on the surface for further increasing inter-yarn friction. The reasons underlying the effects of the introduced material on the inter-yarn friction need to be further explored. The particle size in the hydrosol is also an important parameter worth more study because it is related to the preparation temperature. In the preparation, the nano-sized particle hydrosol needs to be prepared near the temperature of 0°C and the submicro-sized particle hydrosol requires higher temperature. The different temperature requirements would add different degrees of difficulty to the reaction control. The curing process is a step usually for fixing coatings on the yarn surfaces. The dependency of inter-yarn friction on this process was investigated. In future research about the fastness of introduced coatings on yarn surfaces, it may be a necessary process worth
investigation.

In addition, compared with the APPCVD method, sol-gel treatment can make use of the existing dip-pad-dry process in fabric dyeing and finishing industry and therein no other new equipment dependency in the treatment process. In this sense, it is an economical and low-cost treatment. Moreover, in the preparation of the hydrosol, it is not high equipment required and thus the cost is not too expensive, mainly in terms of the chemicals. Therefore, surface modification of fabrics by this method for ballistic application is worth further investigations.

6.9 Summary

In this chapter, two types of the ballistic materials, aramid yarn (Twaron®) and UHMWPE yarn (Dyneema®) have been treated by sol-gel method through the dip-pad-dry process for increasing inter-yarn friction. The treatment effects on the two types of yarns have been evaluated in terms of the inter-yarn friction in quasi-static state, tensile properties and the weight add-on. The main results from the sol-gel treatment are summarised as below:

(1) The sol-gel treatments can increase the inter-yarn friction. The parameters in the treatment process including particle size, coated substance and curing process have effects on the inter-yarn friction. The inter-yarn friction resulted from submicro-sized hydrosol treatment is larger than that obtained from nano-sized hydrosol treatment. The TiO₂ coatings on the yarn surface outperforms TiO₂/ZnO coating in increasing the inter-yarn friction. The curing process increases the inter-yarn friction for the treated Dyneema® yarn with nano-sized hydrosol treatment but has little effect on the inter-yarn friction between the treated Twaron® yarns.

(2) The weight added to Dyneema® yarns is less than 9% and that to Twaron® yarns is less than 4%. The less weight add-on for treated Twaron® yarn is attributed to microetch caused by acid hydrolysis of the amide group in the main structure.

(3) With the treatments of TiZn-WD and TiZn-TD for Twaron® yarns and TiZn-TD,
TiZn-TDC, Ti-TDC and Ti-WDC for Dyneema® yarns, the tensile properties of corresponding treated yarns are less affected, around 5%.

(4) The surfaces of the two types of yarns treated with submicro-sized hydrosol are covered with lump-like substance whilst the surfaces with nano-sized one are with scale-like substance with SEM observation. With FTIR and EDX analyses, the coating substances on the yarn surface are mainly titanium dioxide and zinc oxide compounds in the case of TiO₂/ZnO hydrosol and titanium dioxide in the case of TiO₂ hydrosol.

With proper controls such as under the treatments of TiZn-WD and TiZn-TD for Twaron® yarns and TiZn-TD, TiZn-TDC, Ti-TDC and Ti-WDC for Dyneema® yarns, the sol-gel treatment is able to increase the inter-yarn friction with the weight and tensile properties almost unaffected. As such, this treatments will be extended to the corresponding fabrics to increase inter-yarn friction in quasi-static state, and finally improve the ballistic performance.
Chapter 7 Sol-gel Treatment of Fabrics and Evaluation of Experimental Ballistic Performance

7.1 Introduction

To evaluate the effects of inter-yarn friction on ballistic performance of fabrics by ballistic impact tests, there should be fabrics with different levels of inter-yarn friction available. It was found in Chapter 5 that the fabric could not be treated by APPCVD method since the reactor is too small. Nevertheless, in Chapter 6, with proper control of sol-gel treatment, the inter-yarn friction can be increased without significantly affecting the yarn tensile properties and weight. Therefore, the sol-gel technology is applied to treat the fabrics to increase the inter-yarn friction in the fabrics. It should be mentioned that weaving the treated yarns by sol-gel method to achieve the modified inter-yarn friction in the fabric is not practical because the yarns would experience heavy rub with heddle on the heald frame during the weaving process and the coatings on the yarn could be damaged.

The aim of this chapter is to evaluate ballistic performance of fabrics with different levels of inter-yarn friction by ballistic impact tests. Thus, the following work needs to be carried out to complete this aim. Firstly, the inter-yarn friction in the treated fabric will be assessed by the quasi-static yarn pull-out test. The effects of sol-gel treatment on the frictional forces in the treated fabric will be compared with those on the corresponding coefficients of friction of the treated yarns. Further, the effects of inter-yarn friction on the energy absorption of the single-layer fabric and on the traumas caused by deformation of the fabric panel will be evaluated by perforation test and non-perforation test, respectively. Additionally Results with respect to the effects of inter-yarn friction in quasi-static state on the ballistic performance from experimental work will be compared with the predictions obtained from FE simulation. The relationship between the inter-yarn friction in quasi-static state and the ballistic performance will be established.
7.2 Sol-gel treatments to fabrics

7.2.1 Fabrics used for treatments

The Twaron® fabric used for treatment is woven from 93 tex Twaron® yarns with the thread densities of 7.8 ends/cm, which is the same as the structure of the modelled Twaron® fabric in FE simulation. Dyneema® fabric used for the treatment is woven from the Dyneema® yarns with the linear density of 174 tex. Both the warp density and the weft density of Dyneema® fabric are 6.75 ends/cm. The Dyneema® fabric structure is also identical to the Dyneema® fabric model in the FE simulation. Since the treated fabrics are the specimens used for subsequent ballistic impact experiments, the specimens are square in shape and the size is set as 24 cm by 24 cm.

7.2.2 Treatment process to fabrics

7.2.2.1 Treatment conditions for fabrics

Generally, the treatment conditions for the yarns in Chapter 6 are applied to the fabric treatment but there are some differences between the yarn treatment and fabric treatment. The fabric went through dip-pad process four times to achieve even wet pick-up while the yarns experience two times. The drying time was set as 2.5 minutes for the Twaron® fabric and 5.5 minutes for the Dyneema® fabric because the fabric is thick compared with the corresponding yarn and thus needs longer time to be dried. All the other parameter settings are the same.

7.2.2.2 Settings for the fabric treatment

For the settings of the fabric treatments, based on the results from Chapter 6, only TiO$_2$/ZnO hydrosol is selected to treat the Twaron® fabric since the strengths of the yarns treated TiO$_2$ hydrosol have decreased by more, around 15%. Therefore, four treatments listed in Table 6-3 in Chapter 6 will be used to treat the Twaron® fabrics. The Dyneema® fabrics will be treated by all the six treatments for the Dyneema® yarns.
7.2.2.3 Wet pick-up of the fabric

The wet pick-up of the fabric indicates the amount of hydrosol transferred to the fabric. Similarly to the computation method for wet pick-up of the yarn, the wet-pick of the fabric is computed from the dry fabric weight and the wet fabric weight after padding, which are averaged from 15 samples. Tables 7-1 and 7-2 display the percentages of the wet pick-ups for the treated Twaron® and Dyneema® fabrics, respectively. There are differences among the wet pick-ups caused by the types of hydrosols. Nevertheless, the differences are not pronounced, less than 5%. On average, the wet pick-ups of the Twaron® fabrics for the two hydrosols are similar and this is the case for the Dyneema® fabrics with the four hydrosols.

It is interesting to note that for Twaron® material, the wet pick-up of the fabric is a little less than that of the corresponding yarn with the same hydrosol while for Dyneema® material, the wet pick-up of the fabric with a hydrosol treatment equals to that of the yarn with the same hydrosol. This may be associated with the different absorbability of different materials.

Table 7-1 The wet pick-ups for the Twaron® fabrics with different hydrosols

<table>
<thead>
<tr>
<th>Types of hydrosols</th>
<th>Wet pick-up percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Submicro-sized TiO₂/ZnO hydrosol</td>
<td>22.8</td>
</tr>
<tr>
<td>Nano-sized TiO₂/ZnO hydrosol</td>
<td>21.9</td>
</tr>
</tbody>
</table>

Table 7-2 The wet pick-ups for the Dyneema® fabrics with different hydrosols

<table>
<thead>
<tr>
<th>Types of hydrosols</th>
<th>Wet pick-up percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Submicro-sized TiO₂/ZnO hydrosol</td>
<td>49.85</td>
</tr>
<tr>
<td>Nano-sized TiO₂/ZnO hydrosol</td>
<td>46.63</td>
</tr>
<tr>
<td>Submicro-sized TiO₂ hydrosol</td>
<td>45.46</td>
</tr>
<tr>
<td>Nano-sized TiO₂ hydrosol</td>
<td>44.71</td>
</tr>
</tbody>
</table>

7.2.3 Weight add-on for fabrics

The weight add-on for fabrics is indicated by the change of the areal density of the
fabric. Table 7-3 and Table 7-4 list the changes of areal densities for treated Twaron® and Dyneema® fabrics, respectively. They are averaged from 5 samples and the raw data are shown in Table 4 and 5 in the Appendix. Based on P values obtained from significance test at 95% confidence interval, all the increases of the areal densities for the treated fabrics are significant except the Twaron® fabric treated with TiZn-WDC. From Table 7-3 and 7-4, the maximum increase is less than 3% for treated Twaron® fabrics and that is less than 4.5% for treated Dyneema® fabrics. It is also noted that the curing process can reduce the amount of coated substances because it would cause more liquid evaporation at the higher temperature. It should be mentioned that the weight increase percentages added to fabrics differ from those added to the corresponding yarns with the same hydrosol because the fabric undergoes dip-pad process four times while the yarn undergoes the process two times. The process for fabrics is adopted with the consideration that a fabric is thicker than a yarn with a same material.

Table 7-3 Weight add-ons of Twaron® fabrics after sol-gel treatments

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Areal density (g/m²)</th>
<th>Increasing percentage (%)</th>
<th>P value</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>153.61</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>TiZn-WD</td>
<td>157.23</td>
<td>2.36</td>
<td>8.29E-03</td>
<td>Yes</td>
</tr>
<tr>
<td>TiZn-WDC</td>
<td>154.84</td>
<td>0.80</td>
<td>2.00E-01</td>
<td>No</td>
</tr>
<tr>
<td>TiZn-TD</td>
<td>158.17</td>
<td>2.97</td>
<td>5.06E-03</td>
<td>Yes</td>
</tr>
<tr>
<td>TiZn-TDC</td>
<td>155.60</td>
<td>1.30</td>
<td>2.29E-02</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 7-4 Weight add-ons of Dyneema® fabrics after sol-gel treatments

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Areal density (g/m²)</th>
<th>Increasing percentage (%)</th>
<th>P value</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>231.74</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>TiZn-WD</td>
<td>241.16</td>
<td>4.07</td>
<td>1.19E-03</td>
<td>Yes</td>
</tr>
<tr>
<td>TiZn-WDC</td>
<td>240.03</td>
<td>3.58</td>
<td>5.00E-02</td>
<td>Yes</td>
</tr>
<tr>
<td>TiZn-TD</td>
<td>241.45</td>
<td>4.19</td>
<td>5.94E-04</td>
<td>Yes</td>
</tr>
<tr>
<td>TiZn-TDC</td>
<td>240.61</td>
<td>3.83</td>
<td>1.86E-03</td>
<td>Yes</td>
</tr>
<tr>
<td>Ti-WDC</td>
<td>241.68</td>
<td>3.63</td>
<td>2.90E-02</td>
<td>Yes</td>
</tr>
<tr>
<td>Ti-TDC</td>
<td>238.58</td>
<td>2.95</td>
<td>1.09E-02</td>
<td>Yes</td>
</tr>
</tbody>
</table>
7.3 Effects of treatments on the inter-yarn friction in the fabric

According to previous investigations\(^{[25, 60, 8, 9, 33, 252]}\), the yarn pull-out test is one of the commonly used experimental methods to study inter-yarn friction behaviours in the fabric. To indicate the change of inter-yarn friction in the treated fabrics, yarn pull-out test was performed.

7.3.1 Device for yarn pull-out test

To date, there is no yarn pull-out test criterion that can be referred to. In the previous investigations, most of the yarn pull-out experiments have been carried on self-designed devices\(^{[17, 25, 60, 21, 33, 252-254]}\). In the current yarn pull-out test, the test is according to the conception described by Park et al.\(^{[25]}\) and Gong et al.\(^{[253]}\). The experimental set-up is depicted in Figure 7-1(a). A single yarn to be pulled out in a warp direction is selected to figure out the difference of friction inside the treated fabric. As shown in Figure 7-1(b), a warp yarn in the middle of the fabric is chosen to be pulled out and the end of this yarn is clamped in the upper grip. In order to avoid pre-tension produced in this yarn, it is loosely clamped. The bottom side of the fabric is clamped in the lower grip and the end of the yarn to be pulled out is left free. The whole device is mounted on the base of the Instron 4411. The two edges of the fabric sample along the weft yarn direction during the whole test are free from tension. The move of the upper grip stops when the force needed is lower than 0.1N, preventing that the upper grip crashes against the top crossbeam.

In the ballistic impact, the pull-out speed is on the order of \(10^6\) mm/min\(^{[9]}\). Apparently, the pull-out speed in the yarn pull-out experiment cannot satisfy the real yarn pull-out speed in the ballistic impact because the maximum yarn pull-out speed for the used instrument is in the quasi-static state, around 500mm/min. In this sense, to establish relationship between the inter-yarn friction in quasi-static state and ballistic performance is meaningful. Based on previous ingestions\(^{[9, 253, 255]}\), the yarn pull-out forces in the range from 5 mm/min to 500 mm/min is unaffected by pull-out speed. For the current research, the upper grip moves at a speed of 100 mm/min and the force-displacement
curve is recorded in the computer connected with the whole device.

The dimension of the fabric sample for this study is displayed in the Figure 7-1(b). The whole height of the fabric patch is 80mm, in which the pulling-out path is taken 45 mm and the rest is for clamp. The length of the pulling-out path is set to be 45 mm because the maximum displacement set in the machine is 40 mm. The length left for clamp is set as 35 mm to guarantee that the fabric sample is tightly fixed in the lower grip. The total width of the fabric is 65 mm. For the clamp area in the fabric sample, 5 mm in the middle of the fabric is cut off since the end of the warp yarn to be pulled out is not allowed to be clamped. The distance between the two grips is set to be 80 mm.

![Initial cut](image)

Figure 7-1 The yarn pull-out test (a)The device ; (b) Dimensions of fabric sample

### 7.3.2 Characteristics of the yarn pull-out curve

Figure 7-2 displays a load-displacement curve derived from the pull-out test. It is a typical yarn pull-out curve. The curve comprises two regions and one peak load. According to Zhu et al.\[252\], the region I from the start to the peak load is the uncrimping region. The loose yarn is pulled upwards by the grip with a constant speed and gradually straightens up. The tension in this yarn is slowly accumulated little by little as the strain wave progress to more and more orthogonal contacting yarns. It continually builds until the strain wave reaches the upper edge of the lower grip, in other words, the other edge...
of the specimen. At this moment, the pulling force, namely, the tension in the yarn, reaches a peak value sufficient to overcome the static friction exerted by the orthogonal yarns. Finally, the entire pulled yarn starts to traverse vertically through the fabric patch and the pull-out force gradually decreases until the end of the pull-out action in the region II. The region II is called as the translation region\textsuperscript{[252]} or the ejection region\textsuperscript{[254]}. The pull-out force in this region is oscillating, where peak force and valley force arose one after the other. The oscillating in the force–displacement curve corresponds to the pulled warp yarn passing weft yarns. The going-up stage is the stick behaviour of the pulled yarn and the going-down stage is the slip behaviour in the oscillating curve. The stick-slip behaviour at a constant speed is due to the structure of the fabric and the crimp of the yarn. The width between the peak and the valley is dependent on the driving speed and the density of the woven fabric. With the reduction of contact between the pulled yarn and the orthogonal yarns, the pull-out force attenuates gradually. The yarn pull-out forces in all treated fabrics are averaged from 10 samples.

The curve is in agreement with that obtained from Gong et al.\textsuperscript{[253]}, Bilisik et al.\textsuperscript{[60]} and Zhu et al.\textsuperscript{[252]}. The force required to pull the yarn from the fabric structure is the sum of the frictional forces between yarn sets at all the intersecting points\textsuperscript{[8, 9]}. According to the study by Nilakantan et al.\textsuperscript{[254]}, the peak load is defined as the static frictional force for a certain sample size, and the value averaged from the second peak pull-out force value and the first valley value is equivalent to the kinetic frictional force.
7.3.3 Inter-yarn friction in the treated fabrics

The static frictional force and the kinetic frictional force can be used to indicate the magnitudes of inter-yarn friction in the treated fabrics. Figure 7-3 compares the trend of the two forces with that of the two coefficients of friction in different treatment conditions. It is anticipated that the effects of a treatment on the static frictional force and kinetic frictional force are consistent with those on the corresponding coefficient of static friction (CSF) and coefficient of kinetic friction (CKF) between yarns respectively. Based on the curves in Figure 7-3, TiO$_2$/ZnO submicro-sized hydrosol would produce the higher CSF and higher static frictional force than the TiO$_2$/ZnO nano-sized one. The trend is similar except the case of TiZn-WDC treatment. Although the two treatments of TiZn-WD and TiZn-WDC produce the same levels of coefficients of friction, the TiZn-WDC treatment results in lower static frictional force and kinetic frictional force than the TiZn-WD. However, the general trend is not affected because the static frictional force and kinetic frictional force in the case of TiZn-WDC are still higher than that in the case of TiO$_2$/ZnO nano-sized hydrosol.

![Graph showing static frictional force and CSF for different treatments](image-url)
Figure 7.3 Comparisons between the effects of sol-gel treatments on frictional forces and coefficients of friction for Twaron® material (a) static frictional force and CSF; (b) kinetic frictional force and CKF.

Figure 7-4 compare the frictional forces in the Dyneema® fabric with the coefficients of friction of Dyneema® yarns at the same treatment conditions. Generally, the trends of the effects of all the treatments on the static frictional force and kinetic frictional force are highly consistent with these on the CSF and CKF respectively. From the comparisons between the effects of treatment on the frictional forces and the coefficients of friction in the two cases of Dyneema® and Twaron® materials, it can be concluded that the effects of treatment on the inter-yarn friction between individual yarns and friction in the fabric are generally similar. This finding is helpful because the verification of the effectiveness of a treatment for changing the friction in a fabric can be done by treating the corresponding yarns.
Figure 7.4 Comparisons between the effect of sol-gel treatments on frictional forces and coefficients of friction for Dyneema® material (a) static frictional force and CSF; (b) kinetic frictional force and CKF

7.3.4 Coefficients of friction between yarns in the treated fabrics

To compare the effects of inter-yarn friction on the ballistic performance from the ballistic experiment test with the FE prediction, one question to be addressed is to transfer the static frictional force and kinetic frictional force in the treated fabric to the...
coefficients of friction between yarns. During the yarn pull-out test, using an approach similar to Coulomb friction, one could write\textsuperscript{[20]}:

\[ f = \mu F \quad (7-1) \]

Where \( f \) is the frictional force, \( F \) is the stress perpendicular to the frictional force, and \( \mu \) is a coefficient of friction between the individual yarns. Therefore, for the original fabric and treated fabric, Equation 7-2, 7-3 7-4 and 7-5 can be derived from Equation 7-1, respectively.

\[ f_s = \mu_s F \quad (7-2) \]
\[ f_k = \mu_k F \quad (7-3) \]
\[ f'_s = \mu'_s F' \quad (7-4) \]
\[ f'_k = \mu'_k F' \quad (7-5) \]

Where, \( f_s \) and \( f_k \) are the static frictional force and kinetic frictional force for the original fabric, respectively. \( f'_s \) and \( f'_k \) represent the static frictional force and kinetic frictional force for the treated fabric, respectively. \( F \) and \( F' \) denote the applied stress perpendicular to the frictional forces for the original fabric and treated fabric respectively. \( \mu_s \) and \( \mu_k \) denote the CSF and CKF between yarns in the original fabric individually while \( \mu'_s \) and \( \mu'_k \) correspond to the CSF and CKF between yarns in the treated fabric respectively. Therefore:

\[ \frac{f_s}{f'_s} = \frac{\mu_s F}{\mu'_s F'} \quad (7-6) \]
\[ \frac{f_k}{f'_k} = \frac{\mu_k F}{\mu'_k F'} \quad (7-7) \]

During the yarn pull-out test, the test conditions are kept same for all the testing samples and thus it is reasonable to assume that the stress perpendicular to the frictional force are kept at the same value for all fabrics. Thus, the CSF and CKF between yarns in the treated fabric can be computed using Equation 7-8 and Equation 7-9, respectively.

\[ \mu'_s = \frac{\mu_s f'_s}{f_s} \quad (7-8) \]
\[ \mu'_k = \frac{\mu_k f'_k}{f_k} \quad (7-9) \]

Since CSF and CKF are computed from the static frictional force and kinetic frictional force, the significance test at 95% confidence interval for the static frictional force and kinetic frictional force were carried out and the results are shown in Table 7-5. All the P values are less than 0.05 except the two P values of the kinetic frictional force from TiZn-TD and TiZn-TDC treatment. The CSF and CKF based on Equations 7-8 and 7-9 are presented in Tables 7-6 and 7-7. In order to obtain effective results from ballistic impact, the difference between the levels of coefficients of friction should be significant and yarn tensile properties should be little affected. With the considerations in this two aspects, for the Twaron® fabrics, three levels of coefficients of friction are obtained from the original, TiZn-WD and TiZn-TD treatments. In the case of Dyneema® fabrics, three levels of coefficients of friction are acquired from the original, Ti-WDC and TiZn-TDC treatments.

Table 7-5 The significance test results for both static frictional and kinetic frictional forces

<table>
<thead>
<tr>
<th>Types of fabric</th>
<th>Treatments</th>
<th>Static frictional force</th>
<th>Kinetic frictional force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>P value</td>
<td>Significance</td>
</tr>
<tr>
<td>Twaron® fabric</td>
<td>TiZn-WD</td>
<td>1.68E-07</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>TiZn-WDC</td>
<td>4.45E-05</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>TiZn-TD</td>
<td>1.65E-03</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>TiZn-TDC</td>
<td>4.33E-04</td>
<td>Yes</td>
</tr>
<tr>
<td>Dyneema® fabric</td>
<td>TiZn-WD</td>
<td>6.17E-11</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>TiZn-WDC</td>
<td>6.39E-14</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>TiZn-TD</td>
<td>9.74E-05</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>TiZn-TDC</td>
<td>4.28E-11</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Ti-WDC</td>
<td>2.46E-05</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Ti-TDC</td>
<td>7.16E-07</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Table 7-6 The coefficients of friction between yarns in sol-gel treated Twaron® fabrics

<table>
<thead>
<tr>
<th>Treatments</th>
<th>CSF</th>
<th>CKF</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiZn-WD</td>
<td>0.25</td>
<td>0.22</td>
</tr>
<tr>
<td>TiZn-WDC</td>
<td>0.20</td>
<td>0.19</td>
</tr>
<tr>
<td>TiZn-TD</td>
<td>0.19</td>
<td>0.17</td>
</tr>
<tr>
<td>TiZn-TDC</td>
<td>0.19</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Table 7-7 The coefficients of friction between yarns in sol-gel treated Dyneema® fabrics

<table>
<thead>
<tr>
<th>Treatments</th>
<th>CSF</th>
<th>CKF</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiZn-WD</td>
<td>0.20</td>
<td>0.19</td>
</tr>
<tr>
<td>TiZn-WDC</td>
<td>0.20</td>
<td>0.19</td>
</tr>
<tr>
<td>TiZn-TD</td>
<td>0.17</td>
<td>0.15</td>
</tr>
<tr>
<td>TiZn-TDC</td>
<td>0.21</td>
<td>0.17</td>
</tr>
<tr>
<td>Ti-WDC</td>
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<td>0.26</td>
</tr>
<tr>
<td>Ti-TDC</td>
<td>0.27</td>
<td>0.21</td>
</tr>
</tbody>
</table>

7.4 Energy absorption of a single-layer fabric in an impact event

This part focuses on a single-layer fabric subjected to perforation impact. The perforation performance of the single-layer fabric at the three levels of the inter-yarn friction was tested using the device described in Chapter 3 section 3.2. The perforation performance will be evaluated from the aspect of the energy absorption. The data from perforation test are shown in Table 6 and Table 7 in the Appendix.

7.4.1 Reduction of projectile velocity

7.4.1.1 Twaron® fabric

Due to the non-precise control of the gun power, there is an inevitable varieties of impact velocity. In order to evaluate the energy absorption ability of a single-layer fabric at different levels of inter-yarn friction at the same impact velocity, the relationship between impact velocity and residual velocity needs to be built. Linear regression is attempted to describe the relationship between the impact velocity and the residual
velocity. Figures 7-5, 7-6 and 7-7 describe the ballistic perforation results for a single-layer Twaron® fabric at different levels of inter-yarn friction. The vertical and horizontal axes are the impact velocity and residual velocity, respectively. The linear regression is suitable to describe the relationship between the impact velocity and the residual velocity since all of the $R^2$ values at the three levels of inter-yarn friction are larger than 0.9.

Figure 7-5 The impact velocity and residual velocity in case of CSF of 0.16 and CKF of 0.15 for Twaron® fabric

Figure 7-6 The impact velocity and residual velocity in case of CSF of 0.19 and CKF of 0.17 for Twaron® fabric
7.4.1.2 Dyneema® fabric

The perforation tests were also carried out to the single-layer Dyneema® fabric. The impact velocity and the corresponding residual velocity at the three levels of inter-yarn friction are described in Figures 7-8, 7-9 and 7-10, respectively. The linear regression equations for expressing the relationship between the impact velocity and the residual velocity at each level of inter-yarn friction are displayed next to the fitting line. The linear regression equation is also qualified to describe the relationship between the impact velocity and residual velocity obtained from a single-layer Dyneema® fabric subjected to ballistic impact since all the $R^2$ at the three levels of the inter-yarn friction are larger than 0.9.
Figure 7-8 The impact velocity and residual velocity in case of CSF of 0.12 and CKF of 0.11 for Dynema® fabric

Figure 7-9 The impact velocity and residual velocity in case of CSF of 0.21 and CKF of 0.17 for Dynema® fabric
Figure 7-10 The impact velocity and residual velocity in case of CSF of 0.32 and CKF of 0.26 for Dynema® fabric

7.4.2 Effects of inter-yarn friction on energy absorption

In order to evaluate the energy absorption of the fabrics with different levels of inter-yarn friction, the overall energy absorption at impact velocity of 475 m/s are computed from the linear regression equations. The impact velocity of 475 m/s is used with two considerations. One is that the impact velocity is averaged around 475 m/s and the other is that the impact velocity used in FE simulation is also 475 m/s. The projectile energy loss is used to indicate the overall energy absorption of the fabric. It is reasonable since all the energy loss is transferred to the fabric without considering other effects. In addition, due to the difference in the areal density of the fabric at each levels of inter-yarn, the overall energy absorption is normalised to the areal density of the single-layer fabric at the corresponding levels of inter-yarn friction.

7.4.2.1 Results

The overall energy absorption of the single-layer Twaron® fabric at individual level of inter-yarn friction computed based on the corresponding equation displayed in Figures 7-5,7-6 and 7-7 are shown in Figure 7-11(a). Figure 7-11(b) displays the normalised one. For the given Twaron® material and structure, increasing inter-yarn friction from the level of CSF of 0.16 and CKF of 0.15 to CSF of 0.25 and CKF of 0.22, the overall
energy absorption as well as the normalised one of the fabric would decrease. In other words, increasing inter-yarn friction plays a negative role in the energy absorption in this frictional range for Twaron® fabric. The overall energy absorption decreases by 13.76 % at the highest levels of inter-yarn friction.

![Diagram showing energy absorption](image)

**Figure 7-11** The energy absorption of Twaron® fabric (a) overall energy absorption, (b) normalised overall energy absorption

The overall energy absorption and the normalised one of the single-layer Dyneema® fabric at each level of inter-yarn friction is displayed in the bar chart in Figure 7-12. The
Overall energy absorption at each level of inter-yarn friction was obtained based on the linear regression equation displayed in Figures 7-8, 7-9 and 7-10 respectively. In the case of Dyneema® fabric, as the inter-yarn friction increases from the level of CSF of 0.12 and CKF of 0.11 to CSF of 0.32 and CKF of 0.26, the overall energy absorption increases and the normalised one increases as well. The single-layer Dyneema® fabric with the highest levels of inter-yarn friction absorbs 6.74% more energy than the single-layer original Dyneema® fabric.

Figure 7-12 The energy absorption of Dyneema® fabric (a) overall energy absorption, (b) normalised overall energy absorption
7.4.2.2 Discussions

The experimental result for Twaron® fabric with respect to the trend of inter-yarn friction affecting the overall energy absorption agrees with that from FE simulation in Chapter 4, shown in Figure 4-1, where the overall energy absorption decreases with the increase of inter-yarn friction in the frictional range from CSF of 0.10 and CKF of 0.05 to CSF of 0.30 and CKF of 0.25. Nevertheless, the model in Chapter 4 in the case of DYM was not based on the Dyneema® fabric used for ballistic tests because the yarn count and the thread density are different. As such, a FE simulation model for the single-layer Dyneema® fabric was built up, referring to Chapter 3 section 3.3.2, and the ballistic impact with velocity of 475 m/s at the obtained three levels of inter-yarn friction were simulated. Figure 7-13 illustrates both FE simulation and experimental results with respect to the trend of the energy absorption per areal density with the increase of inter-yarn friction in the case of Dyneema® fabric. In the simulation results, the energy absorption increases with the increase of inter-yarn friction. The experimental result also shows that the normalised energy absorption grows as the inter-yarn friction increases in the Dyneema® fabric. Therefore, the trend of inter-yarn friction affecting the energy absorption from experimental work is also in accordance with that from FE simulation in Dyneema® fabric case.

![Energy absorption per areal density vs Inter-yarn friction](image.png)

Figure 7-13 The comparison between FE simulation and experiment for the normalised energy absorption of the Dyneema® fabric
To the Twaron® fabric, near zero friction, it can make use of the comparative advantage of larger transverse deflection ability (referring to Chapter 4 section 4.4.2) to transversely deflect more to alleviate the stress near the impact point and thus to delay fabric failure. Due to the larger transverse deflection, a fabric response with larger depth and smaller radius is formed but it still means more energy absorbed. Under this scenario, slightly increasing the inter-yarn friction is detrimental to the transverse deflection ability and thus would decrease the overall energy absorption for the Twaron® fabric. To the Dyneema® fabric, which does not have the advantage of transverse deflection ability, slightly increasing inter-yarn friction has little effect on the failure time but will significantly enhance the resistant force and thus make the energy loss much more efficiently, leading to larger overall energy absorption of the fabric.

7.5 Analysis of trauma through fabric panel

Blunt trauma caused by the transverse deflection of body armour during the non-perforation test has been regarded as an injury mechanism, for instance, skin and organs contusions, rib fracture, laceration and perforation, in both the military and civilian worlds. [256] Therefore, it is essential to understand the effects of inter-yarn friction on blunt trauma. Upon impact of multi-layer woven fabric panels, three frictional forces are identified: friction between the projectile and the fabric; friction among fabrics in the system, and friction between yarns (inter-yarn friction). Nevertheless, the first two frictional forces are negligible [24, 73]. Thus, the following is to explore the effects of inter-yarn friction on the trauma.

7.5.1 Non-perforation test method

The non-perforation test is conducted according to the NIJ Standard-0101.04, referring to Chapter 2 section 2.2.2. An oil based clay packed in a rigid frame constructed of metal is used to simulate human skin. During the non-perforation test the back of the fabric panel is placed in contact with the clay surface. The image of the clay is shown in Figure 7-14(a). The size of the clay is 22 cm (length) × 22 cm (width) × 10 cm (thickness).
Four shots are planned to be fired on the fabric panel with the size of 24 cm(length) × 24 cm(width). The positions of each shot are 8 cm from the selvedge, as shown in Figure 7-15. Before individual test, the clay is conditioned in the oven at the temperature of 37°C for about 6 hours. For the boundary conditions, two vertical sides of the fabric panel are fixed by rubber band and the other two parallel sides are left free, as shown in Figure 7-14(b). The depth of the hole depressed on the clay by the transverse deflection of the fabric panel is measured using a ruler from the plane defined by the front edge of the clay box fixture and reported in millimetres. The diameter of the hole is calculated from the circumstance of the maximum circle left on the front plane of the clay. The depth of the hole represents the severity of the impact and the maximum diameter of the hole indicates the possible area spread of the blunt trauma. The depth of the hole and the diameter of it are termed as the trauma depth and trauma diameter respectively. The lower the depth and the larger the diameter are, the better is the performance of a fabric panel\[160\].

Figure 7-15 Four shot points located on the fabric panel
Before non-perforation test, the first thing to be considered is the layers to be used in the fabric panel for the test. Several attempts have been carried out to determine the layers in the fabric panel. Finally, for the original Twaron® and Dyneema® fabric, 24 layers were found to be the minimal laminations that meet the demand of preventing perforation. Since the areal densities of the fabrics in individual levels of inter-yarn friction are different, the trauma depth and the trauma diameter in different levels of inter-yarn friction are normalised to the areal density of the 24-layer fabrics. The areal density of the 24-layer fabric panel is computed using the areal density of the single-layer fabric multiplied by 24. The non-perforation of the fabric panels are assessed at the impact velocities in the range from 460 m/s to 500 m/s.

7.5.2 Effects of inter-yarn friction on the trauma depth

7.5.2.1 Results

Figure 7-16 shows the trauma depth and the normalised one against the impact velocity at each level of inter-yarn friction for Twaron® fabric panel. As the inter-yarn friction increases from the level of CSF of 0.16 and CKF of 0.15 to CSF of 0.19 and CKF of 0.17, a flatter trauma in the case of Twaron® fabric panel is produced, and the trauma depth decreases by 16.99%. Further increasing inter-yarn friction to the level of CSF of 0.25 and CKF of 0.20 still keeps the trauma depth of Twaron® fabric panel at this level. Figure 7-17 shows the trauma depth and the normalised one at the three frictional levels in the circumstance of Dyneema® fabric panel. With the inter-yarn friction levels increasing from CSF of 0.12 and CKF of 0.11 to CSF of 0.21 and CKF of 0.17, the trauma depth formed by the Dyneema® fabric panel depression decreases by 10.73%. When the inter-yarn friction in Dyneema® fabric panel is increased by the level of CSF of 0.32 and CKF of 0.26, the trauma depth becomes a little deeper.
Figure 7-16 Twaron® fabric panels (a) trauma depth, (b) normalised trauma depth
7.5.2.2 Discussion

From the non-perforation ballistic impact investigation, increasing inter-yarn friction to CSF of 0.19 and CKF of 0.17 for Twaron® fabric panel and to CSF of 0.21 and CKF of 0.17 for Dyneema® one is beneficial for reduction of the trauma depth. The reason is as follows. The results in Chapter 4 section 4.4.2 showed that slightly increasing inter-yarn friction would significantly reduce the transverse deflection ability of the single-layer fabric. The trauma depth is positively related to the transverse deflection ability of the
fabric. In other words, the larger transverse deflection ability will result in deeper trauma. Correspondingly, increasing inter-yarn friction would decrease the trauma depth. In addition, from FE analyses in Chapter 4, it is found that an increase in inter-yarn friction will more significantly decrease the transverse deflection ability of the Twaron® fabric than that of the Dyneema® one. Therefore, for the panels constructed from the two types of fabrics, it is reasonable to observe that the Twaron® fabric panel would give rise to more depth reduction with a small increase in inter-yarn friction than the Dyneema® fabric panel. Further increasing inter-yarn friction to CSF of 0.25 and CKF of 0.22 has little effects on Twaron® fabric panel and this is because the transverse deflection ability is no longer affected when the inter-yarn friction reaches the level around CSF of 0.40 and CKF of 0.35, referring to Figure 4-28 in Chapter 4. The threshold from which the transverse deflection ability is uninfluenced for a fabric panel is lower because the fabric panel is thicker, and already in much stiffer state than the single layer fabric. For the Dyneema® fabric panel, the reasons that the trauma depth becomes a little deeper at the level of CSF of 0.32 and CKF of 0.26 might be that the impact velocities are a little larger compared with the velocities at the level of CSF of 0.21 and CKF of 0.17.

7.5.3 Effects of inter-yarn friction on the trauma diameter

7.5.3.1 Results

Figure 7-18 and 7-19 show the trauma diameter and the normalised one of the Twaron® fabric panel and Dyneema® fabric panel respectively with different inter-yarn frictional levels respectively. The trauma diameter indicate the area that the trauma may spread. It is found that the spread area of the blunt trauma is unaffected as the inter-yarn friction increases from CSF of 0.16 and CKF of 0.15 to CSF of 0.25 and CKF of 0.22 for the Twaron® fabric panel and from CSF of 0.12 and CKF of 0.11 to CSF of 0.32 and CKF of 0.26 for the Dyneema® fabric panel.
Figure 7-18 Twaron® fabric panels (a) trauma diameter, (b) normalised trauma diameter
Figure 7-19 Dyneema® fabric panels (a) trauma diameter, (b) normalised trauma diameter

7.5.3.2 Discussion

Trauma diameter by nature represents the area that the transverse wave travels to. In Chapter 4, modelling shows that slightly increasing inter-yarn friction would lead to much faster transverse wave velocity, referring to Figure 4-25. The effect of inter-yarn friction on trauma diameter is positively related to that on the transverse wave velocity of the single-layer fabric. Nevertheless, in the non-perforation test, it is found that trauma diameter is not affected by the inter-yarn friction. The reason may be that from...
the inter-yarn friction level of CSF of 0.10 and CKF of 0.05 to CSF of 0.30 and CKF of 0.25, corresponding to inter-yarn frictional range obtained in experimental work, the difference between transverse wave velocity around 0.1 mm/µs in the FE simulation, referring to Figure 4-25 in Chapter 4, which indicates that the difference is extremely small. As such, in the experimental work, it is more difficult to measure such a small difference. Therefore, the trauma diameters in the different levels of inter-yarn friction change little.

7.6 Summary

In this chapter, the yarn pull-out behaviours in the two types of fabrics, Twaron® fabric and Dyneema® fabric after the sol-gel treatment have been investigated. The effects of sol-gel treatment on inter-yarn friction in the fabric have been evaluated by the quasi-static yarn pull-out test. Also, the effects of inter-yarn friction in quasi-static state on the ballistic performance with respect to the energy absorption and the trauma have been evaluated by means of perforation and non-perforation tests.

The perforation impact test to the single-layer fabric at the impact velocity around 475 m/s have shown that the energy absorption per areal density of Twaron® fabric will be reduced by 13.76% and that of Dyneema® fabric will be increased by 6.74% as inter-yarn friction slightly growing in the range of CSF of 0.10 and CKF of 0.05 to CSF of 0.30 and CKF of 0.25. In the impact velocity range from 460 m/s to 500 m/s, the trauma depth per area density of the Twaron® fabric panel will be reduced by 16.99% and that of the Dyneema® fabric panel will be reduced by 10.73% as the inter-yarn friction growing up to CSF of 0.19 and CKF of 0.17 and CSF of 0.21 and CKF of 0.17 respectively. The trauma diameters per areal density of the panels made from the two types of fabrics are unaffected by the inter-yarn friction.

The comparison between FE simulation and the empirical result shows a good agreement with each other with respect to the trends of the effects of inter-yarn friction in quasi-static state on ballistic performance. In addition, using the sol-gel treatments can increase the yarn pull-out forces for the two types of fabrics. The trend of the effects of
sol-gel treatments on the frictional forces has been found similar to that on the coefficients of friction between individual yarns.

In addition, through increasing inter-yarn friction, the sol-gel treatments can increase the ballistic performance of fabrics without affecting the weight. The Ti-WDC treatment for a single-layer Dyneema® fabric has demonstrated higher energy absorption compared to the untreated one, maximally by 6.74%. The TiZn-TD treatment for the Twaron® fabric panel make the trauma depth reduce by 16.99% and the TiZn-TDC treatment for the Dyneema® fabric panel gives a 10.73% reduction of the trauma depth.
Chapter 8 Conclusions and Future Work

Woven fabrics with high-performance yarns are extensively applied to construct soft body armour. For the soft body armour, it develops towards lighter weight and more reliability. Nevertheless, increasing the reliability generally means that the weight would increase as well. It is more desirable that the soft body armour would become more reliable with the weight kept unchanged or become lighter. This research aims to employ surface modification method to increase inter-yarn friction for improving ballistic performance of woven fabrics used for soft body armour with the weight unaffected. The achievements will be highlighted and the work to continue in future will be presented.

8.1 Conclusions

To achieve the aim of this research, three parts of work have been carried out, including (i) FE analyses on the mechanism of inter-yarn friction in quasi-static state on ballistic performance, (ii) practical surface modification of yarns and fabrics to increase inter-yarn friction, and (iii) establish the relationship between the ballistic performance of fabrics and inter-yarn friction in quasi-static state with both experimental work and numerical investigation. The main achievements from this research are given below:

(1) It has been established and confirmed that increasing inter-yarn friction in quasi-static state improves ballistic performance of fabrics through both numerical and experimental investigation.

The FE investigation reveals that the overall energy absorption of Dyneema® fabric will be increase by 5.30% as the inter-yarn friction growing to the level near CSF of 0.3 and CKF of 0.25. Moreover, the single-layer TM fabric will absorb 28.05% more energy as the inter-yarn friction increases from CSF of 0.3 and CKF of 0.25 to CSF of 0.8 and CKF of 0.75. Also, the DYM fabric will absorb 60.80% more energy when the inter-yarn friction reaches the level of CSF of 0.6 and CKF of 0.55 compared to zero friction. In addition, increasing inter-yarn friction leads to more globalised fabric response.
The ballistic impact tests shows that increasing inter-yarn friction to the levels of CSF of 0.19 and CKF of 0.17 for Twaron® fabric and CSF of 0.21 and CKF of 0.17 for Dyneema® fabric respectively, the energy absorption per areal density of the Dyneema® fabric can be increased by 6.74%, the trauma depth per areal density of the Twaron® fabric panel will be reduced by 16.99% and that of the Dyneema® fabric panel will be decreased by 10.73%.

(2) The mechanisms of inter-yarn friction in fabrics during ballistic impact have been identified through FE simulation and analyses.

(a) The reasons that higher inter-yarn friction increasing the overall energy absorption are given below:
   (i) The fabric with higher inter-yarn friction presents higher resistance to the projectile, thus increasing the energy absorption rate and enabling the fabric to dissipate the impact energy much more efficiently.
   (ii) At higher levels of inter-yarn friction, the structures of fabric can be kept much more stable, leading to more yarns engaged in resisting the projectile.
   (iii) More inter-yarn friction leads to more involvement of secondary yarns to participate in taking the impact energy thus alleviating the loads in the primary yarns and delaying the primary yarns to fail.
   (iv) Increasing inter-yarn friction can increase both KE and FDE percentages.

(b) The reasons for higher inter-yarn friction decreasing the trauma depth are as follows. Increasing inter-yarn friction will decrease the transverse deflection ability. Correspondingly, the response of the fabric will transfer from a localised one to a globalised one.

It should be noted that much higher inter-yarn friction is counterproductive because it will cause the stress to concentrate more on the primary yarns, resulting in the earlier failure of the fabric, and also reduce the FDE percentage. Also, near zero friction, the TM fabric absorbs more energy, most of which is in the form of SE. However, it is not the desirable energy absorption mode because it is a localised response. In addition, it
was found that the fabric with yarns of lower Young’s modulus possesses larger transverse deflection ability, and vice versa.

(3) It is confirmed through experiments that the inter-yarn friction can be increased by APPCVD and sol-gel treatments without significantly affecting the yarn weights and the yarn tensile properties.

(a) For APPCVD treatment, the CSF and CKF of Twaron® yarn treated for 4 minute have been increased by 83.68% and 56.73% respectively. The increase percentages of 90.61% and 69.90% have been reached for the CSF and CKF of the Dyneema® yarn treated for 2 minutes respectively. After APPCVD treatments, the tensile properties of treated yarns are almost unaffected and the weight change of the treated yarns are negligible. The increase of inter-yarn friction for Twaron® yarns after APPCVD treatment is attributed to much rougher yarn surfaces from SEM analyses and that for Dyneema® yarns is owing to the polar groups identified by FTIR.

(b) For the sol-gel treatment, the CSF and CKF can be increased by 52.10% and 44.49% respectively for Twaron® yarns with TiZn-WD treatment and 89.61% and 74.03% respectively for Dyneema® yarns with Ti-WDC treatment. Simultaneously, the tensile properties and weight are almost unaffected. The reason for the increase of inter-yarn friction after sol-gel treatment is that the surfaces of yarns become much rougher from SEM observations.

(4) The treatment time associated with APPCVD treatment and the parameters like the particle size in the sol, the curing process and the coated substance with sol-gel treatment affect the inter-yarn friction.

In the APPCVD treatment, prolonging the treatment time from 21 seconds to 4 minutes will increase the inter-yarn friction. In the sol-gel treatment, the parameters including the particle size in the hydrosol, the coated substance and the curing process can affect the inter-yarn friction. The submicro-sized particle hydrosol results in higher-inter-yarn
friction than the nano-sized one. The TiO$_2$ coating gives higher levels of inter-yarn friction compared with the TiO$_2$/ZnO coating. The curing process increases the inter-yarn friction for the treated Dyneema® yarns with nano-sized hydrosol treatment but has little effect on that of the treated Twaron® yarns. In addition, the trend of the effects of sol-gel treatments on the frictional forces has been found similar to that on the coefficients of friction between individual yarns.

(5) Sol-gel treatment has been established as an effective method for improving ballistic performance without significant weight increase.

The Ti-WDC treatment increase the energy dissipated by a single-layer Dyneema® fabric by 6.74% compared to the untreated one. The TiZn-TD treatment for the Twaron® fabric panel make the trauma depth reduce by 16.99% and the TiZn-TDC treatment for the Dyneema® fabric panel gives a 10.73% reduction of the trauma depth. Meanwhile, the weights of the fabrics treated by sol-gel method have not been significantly increased. Although the APPCVD treatment has not been applied to the fabric treatment, it is believed that it would increase the ballistic performance as well because of the increased inter-yarn friction.

8.2 Future work

Due to difficulties in inventing new materials for ballistic application, using the current high-performance yarns to develop high-quality soft body armour is still the future trend. For a designer of soft body armour, a comprehensive and sophisticated understanding of the role of each factor and the relationships between these factors is essential because each factor is not isolated from the other. This investigation has covered the single-layer fabric performance and multi-layer fabric panel investigation. It was found that the decrease of energy absorption of a single-layer fabric does not indicate that the non-perforation performance of the multi-layer fabric formed from it would be worse. The relationship between the single-layer fabric performance and the multi-layer fabric performance is worth further investigation.

Except the principle of roughening up the yarn surface to increase inter-yarn friction, it
is also found that changing the chemical groups on the surface of Dyneema® yarn to form hydrogen bonds can increase the inter-yarn friction. It may be a new direction for improving the inter-yarn friction through surface modification of the chemical groups built in the yarn chemical structure.
References

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[57] Prather RN, Swann CL and Hawkins CE (1977) Backface signatures of soft body armors and the associated trauma effects. Army Armament Research and Development Command Aberdeen Proving Ground MD Chemical Systems Lab,


[64] Department of Defense USoA V59 Ballistic Test for Armour.


[140] Standard test method for coefficient of friction, yarn to yarn.


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[188] Prescribed conditions, constraints and interactions, frictional behavior: including friction properties in a contact property definition, Abaqus analysis user’s manual vol 5. ABAQUS, Inc.
deposition methods. *Ceramics International* 39 (3):2787-2794


## Appendix

### Table 1 The wavelength of the yarn for TM and DYM fabric

<table>
<thead>
<tr>
<th>No.</th>
<th>Length of waviness span (cm)</th>
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<td>2</td>
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### Table 2 The width of the yarn cross-section for TM and DYM fabric

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<td>CV%</td>
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<th>The energy absorption (J)</th>
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<td>1.46</td>
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<td>480.08</td>
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</tr>
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<td>C.V. (%)</td>
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### Table 4 The areal density for Twaron® fabric by sol-gel treatments

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### Table 5 The areal density for Dyneema® fabric by sol-gel treatments

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Table 6 The ballistic impact test for a single-layer Twaron® fabric

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