Applied Surface Science 406 (2017) 77–83

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Full Length Article

Modifying friction between ultra-high molecular weight polyethylene (UHMWPE) yarns with plasma enhanced chemical vapour deposition (PCVD)

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ARTICLE INFO

Article history:
Received 8 October 2016
Received in revised form 18 January 2017
Accepted 13 February 2017
Available online 16 February 2017

Keywords:
Fibre
Inter-yarn friction
Ballistic impact
Plasma
PCVD
UHMWPE

ABSTRACT

Ultra-high molecular weight polyethylene (UHMWPE) yarns are widely used in military applications for protection owing to its high modulus and high strength; however, the friction between UHMWPE yarns is too small, which is a weakness for ballistic applications. The purpose of current research is to increase the friction between UHMWPE yarns by plasma enhanced chemical vapour deposition (PCVD). The changes of morphology and chemical structure were characterised by SEM and FTIR individually. The coefficients of friction between yarns were tested by means of Capstan method. Results from tests showed that the yarn–yarn coefficient of static friction (CSF) has been improved from 0.12 to 0.23 and that of kinetic friction (CSF) increased from 0.11 to 0.19, as the samples exposure from 21 s to 4 min. The more inter-yarn friction can be attributed to more and more particles and more polar groups deposited on the surfaces of yarns, including carboxyl, carbonyl, hydroxyl and amine groups and compounds containing silicon. The tensile strength and modulus of yarns, which are essential to ballistic performance, keep stable and are not affected by the treatments, indicating that PCVD treatment is an effective way to improve the inter-yarn friction without mechanical property degradation.

1. Introduction

Ultra-high molecular weight polyethylene (UHMWPE) yarns, one of the commercial polyethylene-based materials and manufactured from gel-spun, is in wide use as ballistic body armour owing to its high modulus and high strength but low density, of which the tenacity is approximately ten times than steel but the density is lower than water, only 0.96 g/cm^3 [1,2]. Nevertheless, for ballistic protection, it's not enough just to be high modulus and strength because the inter-yarn friction also plays a significant role in preventing the yarns from being pulled out during a ballet impacting a fabric [3–6]. It has been found that higher friction between yarns at crossover provides assistance in resisting the projectile and as the inter-yarn friction approximately close to zero, energy absorption by the whole fabric panel system becomes smaller [7–10]. However, the fact is that friction between UHMWPE yarns is relatively much smaller, compared with other fibres commonly used as ballistic materials, such as para-aramid fibre. Consequently, how to improve yarn–yarn friction for polyethylene-based materials without degrading the mechanical property provide a new challenge for body armour researchers.

Through Coulomb theory, the possibility of the friction arises from the adhesion between the surfaces, essentially from the asperities present on all surfaces. Based on this theory, several other theories of friction have been developed, but they all fall into two main divisions: the coulomb or surface roughness theory and the surface interaction theory [11]. For polymer–polymer pairs in contact, adhesion may play a dominant role and surface roughness may lead to an abrasive mechanism, if the roughness is more than nearly 0.8–1 μm [12]. Hence, modifying the surface would change the friction between yarn themselves. Nevertheless, the surface of polyethylene fibre is inert [13–15], it is impossible to modify its surface using normal chemical technology. In addition, most of the traditional chemical treatment would process at higher temperature for making the finishes more adherent to the substrate, whereas Dyneema® yarns would degrade considerable when exposure to temperature more than 160 °C.

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http://dx.doi.org/10.1016/j.apsusc.2017.02.109

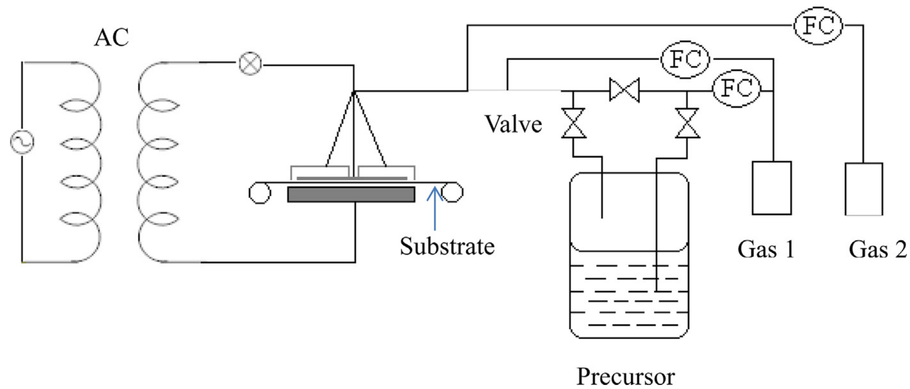

Fig. 1. Schematically illustration for PCVD under atmospheric pressure [21].

Recently, plasma treatment technology has been employed to modify the surface of fibre owing to its environment friendly and non-water effluent. Most substantial investigations showed that the surface treated by plasma become much rougher. The principle of plasma treatment is to make use of energetic particles to etch the surface of the fibre. In the etching process, some of the surfaces would be attacked and come off, causing accidented effect on the fibre and resulting in physical or chemical differences [22]. The application of plasma on UHMWPE fibre can be referred to works from Moon et al. [15–17], Lee et al. [18], Sheu and shyu [19], and Zhang et al. [20]. Although the surface of fibre treated by plasma become a little rougher but compared the surface modified by plasma enhanced chemical vapour deposition (PCVD), the increase of coarseness is far enough. This can be seen from our former research results about PCVD on para-aramid fibre [21]. Similarly to plasma treatment, the etching actions also occur during PCVD treatment, where the difference is that the plasma in PCVD can also make precursors break down to monomer polymerize or inorganic oxide deposited on the surface of fibre [23]. The precursor can be chemicals easier or not easier to react since the chemical react under higher energetic electrons or more active species created by plasma. Both the surface chemistry and surface topography are affected and the specific surface area of fibres is significantly increased by the formation of new substance on the surface of fibre. The bulk property of fibre would remain unaffected since the plasma only interacts strongly with upper molecular layers.

Accordingly, in this research, a commercial product of the UHMWPE yarns, Dyneema® yarn will be exposed to PCVD treatment for different treatment times. The differences with respect to morphology of fibre and chemical structure will be examined by SEM and FTIR respectively. The coefficients of friction between yarns as well as tensile strength after treatment will be deeply investigated as well.

2. Materials and experiments

2.1. Materials

Dyneema® yarns were offered by DSM Company and the linear density of the yarn is 176 tex. The tex defined as the weight, in grams, of 1000 m of filament or yarns on the condition of commercial moisture regain. The precursor of chemical $(CH_3)Cl_2Si$ is provided by University of Salford. The yarns are wrapped on a strip for the convenience of treatment.

2.2. PCVD treatment

The PCVD treatment is divided into two steps: the surface of the yarns is firstly activated by gas plasma followed by a second stage of the deposition onto previously activated fibre surface. The chamber in the reactor is rectangular with size of 10cm × 5 cm. The yarns wrapped on a thin and smooth paper were positioned statically in the sample holder. The precursor of chemical $(CH_3)_2Cl_2Si$ was thermostablized outside the reactor and was carried in the reactor by the carrier gas.

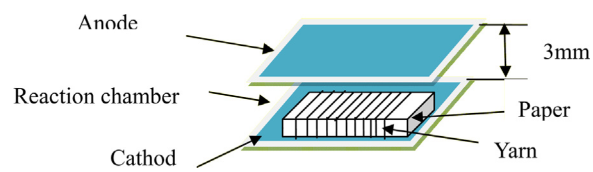

Fig. 2. The position of the yarn between the gap of the electrodes.

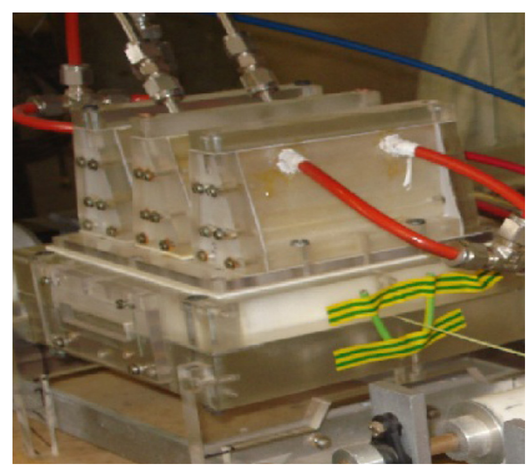

Fig. 3. The equipment of PCVD.

Fig. 1 is a schematically illustration for chemical vapour deposition on yarns under atmospheric pressure which is similar to the equipment used in reference[21]but with the difference of air atmospheric pressure. The yarns were treated by means of PCVD at atmospheric pressure rather than vacuum pressure because the plasma treatment can potentially be realised with less technical effort. The position of the yarn between the gap of the electrodes is shown in Fig. 2. The gap between two electrodes is 3 mm in the reactor. Fig. 3 is the reactor for treatment. The carrier gas is nitrogen and the chemical subject to plasma action is $(CH_3)_2Cl_2Si$. A nitrogen plasma was chosen because of its low degrading effect and high radical density creation [17,24] and environment non-pollution. The plasma source is alternating current (AC) with input voltage 21.9 v and frequency of 3.25 kHz. The nitrogen gas flow rate is 5 l/min and the chemical flow rate is 0.2 l/min, respectively.