

An investigation on sol–gel treatment to aramid yarn to increase inter-yarn friction



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ABSTRACT

Inter-yarn friction helps to increase energy absorption in ballistic fabrics. This paper reports on the results of sol–gel treatment on aramid yarns to increase the inter-yarn friction. Two types of TiO₂/ZnO hydrosols (submicro-sized and nano-sized) prepared using hydrolysis and peptization methods were used to treat aramid yarns with and without curing. SEM was used to characterize the change in morphology. FTIR and EDX analyses were applied to identify the coating substance. The inter-yarn friction was tested using Capstan method. Images from SEM showed that the surface of the yarn treated with TiO₂/ZnO submicro-sized hydrosol was covered with lump-like coating whilst in the case of TiO₂/ZnO nano-sized sol treatment, the coating on the fibres was more film-like. The substance in the coating was confirmed as titanium dioxide and zinc oxide by FTIR and EDX analyses. The test results for coefficient of friction revealed that the coefficient of friction between the yarns treated by submicro-sized hydrosol was 54% higher than the non-treated, and the nano-sized hydrosol was associated to a 10% increase. However, the curing process had little effect on the coefficient of friction between yarns. The study also showed that the tensile properties of the treated yarns and the weight add-on were not significantly affected.

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1. Introduction

Aramid yarns are widely used for ballistic protection because of their high strength and high modulus and also the fibre flexibility. For a ballistic fabric made from such yarns, parameters including the mechanical properties of the yarn, the structure of the fabric, the crimp of yarn in the fabric, the multi-layer interaction, the inter-yarn friction are of importance to dissipate the impact energy during a ballistic event [1].

Inter-yarn friction is of interest to the engineering and development of ballistic fabrics. One of the frequent methods used to study the effect of inter-yarn friction on the ballistic performance is the finite element (FE) method. Different levels of coefficients of friction were selected to indicate the change of inter-yarn friction in the fabric. It is reported that higher coefficient of friction would lead to higher energy dissipation by the fabric [2–6]. Recently, Zhou et al. [7] used the 3D solid continuum method and built up a model for Dyneema[®] fabric subject to impact from a cylindrical projectile with velocity of 500 m/s. Coefficient of friction was set from 0 to 1.0

with 0.1 intervals. The results showed that the energy absorption of the fabric increased in the frictional range from 0.1 to 0.4. Briscoe and Motamedi [8] devised changes in coefficient of friction between yarns and studied the effects of these measures. They found that the fabric with higher coefficient of friction between yarns was associated to lower residual velocity with the impacting velocity around 250 m/s. Analytical, numerical and empirical researches were carried out to study the quasi-static yarn pull-out behaviour in fabrics by many researchers, where the yarn pull-out force was used as an indicator of the inter-yarn friction in the fabrics of concern. They noticed that yarn pull-out mechanism contributes to the energy absorption in the fabric during the impact process [1,9–13].

The inter-yarn friction is highly relevant to the morphology of a fibre, and coating seems to be an effective approach influence the inter-yarn friction. Sun and Chen [14] applied plasma enhanced vapour deposition (PCVD) to the aramid yarns and found that the surface of the yarn becomes much rougher and the yarn pull-out peak force increased dramatically after the treatment. Furthermore, in our previous investigation [15], we found that the coefficient of the friction of the PCVD treated yarns increased with the increase of treatment time.

Sol–gel technology is a frequently used method for general surface coating and it is able to introduce coatings to the yarn surface to modify the surface morphology of the yarn [16,17]. This method

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has the advantage of convenience in application and is suitable for batch processing. The attractive feature of this approach is that it can easily introduce the metallic oxide with higher coefficient of friction to the surface of the fibre [18]. In general cases, most of the sol is alcosol, and it needs to use a large amount of ethanol as dispersant, whereas in our work, hydrosol was used instead of alcosol, reducing the amount of ethanol in the process and make the process more environmentally friendly.

The sol–gel technology is based on colloidal suspensions, popularly known as sols, made from the hydrolysis of appropriately selected precursors, mostly organometallic compounds, catalysed by a certain acid or alkaline [18,19]. 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, 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 [20,21].

This paper aims to modify the surface friction of aramid fibres using the sol–gel technology. TiO_2/ZnO hydrosol prepared using peptization and hydrolysis methods is chosen for the yarn treatment. The effects of particle size in the sol and the curing process on the coefficient of friction will be investigated. In addition, the weight change of yarns and the tensile properties of yarns would also be investigated. The morphology change on the fibre surface will be characterized using SEM and the substances introduced to the yarn surface will be analysed by FTIR and EDX. It is anticipated that the results from this research will provide new information for treating aramid ballistic fabrics for improved performance against high velocity impact.

1.1. Materials

The chemicals including titanium (IV) butoxide $\text{Ti}(\text{OC}_4\text{H}_9)_4$, 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 for preparation of sol–gel solution. All the chemical reagents were used as received.

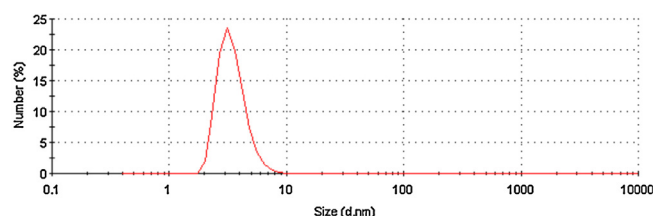
1.2. Preparation of hydrosols

The preparation of the hydrosols started from creating ZnO hydrosol using the peptization method. Zinc acetate dehydrate dissolved in a solution of deionized water with ethanol and ethanolamine were used as the reaction initiating materials. The mole ratio between zinc acetate dehydrate and ethanolamine was 1:1. Acetic acid was used as the peptizer for producing ZnO hydrosol. The second step in this process is to create the mixture of Titanium (IV) butoxide and dehydrate alcohol with an optimal amount of glacial acetic acid. This product was then dropped into ZnO hydrosol. After a 2-h vigorously stirring, the compound TiO_2/ZnO hydrosol was obtained [16,17]. By controlling the reaction temperature, TiO_2/ZnO hydrosols with two different particle sizes were prepared.

1.3. Characterization of the particle size in the sol

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

(a) Nano-sized hydrosol (at reaction temperature of 5 °C)



(b) Submicro-sized hydrosol (at reaction temperature of 60 °C)

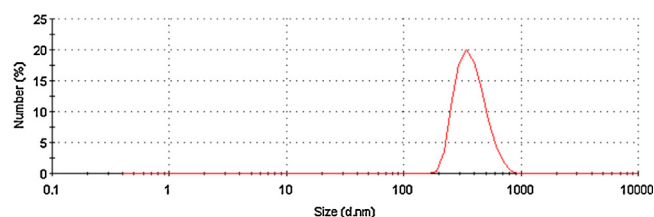


Fig. 1. The size distribution of TiO_2/ZnO hydrosols, (a) nano-sized hydrosol (at reaction temperature of 5 °C); (b) submicro-sized hydrosol (at reaction temperature of 60 °C).

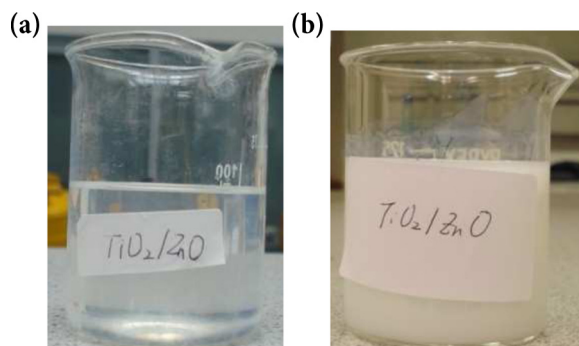


Fig. 2. Images of different hydrosols (a) TiO_2/ZnO nano-size hydrosol (b) TiO_2/ZnO submicro-size hydrosol.

The sizes of the particle in the hydrosols made at different reaction temperature were shown in Fig. 1, which describes the statistical number of hydrosol particles. The size of the particle in the TiO_2/ZnO 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. pH values of the two types of hydro sol are around 4 since the pH of acetic acid is around 4, as shown in Table 1. The pH of TiO_2/ZnO submicro-sized hydrosol is a little lower than the TiO_2/ZnO nano-sized hydrosol because the liquid in the TiO_2/ZnO submicro-sized hydrosol evaporates more due to the higher reaction temperature. The appearances of the two types of TiO_2/ZnO hydrosols are shown in Fig. 2.

2. Sol–gel treatment for Twaron® yarn

2.1. The treatment conditions

The yarn for sol–gel treatment is Twaron® 930 dtex produced by Teijin Aramid without any further cleaning. The TiO_2/ZnO hydrosol was applied on the Twaron® yarn using the Dip-Pad-Dry method. The Twaron® 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

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