



# Impact resistance of shear thickening fluid/Kevlar composite treated with shear-stiffening gel

Qianyun He, Saisai Cao, Yunpeng Wang, Shouhu Xuan\*, Pengfei Wang, Xinglong Gong\*

CAS Key Laboratory of Mechanical Behavior and Design of Materials, Department of Modern Mechanics, University of Science and Technology of China (USTC), Hefei 230027, PR China



## ARTICLE INFO

### Article history:

Received 28 June 2017

Received in revised form 12 December 2017

Accepted 19 December 2017

Available online 20 December 2017

### Keywords:

A. Nanocomposites

B. Impact behavior

D. Mechanical testing

Shear thickening

## ABSTRACT

In this work, shear-stiffening gel (STG) was introduced into shear thickening fluid (STF)-impregnated-Kevlar<sup>®</sup> woven fabric (Kevlar/STF) to improve the impact resistance. The STF filled within the yarns of Kevlar and the STG covered the Kevlar/STF to form Kevlar/STF/STG composite. The STG in the Kevlar/STF/STG not only protected STF but also improved the impact resistance of the fabric because of its excellent shear-stiffening characteristics. A series of experiments including the yarn pull-out test, the split Hopkinson pressure bar impact test, rod penetration test, and knife cutting test were carried out to verify the enhancement effect. The improvement mechanism of the impact resistance for the Kevlar/STF/STG was studied. Under the similar anti-impact performance, the Kevlar/STF/STG possessed lower weight than the Kevlar and its strong impact resistance originated from the synergetic effect among the STF, STG and Kevlar. Therefore, the Kevlar/STF/STG exhibited broad potential in the soft body armor.

© 2017 Elsevier Ltd. All rights reserved.

## 1. Introduction

Body armor, which is designed to weaken slashing or penetrating attacks, mainly consist of hard-plate reinforced body armor and soft non-plated body armor. The hard one can protect high-risk areas from the impact of high-speed bullet. Since the main part is a ceramic or steel plate, the cumbersome nature restricts the movement of the wearer. The soft one mainly protects the arms and legs against the low-speed impact. Usually, it is prepared with multi-layer woven fabrics [1]. These fabrics are usually made of high performance fibers (such as Kevlar, Twaron, Spectra, Dyneema) with high strength, large modulus and low density [1,2]. Because the stacked multilayer fabrics are still heavy, how to reduce the weight of soft body armor under the same protective effect become a challenge.

Wagner et al. firstly introduced the shear thickening fluid (STF) into aramid Kevlar<sup>®</sup> woven fabric to develop the STF/Kevlar soft armor and they found that the STF significantly improved the ballistic performance of Kevlar [2]. The STF is a kind of densely packed suspensions whose viscosity increases rapidly with the increasing of shear rate or shear stress. When subjected to high-speed impact, the STF transits from liquid to solid-like state and returns to the initial liquid state when the external force disappears [3,4]. Due to the typical shear thickening behavior, STF can be used in

damping devices and soft armor [5,6]. Inspired by the Wagner's idea, various in-depth investigations on the mechanical properties of the Kevlar/STF were carried out. Both experiment tests and numerical simulations indicate that the impact resistance of the Kevlar/STF is much stronger than pure Kevlar fabric [7–14]. It is found that the impact resistance of Kevlar/STF is affected by various factors, such as the dispersed particle type, hardness, concentration in STF, dispersing medium type, solvent ratio on STF, additives (such as, silicon carbide, carbon nanotubes), padding pressure, the weave of fabric construction and the change of shot location [15–21]. However, although the Kevlar/STF exhibits high protecting performance, some shortcomings are still exist. Firstly, the STFs are prepared by dispersing the particles in a hygroscopic liquid, such as ethylene glycol, PEG200. Once the STF is long-timely exposed to the air, the shear thickening performance will be reduced because it absorbs water in the moisture. Secondly, part of the fluidic STF will inevitably lost in the Kevlar/STF without any protection. Therefore, more work should be done to improve the stability of the Kevlar/STF.

The shear-stiffening gel (STG) is a typical visco-elastic material [22] whose mechanical properties, such as storage modulus, elastic modulus and yield stress, are critically enhanced under applying the external forces (quasi-static compression, shear loading, dynamic shear loading, and high strain rate compression) [22–24]. As the strain rate increases, the STG changes from the viscous liquid to the rubbery state, and then becomes a glassy state. During the transition, the impact energy is absorbed to against

\* Corresponding authors.

E-mail addresses: [xuansh@ustc.edu.cn](mailto:xuansh@ustc.edu.cn) (S. Xuan), [gongxl@ustc.edu.cn](mailto:gongxl@ustc.edu.cn) (X. Gong).

the deformation, thus the STG exhibits good impact protection performance [25]. By introducing different additives, such as borax, silicates, magnetic carbonyl iron particles, multi-walled carbon nanotubes, multifunctional STG with magnetic-mechanical or electric-mechanical coupling behaviors can be successfully obtained [26,27]. Very recently, our group developed a novel STG/MWCNT/Kevlar-based wearable electronic sensing textile by doping the STG and MWCNT into the Kevlar fabric. The safeguarding performance of the Kevlar/MWCNT can be significantly enhanced by STG due to its excellent shear stiffening character [28]. In consideration of the gel-like state, the STG will be favorable to protect the STF from the moisture after doping them into the Kevlar/STF. Therefore, high impact protecting performance will be expected by impregnating the STG into the Kevlar/STF composite.

In this work, the novel STG doped Kevlar/STF was developed to form Kevlar/STF/STG composite and its anti-impact performance was investigated. In comparison to the Kevlar/STF, the Kevlar/STF/STG composite exhibited better mechanical properties. A series of experiments, including the yarn pull-out test, the modified split Hopkinson pressure bar (SHPB) impact test, rod penetration test, and knife cutting test, were carried out to verify the enhancement effect. The enhancing mechanism of the impact resistance was systematically analyzed. At last, different doping methods were compared and the relative improvement nature was discussed.

## 2. Experimental

### 2.1. Materials

The materials included tetraethyl orthosilicate (TEOS), aqueous ammonia solution ( $\text{NH}_3 \cdot \text{H}_2\text{O}$ ), ethanol, polyethylene glycol (PEG200), ethylene glycol (EG), boric acid, dimethyl silicone oil, benzoyl peroxide (BPO), acetone. The reagents mentioned above were all purchased from Sinopharm Chemical Reagent Co., Ltd., and used without further purification. The high-performance fibers Kevlar®129 were woven into plain weave fabrics (1000 denier, 22.5 yarns per inch, Beijing Junantai Protection Technology Co., Ltd., China) with an areal density of  $200 \text{ g/m}^2$ . Two kinds of particles were used to prepare STF. (a) The silica nanospheres with an average diameter of 230 nm ( $\text{SiO}_2$ ) (Fig. 1b) were synthesized following the sol-gel method. (b) silica particles with an average diameter of  $2.6 \mu\text{m}$  ( $\text{mSiO}_2$ ) (Fig. 8a inset) were obtained from industrial grinding.

### 2.2. Preparation of fabric composites

Synthesis of  $\text{SiO}_2$  nanospheres: ethanol (500 mL), deionized water (50 mL) and  $\text{NH}_3 \cdot \text{H}_2\text{O}$  (50 mL) were mixed at  $30^\circ\text{C}$ , and TEOS (50 mL) was quickly added after 30 min. The reaction was maintained with mechanical stirring for 12 h. The  $\text{SiO}_2$  nanoparticles were collected by centrifugation, washing, dried in a vacuum oven and milled to powder.

Preparation of STF and mSTF: the most commonly used STF in this work was prepared by dispersing the nanospheres  $\text{SiO}_2$  in PEG200 with a fraction of 60 vol%. Besides, the micron-sized  $\text{mSiO}_2$  were dispersed in EG to prepare mSTF with a fraction of 56 vol%.

Preparation of STG: boric acid was heated at  $160^\circ\text{C}$  for 2 h to form pyroboric acid. Then, the pyroboric acid, dimethyl silicone oil, and ethanol were mixed (at a ratio of 2 g:15 g:1 mL) and reacted at  $240^\circ\text{C}$ . 9 h later, the reaction system was cooled down to get the polymer precursor. The STG was obtained by mixing the precursor with BPO at a ratio of 25:1 and then be vulcanized at  $95^\circ\text{C}$  for 2 h.

Preparation of Kevlar/STF composite: the STF was diluted with ethanol (1:4). The fabrics which could be cut into different sizes were immersed in the diluted solution for 3 min, and placed in an oven at  $60^\circ\text{C}$  for 1 h to evaporate the ethanol.

Preparation of Kevlar/STF/STG composite: Kevlar/STF/STG was fabricated by a “dip and dry” method. The above polymer matrix and BPO were dissolved in 200 mL of acetone at a ratio of 25:1. Then, the Kevlar/STF was dipped in the homogeneous mixture for 5 s, dried in an oven at  $40^\circ\text{C}$  for 30 min, and vulcanized at  $95^\circ\text{C}$  for 2 h.

Preparation of Kevlar/STF/STG (hlm) composite: a more straightforward approach was used. The STG was directly placed on the Kevlar/STF by “hand layup method”, and the composite was abbreviated as Kevlar/STF/STG (hlm).

To simplify the description, Kevlar/STF(x) means that the mass ratio of Kevlar to STF is 1:x, and Kevlar/STF(y)/STG(z) represents the ratio of three components is 1:y:z.

### 2.3. Material characterization

First, the macroscopic and microscopic morphological characterization of the material was carried out. Fig. 1a showed the photographs of STF, STG, and Kevlar/STF/STG composite. The fluidic STF prepared by 230 nm  $\text{SiO}_2$  was a white suspension. The STG was solid and its shape changed under the gravity thus it showed a cold flow behavior. Because the weight ratios of the STF and STG in the Kevlar/STF/STG were very small, the visual appearance of Kevlar/STF/STG was similar to the neat Kevlar. The morphology of the 230 nm  $\text{SiO}_2$  in STF and Kevlar/STF was observed using a scanning electron microscope (SEM, JEOL JSM-6700F). After the STF was immersed into Kevlar, the dispersant would evaporate in high vacuum. It was found that a large number of particles were distributed on the surface of the filaments, and the particle size was much smaller than the diameter of filaments (Kevlar/STF in Fig. 1c and d). Fig. 1e and f showed the SEM image of Kevlar/STF/STG, which indicated that the STG covered the surface of the  $\text{SiO}_2$ -attached-filaments and fulfilled the gap between the filaments, thus increased the interconnection between the filaments. To clearly understand the interaction among the three components, a scheme for the cross-sectional structure of the Kevlar/STF/STG was shown in Fig. 2. The  $\text{SiO}_2$  particles in the STF were mainly distributed on the surface of the filaments, while STG covered the surface of the Kevlar/STF filaments. Clearly, the STG isolated the STF from the air.

The rheological properties of the STF and STG were tested using a controlled-stress rheometer (Anton Paar MCR 301). A cone-plate geometry with a cone angle of  $2^\circ$  and a diameter of 25 mm was used for testing STF, while a parallel-plate geometry with a diameter of 20 mm was selected for STG. The viscosity vs. shear rate curve for the 60 vol% STF under steady shear (Fig. 3a) indicated a significant shear thickening behavior. With the increment of shear rate from 11.8 to 55.1 1/s, the viscosity increased from 15.1 to 1310 Pa·s. Fig. 3b depicted the storage modulus and loss modulus of STG under dynamic oscillatory shear ( $\gamma = 1\%$ ). The shear frequency varied from  $10^{-1}$  to  $10^2$  Hz, while the storage modulus changed from 324 Pa to 1.02 MPa. Obviously, the STG showed a typical shear stiffening character and it changed from viscous state to elastic state under shear.

### 2.4. Yarn pull-out test

Yarn pull-out test was used to study the effect of STF and STG additives on the friction between yarns. The composite fabrics were cut into pieces with a size of  $80 \times 50 \text{ mm}^2$ . Table 1 listed the composition and mass ratio of different composite fabrics

Download English Version:

<https://daneshyari.com/en/article/7889677>

Download Persian Version:

<https://daneshyari.com/article/7889677>

[Daneshyari.com](https://daneshyari.com)