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CNT/STF/Kevlar-based wearable electronic textile with excellent anti-impact and sensing performance

Mei Liu[a], Shuaishuai Zhang[b], Shuai Liu[b], Saisai Cao[b], Sheng Wang[b], Linfeng Bai[a], Min Sang[a], Shouhu Xuan[b], Wanquan Jiang[a,*], Xinglong Gong[b,*]

[a] Department of Chemistry, University of Science and Technology of China (USTC), Hefei 230026, PR China
[b] CAS Key Laboratory of Mechanical Behavior and Design of Materials, Department of Modern Mechanics, CAS Center for Excellence in Complex System Mechanics, USTC, Hefei 230027, PR China

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ABSTRACT

This work reports a novel CNT/STF/Kevlar-based (CNT, carbon nanotubes; STF, shear thickening fluid) wearable electronic textile (ET) composite with excellent protective and sensing performance. The dynamic impact resistance test shows the maximum resistance force of the single-layer ET composite reaches as high as 1232 N, which is much larger than the neat Kevlar (746 N), indicating that the ET composite can absorb more energy and sustain higher impact force. Due to the incorporation of the carbon nanotubes (CNTs), the ET composite shows excellent conductivity, thus it can be applied as a sensor to monitor signals of various human body movements. Due to the good flexibility, high sensitivity, and excellent protective performance, the ET composite exhibits high potential in the intelligent wearable electronic textile product, which possesses both excellent protective and sensing performance for human bodies in different environments.

1. Introduction

Terrorist activity offenses are rampant increasingly worldwide, the flexible and comfortable body armors have become more important than ever. Traditional body armors are made of the ceramic and steel plate, which are bulky, rigid and uncomfortable. During the past decades, a series of soft body armor materials, such as Kevlar, Twaron and Spectra, are developed to replace the traditional body armors. These fabrics are made of high performance fibers with high strength, large modulus and low density [1–4]. Kevlar fabric, a type of aramid-based fabric, is one of the most widely used materials in soft body armors. Although the fabric is light-weight, flexibility, it still needs dozens of layers to achieve bulletproof effect [5]. Stacked multilayer fabrics are also bulky and uncomfortable for the wearer. In order to ensure the light-weight and high flexibility of the soft body armors, various composites based on the neat Kevlar fabric have been developed.

Recently, as a non-Newtonian fluid, shear thickening fluid (STF) receives more and more attention due to its unique shear thickening performance. Its viscosity increases dramatically when encountering asudden force, exhibiting a reversible transition from fluid-like to solid-like state. When the applied stress is relieved, the viscosity recovers to the initial state immediately [6,7]. Adding additives to the STF is a common method to tune the rheological properties of the STF. The additives such as carbide particles [8], carbon nanotubes [9] and ceramic particle [10] are invited to enhance the rheological behavior of the STF. As a kind of special energy absorbing material, STF is expected to improve the bulletproof performance of the fabric armor. Norman J. Wagner group develops the STF/Kevlar body armor by introducing the STF into the Kevlar fabric [11]. It is found that the STF markedly improves the bulletproof performance of Kevlar fabric. Furthermore, STFs with various additives are compounded with fabrics and the effects of the additive on the protective performance of the fabric composite have been systematically studied [12–14]. Various tests, such as knife stab resistance and ballistic impact tests for the STF/Kevlar are carried out [15–17] and the results indicate that the protective performance of STF/Kevlar are markedly improved compared with the neat Kevlar. During the application, the *in situ* sensing of the external impacts by the body armor is very important because the people can simultaneously find out the extent of injury during the attack. However, as a kind of wearable material, most of the present STF/Kevlar fabric composite has only a single protection performance which is far from meeting the next generation of intelligent wearable materials. Therefore, novel protective fabric composite material with sensing and response properties is urgent needed.

* Corresponding authors.
E-mail addresses: jiangwq@ustc.edu.cn (W. Jiang), gongxl@ustc.edu.cn (X. Gong).

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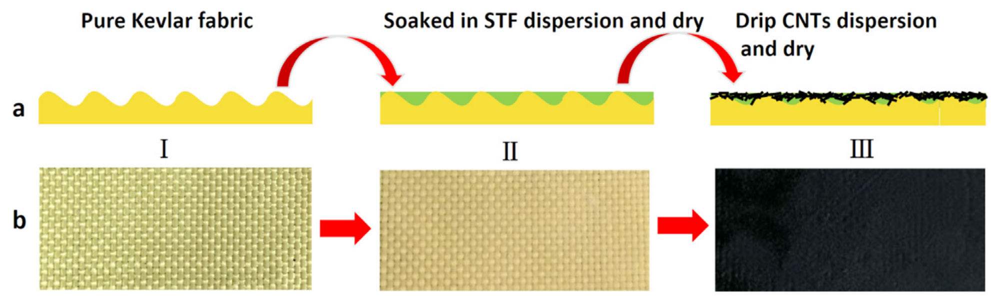

Fig. 1. (a) Illustration of the procedure of the CNT/STF/Kevlar composite; (b) neat Kevlar (I); STF/Kevlar (II); CNT/STF/Kevlar composite (III).

Nowadays, wearable electronic textile has drawn extensive attention due to the wide applications in wearable electronics and intelligent robots [18–20]. Flexible fabric sensors can be applied in electronic skins, touch sensing, heath motion detection, environmental stimuli, and so on [21,22]. Particularly, flexible fabric sensors with high sensitivity, good flexibility and excellent stability are desirable for practical application. Various approaches have been reported to fabricate wearable sensors, one of the most commonly used method is incorporating nanofillers into the insulating fibers. Carbon nanotube (CNT), with remarkable mechanical, electrical and thermal properties, is one of the most commonly investigated conductive filler in fabricating textile sensors [23–25]. CNT-based textile sensors have been extensively developed in strain sensor, pressure sensors, temperature sensors and humidity sensors. CNT-based textile strain sensors, with ultrahigh strain sensing range, excellent stability and good washing durability, are fabricated by dipping and drying CNTs into cotton roving by using traditional yarn manufacturing process [26]. A high sensitive CNT-based water sensor is fabricated by directly depositing CNT onto cellulose fibers through dip coating [27]. Recently, it is reported that the poly (styrene-butadiene- styrene)/carbon nanotube (SBS/CNT) hybrid fiber prepared by using the scalable wet spinning process possesses not only high sensitivity and good reproducibility but also excellent mechanical reliability [28]. Therefore, it will be a good method to introduce CNT to Kevlar fabric to prepare wearable protective materials with sensing performance.

It has been reported that CNT doped STF exhibits an obviously increased shear thickening effect [29]. Recently, Rui Wang group adds oxygen-plasma-modified multi-walled carbon nanotubes (M-MWNT) to STF to improve the quasi-static stab resistance of Kevlar fabrics [30]. The yarn friction and the quasi-static stab resistance of M-MWNT/STF/Kevlar fabric are enhanced obviously after the addition of the M-MWNTs. However, the amount of M-MWNTs added in STF is limited, because the serious agglomeration which usually reduces the shear thickening properties is appeared with a high additive content. To this end, although the M-MWNT has excellent conductivity, M-MWNT/STF/Kevlar fabric cannot exhibit obvious conductivity because the limited M-MWNTs cannot form effective conductive path. Therefore, it is very important to develop a facile method to introduce conductive CNTs into STF/Kevlar to achieve wearable textiles with both sensing and protective properties.

In this work, a novel CNT/STF/Kevlar-based wearable electronic textile with both anti-impact and sensing performance is developed by a “dip and dry” method. STF/Kevlar is firstly fabricated and then the CNT is introduced to cover the STF/Kevlar. Both the mechanical property and the electric conductivity of the CNT/STF/Kevlar-based wearable electronic textile are analyzed. The anti-impact and sensing mechanisms are discussed. Base on this analysis, it is worth mentioning that the anti-impact ET composite also can be applied as a sensor to efficiently detect various body movement under different conditions.

2. Experiments and characterization

2.1. Materials

Tetraethylorthosilicate (TEOS, chemical pure), ethanol (analytical reagent), ammonium hydroxide ($NH_3 \cdot H_2O$, 25–28%, analytical reagent), ethylene glycol (EG, analytical reagent), and poly (ethylene glycol) 200 (PEG 200, analytical reagent) are all purchased from Sinopharm Chemical Reagent Co. MWCNTs with a diameter of 8–13 nm and length of 3–12 um are purchased from Conductive Materials of Heluelida Power Sources Co., Ltd, Xinxiang City, Henan province, China. Kevlar fabric is a type of plain-woven aramid with an area density of 200 g cm$-^{2}$ and is purchased from Beijing Junantai Protection Technology Co., Ltd. All chemicals are used directly as received without further treatment. Re-distilled water is used in this work.

2.2. Experimental

Firstly, SiO_2 nanoparticles are prepared by the modified Stöber method. Then, STF is prepared by dispersing a certain amount of SiO_2 nanoparticles into PEG 200 and the mixture is mixed in a ball crusher up to about 24 h in order to obtain a uniform distribution. In this work, the mass fraction of the SiO_2 in STF is 71%.

Fig. 1(a) shows the preparing illustration of the CNT/STF/Kevlar composite. The STF/Kevlar composite is fabricated by a simple and effective “soak and dry” method. The STF sample is firstly diluted with ethanol by 1:4 and then mixed for 30 min by ultrasonic dispersion method to ensure the dispersion being well distributed. The Kevlar fabric is cut into specific dimensions. Then the Kevlar fabric is soaked in the diluted dispersion for 5 min. After the impregnation, drying the ethanol-STF-Kelvar in a heating oven at 50 °C to evaporate the ethanol. Hence, the STF in the STF-Kelvar kept its original mechanical property. The “soak and dry” process is repeated several times to ensure that sufficient STF is soaked in Kevlar fabric. The weight of each fabric is recorded before and after the impregnation. Fig. 1(b, I, II) shows the pictures of the pure Kevlar and STF/Kevlar respectively. The concrete experimental detail is found in the Supplementary materials.

2.3. Characterization

The morphology of the Kevlar fabric, STF/Kevlar and CNT/STF/Kevlar are characterized by SEM (JEOL JSM-6700F). The rheological properties of the STF are measured by using the rheometer (Physical, MCR301, Anton Paar) at 25 °C with cone-plate having a cone angle of 2° and a diameter of 25 mm. The rheological properties of each sample are measured under rotating shear conditions. In order to remove loading effects, a pre-shear of 1 s^{-1} is applied for 20 s before collecting the experimental data. The detail of the stab resistance tests and yarn pull-out tests is depicted in the Supplementary materials.

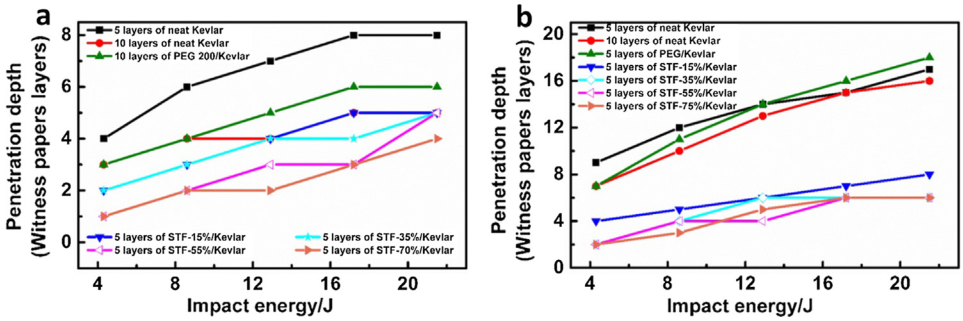

Fig. 2. The results of drop tower stab resistance tests for neat Kevlar fabric, PEG 200/Kevlar fabric and different content of STF/Kevlar composite (STF-15%/Kevlar, STF-35%/Kevlar, STF-55%/Kevlar and STF-75%/Kevlar). Knife stab test (a). Spike stab test (b). The targets of the neat Kevlar fabric and STF/Kevlar composite are composed of 5 layers. The target of the PEG 200/Kevlar fabric is composed of 10 layers.

3. Result and discussion

3.1. Anti-impact performance of the STF/Kevlar fabric

The influence of STF content on the impact resistance of STF/Kevlar has been investigated. The stab resistance tests are conducted by a drop hammer test device. The knife and spike impactors used in the drop hammer stab resistance test are shown in Fig. S2(d1 and d3). The impact energy is calculated by the formula of $E = mgh$, where E is the impact energy, m is the drop mass, g is gravitational acceleration and h is the drop height. The drop height ranges from 0.2 m to 1.0 m. The impact energy increases with the increasing of the drop height. The drop mass of the knife impactor is fixed at 2.2 kg. The neat Kevlar fabrics and PEG 200/Kevlar fabrics are control groups in the test. Neat Kevlar fabrics and STF/Kevlar composite targets are composed of a thickness of 5 layers. PEG 200/Kevlar fabrics are composed of 10 layers. As shown in Fig. 2a, the penetration depth increases with the increasing of the impact energy. For the STF-15%/Kevlar fabric, the penetration depth is 5 layers of witness papers when the impact energy is 17.2 J (0.8 m falling height). While for 5 layers of neat Kevlar fabric, the penetration depth is 8 layers of witness papers. For 10 layers of neat Kevlar fabric, the penetration depth is 5 layers of witness papers. This result represents that there is 200% improvement in impact resistance for STF-15%/Kevlar fabric compared with the neat Kevlar fabric. Similarly, the penetration depth of witness papers reduces significantly with increasing of the STF content in the STF/Kevlar composite, which indicates that anti-impact performance becomes better with the STF weight ratio. STF-55%/Kevlar and STF-75%/Kevlar shows the better stab resistance than the STF/Kevlar with lower content of STF. However, due to the high content of STF, the weight of the STF-75%/Kevlar also increases markedly.

The viscosity of STF increases due to the shear stress which arise from the slippage between fabric yarns when the Kevlar fabric is impacted. The higher viscosity of STF between yarns accounts for larger friction, which will hinder fabric yarns from slipping, and so the anti-impact performance is improved. In contrast, when the Kevlar fabric is treated only with PEG 200, the penetration depth is larger than the neat Kevlar fabric, thus exhibits a worse impact resistance. The reason is the PEG 200 acts as a lubricant and reduces the friction between fabrics. In conclusion, the improvement in impact resistance is mainly due to the shear thickening effect and the enhanced friction between fabrics.

Besides, the stab resistance for STF/Kevlar fabric is also remarkably improved (Fig. 2b). When the impact energy is set at 8.6 J (0.4 m falling height), the penetration depth is 12 layers of witness papers for 5 layers of neat Kevlar fabric. While the penetration depth is 5 layers of witness papers for the STF-15%/Kevlar fabric under the same impact energy. So the spike stab resistance performance improves more than double when the STF is integrated into Kevlar fabric. Similarly, when the impact energy is set at 17.2 J, the penetration depth is 15 layers of witness papers for 10 layers of neat Kevlar fabric, while the penetration depth is 6 layers for 5 layers of STF-55%/Kevlar fabric. Clearly, STF/Kevlar fabric composite exhibited a better spike stab resistance than the neat Kevlar fabric. However, the improvement in the impact resistance of STF/Kevlar fabric composite is not very remarkable when further increasing the content of STF. Particularly, the improvement of anti-impact performance of the STF-75%/Kevlar fabric is limited and the weight of STF also increases markedly compared with STF-55%/Kevlar fabric. In conclusion, it is obvious that the lighter STF/Kevlar fabric composite target possesses better protective performance compared with neat Kevlar fabric target.

To further explore the effect of STF content on the anti-impact performance of the STF/Kevlar fabric, yarn pull-out experiments are performed (Fig. 3). When the yarn is pulled out by an external force, it will rub against the surrounding yarns. The pull-out force increases markedly and rapidly when the yarn changes from relaxation to tension. After the pull-out force reaches the maximum value, it gradually reduces when the yarn is pulled through the STF/Kevlar fabric. Finally, as the displacement continue increases, the yarn is pulled out of the fabric completely, the pull-out force reduces to zero. In Fig. 3a, for the neat Kevlar fabric, it can be observed that the pull-out forces are nearly unchanged (around 4.0 N) at different pull-out speeds. For the PEG 200/Kevlar in Fig. 3b, there is also almost no fluctuation about the pull-out forces at different pull-out speeds. Because the PEG 200 acts as a lubricant and reduces the friction between fabrics, the maximum value of the pull-out force reduces to 3.3 N. Based on the above analysis, it is found that the pull-out force is hardly dependent on the pull speed for neat Kevlar fabric and PEG 200/Kevlar, which may account for the reason that the friction between yarns is relatively small.

For the STF/Kevlar fabric, all the maximum value of pull-out forces are higher than the neat Kevlar fabric, and they are affected by pull-out speeds. The pull-out forces of STF/Kevlar change clearly at a low level (10 and 50 mm/min) and at a high value (100 and 200 mm/min). In Fig. 3c, the average force for STF-15%/Kevlar is 6.5 N when the speed are 10 and 50 mm/min, while the force reaches to around 9.5 N when the pull-out speed increases to100 and 200 mm/min. Other STF/Kevlar fabrics show a similar changing behavior. It indicates that the STF works effectively in the dynamic process when the speed reaches to a critical value. STF exhibits shear thickening behavior when the pull-out speed reaches to the critical shear rate, thus the pull-out force increases at high pull-out speed. Meanwhile, the maximum value of pull-out forces increase with increasing of the STF content in the Kevlar fabrics (In Fig. 3c–f). Therefore, it can be concluded that a higher content of STF in the Kevlar fabrics leads to a larger friction between yarns. To this end, the STF/Kevlar fabric is a promising material for the soft body armor with better anti-impact performance than neat Kevlar fabric.

3.2. Anti-impact performance of the CNT/STF/Kevlar fabric

Based on above experiment studies, STF-55%/Kevlar fabric is selected as the optimum sample to further to prepare the conductive CNT/STF-55%/Kevlar-based electronic textile (ET) due to its good anti-impact performance. The ratio of CNT to Kevlar is set at 7 wt%, since too much CNT will lead to serious agglomeration on the Kevlar surface while too little CNT cannot form effective conductive path. here, the

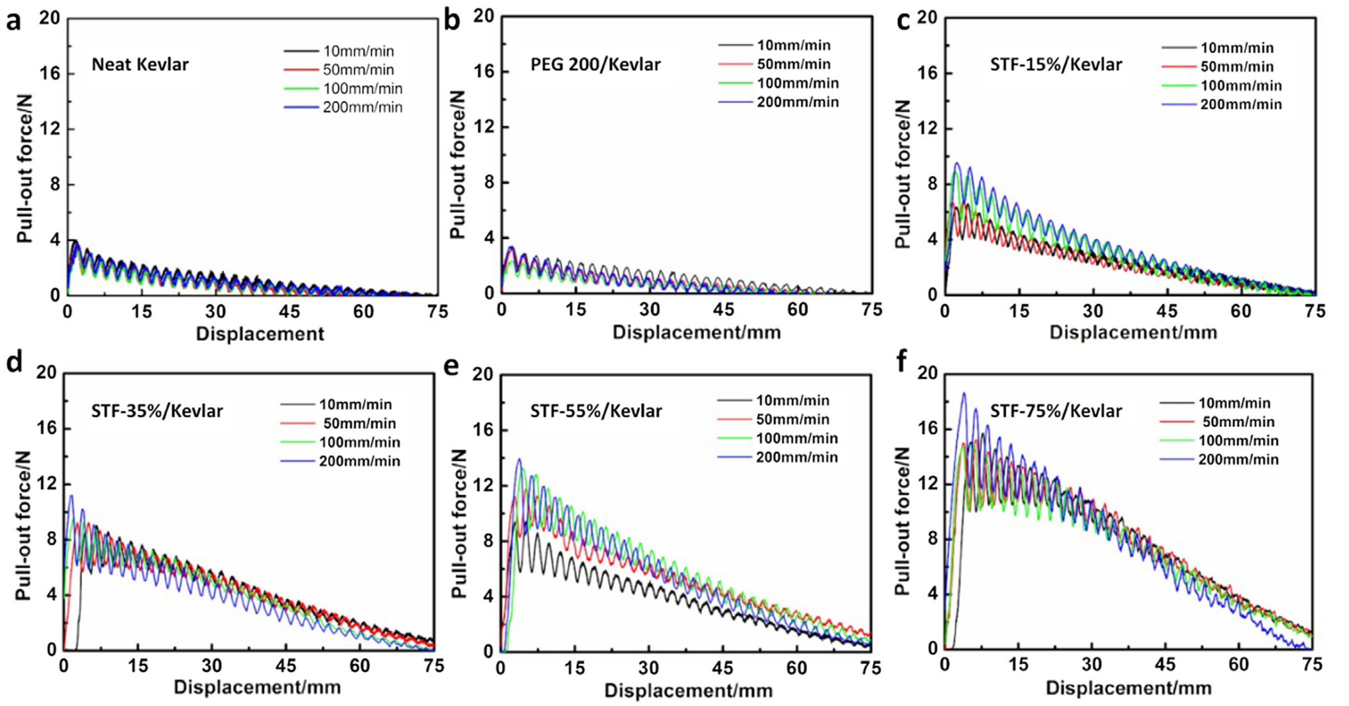

Fig. 3. The yarn pull-out force vs. displacement curves of neat Kevlar (a), PEG 200/Kevlar (b), STF-15%/Kevlar (c), STF-35%/Kevlar (d), STF-55%/Kevlar (e), STF-75%/Kevlar (f) at different pull-out speeds of 10, 50, 100, 200 mm/min.

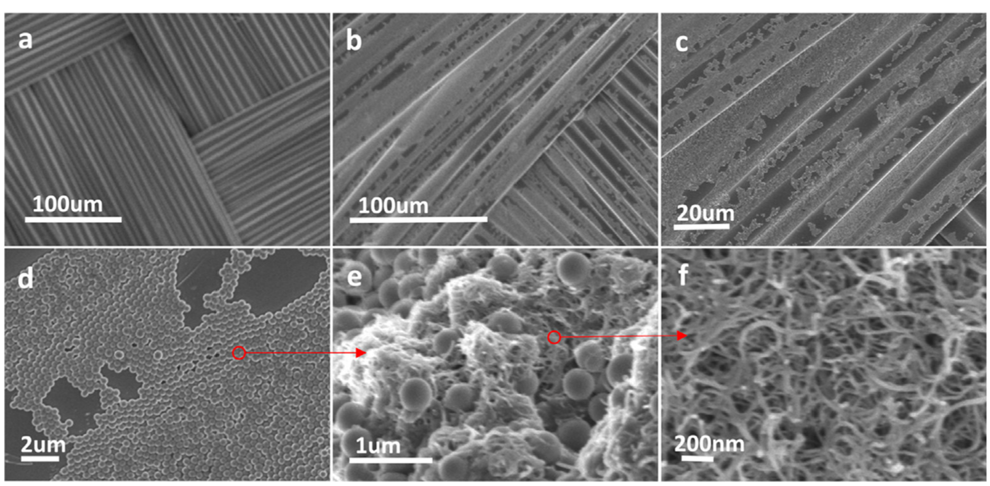

Fig. 4. SEM images of neat Kevlar fabric (a) and CNT/STF-55%/Kevlar composite under different magnifications (b–f). Images of STF and CNT on the surface of Kevlar fabric (e). Images of CNT in a smaller region at a larger magnification rate (f).

CNT/STF/Kevlar ET is prepared via both the “soak and dry” and “drip and dry” processes. Fig. 4 shows SEM images of neat Kevlar fabric (a) and CNT/STF-55%/Kevlar composite (b-f). In comparison to the neat fabric (Fig. 4a), we can observe that the surface of CNT/STF-55%/Kevlar composite is obviously rougher (Fig. 4b and c). The larger magnification SEM images (Fig. 4b–d) indicate that CNT and STF are well distributed on the surface of the yarns and part of them spread into the spaces between the fabric yarns.

Fig. 4e shows larger magnification SEM image of the CNT/STF-55%/Kevlar fabric. Clearly, the CNTs are well mixed with SiO_2 nanoparticles, which indicates that CNTs have a good dispersion in STF and they are homogeneously dispersed on the surface of the Kevlar fabric. The well distribution of the CNTs is important for the formation of the conductive path on the composite. Fig. 4f is the image of the CNTs in a smaller region, which shows that there is no agglomeration of the CNTs. Therefore, CNTs on the Kevlar surface form uniform conductive path and impart conductivity to the fabric. Finally, the STF and CNTs endow the Kevlar fabric with an enhanced anti-impact performance and conductivity.

The anti-impact performance of the CNT/STF/Kevlar composite (ET) is further studied by static stab resistance tests. The knife impactor is fixed on the jaw of the MTS Criterion^{TM} Model 43 tensile testing machine (MTS), and compressed at a rate of 3 mm·min^{-1} under quasi-static compression until the fabric is completely pierced. A single layer of the ET is fixed by a clamp, commercial conductive tapes are stuck on the surface of the target to avoid short circuit and the electric signals are record by electrochemical impedance spectroscopy system. Fig. 5a shows the force-displacement curve of neat Kevlar fabric and ET under quasi-static compression conditions. Clearly, once the knife contacts the fabric, the resistance force begin to increase. For the neat Kevlar, the resistance force value increases rapidly and reaches the maximum value when the displacement is 4.0 mm. For ET composite, the curve slope

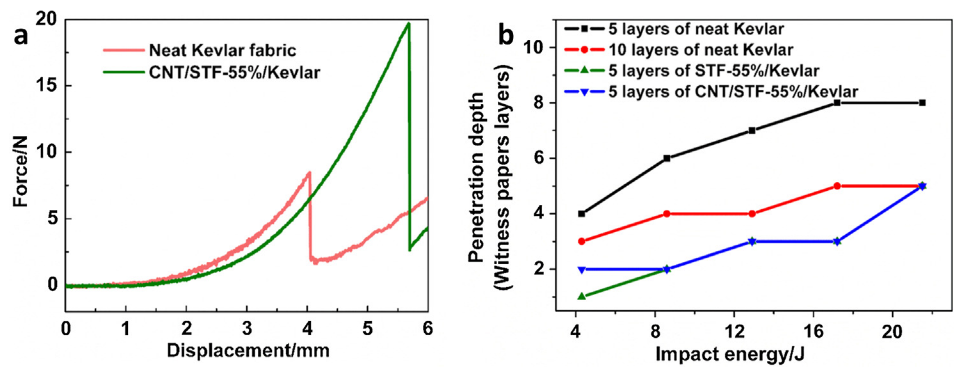

Fig. 5. Knife stab resistance test results of neat Kevlar fabric, STF-55%/Kevlar and the CNT/STF-55%/Kevlar-based electronic textile (ET): force-displacement curves under quasi-static compression (a) and protective performance tests under dynamic impact conditions (b).

increases slower than the pure Kevlar, indicating that STF has a certain buffering effect on the impact of external force. When the displacement value is 5.6 mm, it reaches the maximum value (19.7 N), which is two times larger than the neat Kevlar fabric (8.4 N). This indicates that after incorporation of STF and CNT into the Kevlar fabric, the friction between yarns of the ET increases obviously and the knife resistance enhances markedly.

Fig. 5b shows drop tower knife stab resistance test results of neat Kevlar fabric and the ET composite. The drop mass is fixed at 2.2 kg and the drop heights ranges from 0.2 m to 1.0 m. With increasing of the drop height, the penetration depths increase. It can be observed from Fig. 5b that the penetration depth for ET is lower than the neat Kevlar fabric. When the impact energy is 12.9 J (0.6 m falling height), the penetration depth is 7 and 4 layers of witness papers for the 5 and 10 layers of neat Kevlar fabric. On the other hand, the penetration depth is 3 layers of witness papers for the ET with 5 layers. The anti-impact performance represents more than 50% increment compared with the 5 layers neat Kevlar fabric. Additionally, STF-55%/Kevlar and the ET almost exhibit the same protective performance, which indicates that the addition of CNT show little influence to the anti-impact performance of STF-55%/Kevlar. Whatever, the ET also shows a remarkable improvement in the anti-impact performance compared with neat Kevlar fabric.

In order to further assess the anti-impact performance of the ET, dynamic impact resistance tests are performed using a blunt impactor with a hemispherical head of 10 mm (Fig. S2d2), which is mounted on the jaw of a drop hammer test machine (Fig. S2b). The target samples are fixed by a clamp (Fig. S2e), the drop mass is set at 4.5 kg and the acceleration sensor apparatus records the real-time acceleration values of the blunt impactor against the composite. The insets in Fig. 6a and b (Fig. S3 shows the separate picture) show that the single-layer neat Kevlar fabric is totally penetrated while the ET is still intact when the falling height is 0.3 m, which clearly shows that the anti-impact performance of the ET is far better than the neat Kevlar. Fig. S3

The resistance force begins to increase as the blunt impactor contact the fabric, the fabric starts to deform until some yarns are drawn out and finally be penetrated. During the impact process, the impact energy is thoroughly absorbed for the single-layer ET, and the maximum resistance force is as high as 1232 N (Fig. 6b), while the maximum force for the single-layer neat Kevlar is 746 N and it is punctured. This shows that the untreated Kevlar absorbed a small amount of energy compared with the ET. Fig. 6b–d show that the maximum force values also increase as the increasing of the falling height, which demonstrates the ET exhibits a substantial improvement in the absorbed energy. As a result, the ET exhibits a better anti-impact performance than neat Kevlar fabric by absorbing more energy and sustaining higher impact force.

3.3. Monitoring human motions

Different from the previously reported STF/Kevlar nanocomposite [12,14,29], our ET possesses not only excellent protective performance but also wonderful sensing characteristic to external forces, thus has a broad potential in the next generation of intelligent wearable human protective material. As shown in Fig. 7a and b, the ET is a part of a conductive circuit comprising a LED bulb and a cell. The LED bulb lightens up when the circuit is connected, indicating that the ET has a good conductivity. Fig. 7c shows the normalized resistance change during a cyclic bending test. The ET fabric sensor is clamped by the jaw of a gripper (d and e) mounted on the MTS. The ET is subjected to a cyclic bending test applied by the MTS. The edges of the ET contacted with the gripper is stuck with insulating tape in case of short circuit of the steel gripper. The electrical resistance signal change of the ET is recorded by the electrochemical impedance spectroscopy system. In Fig. 7c the blue dashed box shows the bending angle is 30° and normalized resistance changes ($\triangle R/R_0$) ranges from +5% to −4.5%. The compression frequency is 4.7 s/times (the cycle time is 40 times and the total time is 188 s). For the red dashed box, the bending angle is 60° and $\triangle R/R_0$ ranges from +3% to −5%. The compression frequency is 3.4 s/time (the cycle time is 40 times and the total time is 137 s). From the test results, it can be observed that the response signal to different bending angles and frequencies is easily distinguishable and has an excellent stability after repeating many cycles. Clearly, the ET composite exhibits good stimuli responsive property, cycle stability and fatigue resistance.

Owing to the high sensitivity to various deformations and impacts, the flexible ET also has a good prospect in monitoring human body motions. In Fig. 8, the ET is attached on different parts of the body. The voltage is kept at 1 V and the signal change is recorded by the electrochemical impedance spectroscopy instrument. As shown in Fig. 8a, the signal changes of ET sensor monitoring a series of human motions. The ET sensor is affixed on the finger knuckle and bending movements are monitored at different angles *via* recording the electrical resistance change signal. The electrical resistance depends on the bending angle. When the finger bends to 90°, $\triangle R/R_0$ ranges from about −9.4% to 6.6%. When the finger bends to 30°, $\triangle R/R_0$ ranges from −8.7% to 24.0%. The difference of the resistance change is obvious and it is stable after dozens of repeated cycles. Finger postures and movements can be clearly identified according to the measured electrical signal, which shows that the ET sensor is sensitive and reliable. Similar to the results obtained from the finger-bending, when the ET sensor is mounted on the arm of a human body, it can also sense and distinguish the motion of the elbow bending to any angle (Fig. 8b). $\triangle R/R_0$ ranges from 25.0% to −20.5% when the elbow joint bent to 90°. $\triangle R/R_0$ ranges from 18.0 to −17.5% when the elbow joint bent to 30°. Based on above results, the ET sensor has the potential to detect various motions of a human or robot body by recording electrical signal changes.

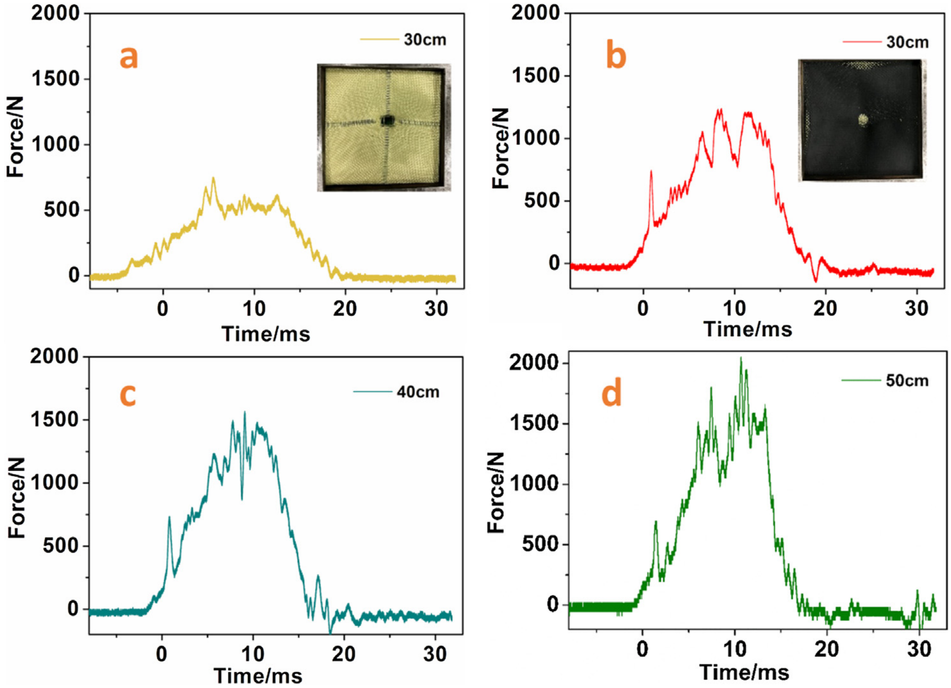

Fig. 6. Dynamic impact resistance test and the relative resistance force values of the single-layer neat Kevlar fabric (a) and the single-layer ET (b–d) under blunt impact with a falling height of 30 cm (b), 40 cm (c) and 50 cm (d).

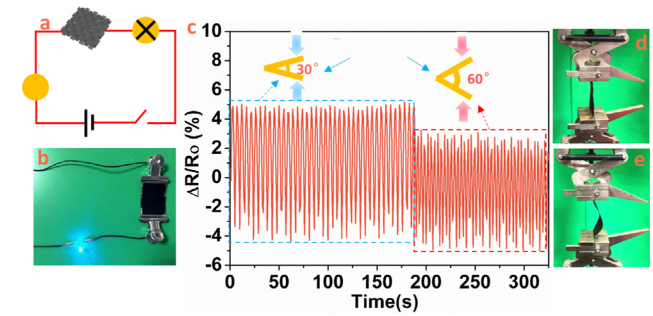

Fig. 7. Illustration (a) and photograph (b) of a conductive circuit composed of the ET fabric, a LED bulb and a cell. Normalized resistance changes ($\triangle R/R_0$) of the ET sensor during a cyclic bending test (c). Photographs of the ET sensor on a steel clamp that undergoes a bending test (d and e).

The ET composite exhibiting good sensing performance mainly due to the introducing of CNTs. Fig. 9(c and d) shows the illustration of partial magnification of the cross section of the yarns of the CNT/STF/Kevlar composite. The fabric is made up of a number of filaments and the STFs are distributed between the filaments. CNTs are distributed on the surface of the STF/Kevlar. Due to the liquid property of the STF

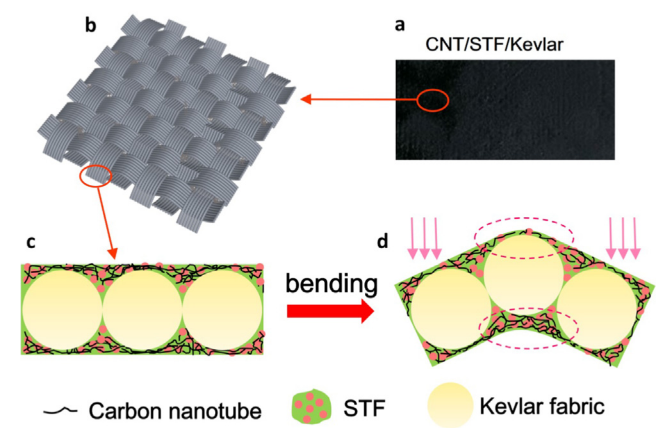

Fig. 9. The illustration image of the CNT/STF/Kevlar composite (a). The illustration of partial magnification of the CNT/STF/Kevlar composite (b). The illustration of partial magnification of the cross section of the yarns of the CNT/STF/Kevlar composite (c and d).

under static state, CNTs are easily adhered on the STF to form conductive paths. When the CNT/STF/Kevlar composite is bended by

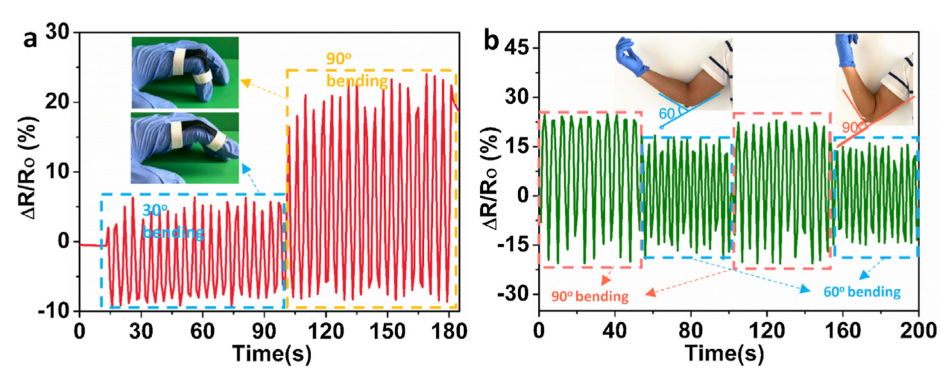

Fig. 8. Relative normalized resistance change of the ET in monitoring movements of finger (a) and elbow at different angels (b).

external force, the conductive paths in the bending position (red dashed box) is influenced obviously. Part of CNT conductive paths are destroyed, so the electrical resistance changes rapidly. The electrical signal changes with the deformation of ET, which accounts for the sensing performance of the ET. Additionally, when the ET recovers to the original shape, the conductive paths also recover quickly due to the good fluidity and affinity of the PEG 200. As a result, the conductivity of the ET sensor has good repeatability when encountering the external stimuli.

4. Conclusion

In this work, a novel wearable electronic textile based CNT/STF/Kevlar with excellent protective and sensing performance is fabricated. The yarn pull-out experiments and stab resistance tests show that the impact resistance is notably enhanced due to the introduction of the STF and CNT fillers. The maximum resistance force of the ET composite is two times larger than neat Kevlar fabric in the stab resistance performance tests. ET composite represents more than 50% increment compared with the neat Kevlar fabric in the drop tower knife stab resistance test. The dynamic impact resistance test shows the maximum resistance force of the single-layer ET composite reaches as high as 1232 N, which is much larger than the neat Kevlar (746 N), indicating that the ET composite can absorb more energy and sustain higher impact force. Particularly, the excellent conductivity endows the ET composite with excellent sensing performance in monitoring the movements of human body under different conditions. In conclusion, the CNT/STF/Kevlar-based electronic textile shows a good potential in wearable electronic textile due to its high flexibility, good sensitivity, and excellent protective performance.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compositesa.2019.105612.

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