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Conductive shear thickening gel/polyurethane sponge: A flexible human motion detection sensor with excellent safeguarding performance

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ABSTRACT

A novel composite with excellent sensing property and safeguarding performance is fabricated by impregnating the carbon black (CB)/shear thickening gel (STG) hybrid into polyurethane sponge (PUS). This STG-CB/PUS composite presents typical shear thickening characteristic, as the storage modulus (G′) rises from 0.21 MPa to 1.52 MPa when shear frequency increases from 0.1 Hz to 100 Hz. Under external strain, the conductivity of STG-CB/PUS varies quickly, thus it can be applied as strain sensors. During the impact, STG-CB/PUS can detect impact stimuli (0.147–1450 mJ) and decrease attacking force by 63% simultaneously. Additionally, it is found that the 'B—O cross bond' is responded for the shear thickening property and the structure-dependent electrical behaviors contribute to the sensing activity. Finally, a STG-CB/PUS enhanced kneepad is prepared. It possesses a reliable safeguarding performance by reducing 44% attacking force and can effectively trace human body motions such as walking, running and jumping.

1. Introduction

Body armors are widely used in police affairs and military actions to protect against external impact. Hard body armors, with ceramic [1] or steel [2] sandwiched between fabrics, were first applied to prevent high-speed bullets/projectiles from penetrating. Nevertheless, due to their rigidity and heaviness, these structures discomforted the wearers and impeded daily works. To satisfy the customized fit, a number of soft body armors [3–5], such as the Kevlar29, Vectran, and Polyester triaxial woven fabrics based soft armors [3], were developed. These soft body armors exhibited wonderful protective performance under impact and the safeguarding performance could be further enhanced by introducing resin matrix [4]. Various computational and experimental models [6–8] were also developed to discover the underlying mechanisms. Among the anti-impact materials, polyurethane sponge (PUS) was very attractive since the advantages of flexibility and porosity, thus it has been widely applied in damping [9], energy-absorption [10] and body armors. However, due to the weak strength, the safeguarding performance of the PUS is limited.

During past decades, various efforts have been conducted to improve the PUS by integrating it with functional materials so as to enlarge its applications. Shear thickening materials, whose mechanical properties such as the viscosity, storage modulus increased with the external stress/strain rate, have drawn the worldwide attention in energy absorption. Because of the excellent shear thickening effect, the shear thickening fluid (STF) was impregnated into PUS to enhance the anti-impact performance [11]. The STF/PUS composites exhibited significant energy absorption in low-velocity drop weight impact tests, revealed a broad potential in impact protection padding material. However, the application of the STF/PUS is restricted since the sedimentation problem of the liquid STF. Shear thickening gel (STG) [12] is a kind of soft polymer and its storage modulus increases 3–4 orders of magnitude with the increase of shear frequency. Very recently, our group penetrated STG into PUS to develop high performance anti-impact materials [9]. Due to the synergistic effect between STG and PUS, the STG/PUS not only overcame the creep of STG but also improved the energy absorption. Considering the superior impact resistance performance of STG/PUS, more work should be done to enlarge its application in body armor.

Force sensing is critical in body armor because the damage can be detected during resisting impact. Flexible sensors [13–15], as the essential part of wearable devices or e-skin, exhibit desirable application perspective in human motion detection [16], health-monitoring [17], soft robotics, and so forth. Besides the body protection, the PUS also has been proven to be effective in wearable devices. By combining conductive materials, such as Ag nanowires [18], Ag nanoparticles [19],

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carbon black (CB), graphene, etc. into the interconnected three-dimension (3D) networks of the PUS, human activities can be detected by measuring and analyzing the generated electrical signals. These strain sensors exhibited high stability (1000 cycles at 50% strain), thus they became favorable in wearable devices. Typically, the CB/PUS [20] was able to detect ultra-small motion (91 Pa pressure, 0.2% strain) and large motion (16.4 kPa pressure, 60% strain). Recently, a novel graphene/PUS [21] was also prepared via the fractured microstructure design method and this piezoresistive sensor had been demonstrated to be effective in detecting super low pressure (9 Pa). In consideration of the outstanding anti-impact performance, the conductive STG/PUS with both excellent sensing property and safeguarding performance will be attractive in multifunctional body armor and wearable devices.

In this work, a novel STG-CB/PUS composite is developed by impregnating STG-CB into stretchable PUS. Besides resisting the external impact, the STG-CB/PUS can trace dynamic impact energy and detect static strain, demonstrating its promising perspective as flexible sensors. The detailed mechanism for the multifunctional STG-CB/PUS was discussed. It was found that the shear thickening characteristic, originated from the reversible 'B—O cross bond', protected human body by buffering impact force. The structure-dependent electrical property of STG-CB/PUS resulted in its sensing behavior. At last, this versatile composite could be applied to enhance the kneepad. The final device not only exhibited outstanding anti-impact performance but also could trace and distinguish body motions, such as walking, running and jumping.

2. Experimental section

2.1. Materials

Dimethyl siloxane, boric acid and benzoyl peroxide (BPO), which were used to prepare the shear thickening gel (STG), were purchased from Sinopharm Chemical Reagent Co. Ltd, Shanghai, China. All the reagents were of analytical purity and used as received without further purification. Carbon black (CB) (product type: VXC-72) was provided by Cabot Corporation, Boston, Massachusetts, USA. The polyurethane sponges (PUS) were commercially available products.

2.2. Experiments

Fig. 1a presented the fabrication process of STG-CB/PUS. Firstly, a thoroughly stirred mixture, consisting of 15% pyroboric acid, 81% dimethyl siloxane and 4% of ethyl alcohol, was heated at 220 °C for 8 h to obtain STG. Then, STG-CB suspension was synthesized by dispersing STG, benzoyl peroxide (weight ratio of 25:1) and CB into acetone solvent. Then, the suspension was sonicated for 20 min. After removing the solvent, STG-CB was obtained by vulcanization at 85 °C for 2 h. The weight ratio of CB to STG was maintained at 10%, 20%, and 30%, respectively. This polymer was named as STG-xCB and x represented the weight ratio. The polyurethane sponges (PUS), cut into specific shapes, were cleaned in acetone by sonicating for 30 min. Then, the STG-CB suspension was dipped into PUS slowly. Owing to the adsorption of PUS, the suspension would be adopted and limited in PUS. This procedure was not stopped until the suspension was about to leak out. The obtained composite was dried under vacuum for 30 min to remove the solvent. This 'drop and dry' process was carried out several times until the sponges were fulfilled. Finally, STG-CB/PUS was gained after vulcanization at 85 °C for 2 h.

2.3. Characterization

The morphologies of PUS, STG-CB and STG-CB/PUS were characterized by field emission scanning electron microscopy (FE-SEM, XL-30 ESEM). The rheological properties of STG, STG-CB and STG-CB/PUS were tested by using a commercial rheometer (Physica MCR 302, Anton Paar Co., Austria). Cylindrical samples with a thickness of 1 mm and a diameter of about 20 mm were tested between a parallel plate (diameter: 20 mm) with the shear frequency exponentially increasing from 0.1 Hz to 100 Hz and the strain was set at 0.1%. Their creep and recovery behavior were also tested by the rheometer. Before testing, the samples were cut into pieces with cylindrical shape (thickness: 4 mm, diameter: 20 mm).

The static strain sensing performance of the STG-CB/PUS under different mechanical deformations (compression and stretch) were studied by using Material Test System (MTS criterion 43, MTS System Co., America). A drop hammer test device (ZCJ1302-A, MTS System Co., America) equipped with a force sensor and data acquisition system was applied to investigate the dynamic sensing effect and safeguarding performance. In this test, the diameter and height of the cylinder STG-

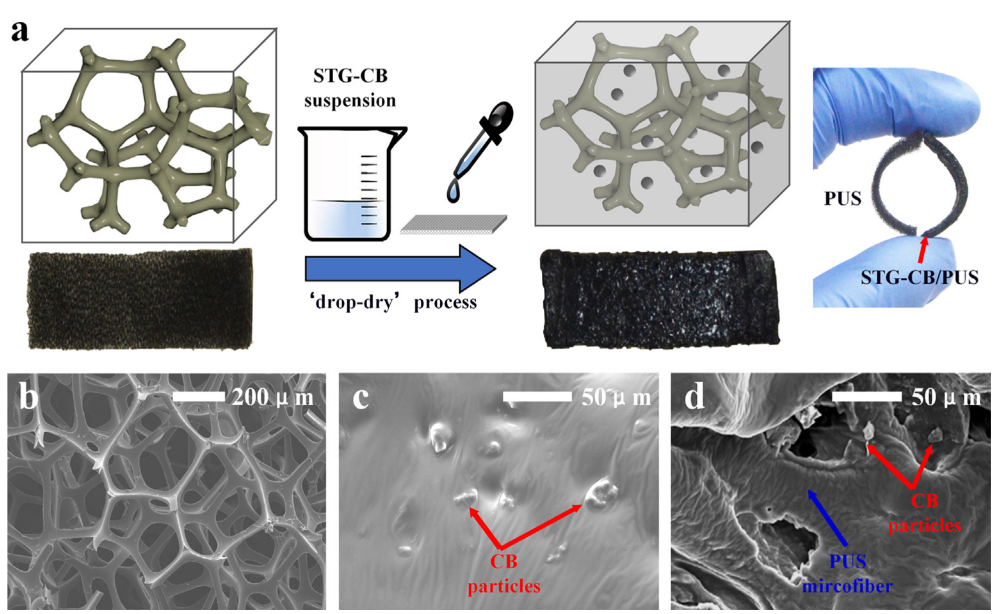

Fig. 1. The fabrication process of STG-CB/PUS (a). SEM morphology of PUS 3D interconnected structure (b), STG-20%CB (c) and STG-20%CB/PUS (d). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)