Composites Science and Technology 153 (2017) 168–177

Contents lists available at ScienceDirect

Composites Science and Technology

journal homepage: http://www.elsevier.com/locate/compscitech

Anti-impact response of Kevlar sandwich structure with silly putty core

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ARTICLE INFO

Article history:
Received 28 June 2017
Received in revised form
5 September 2017
Accepted 20 October 2017

Keywords:
Flexible composites
Sandwich
Aramid fiber
Polymer-matrix composites (PMCs)
Impact behavior

ABSTRACT

A soft sandwich structure consisting of two layer Kevlar face sheets and a silly putty (SP) core was fabricated. The storage modulus of SP, which was prepared by dispersing $CaCO_3$ particles into polyborodimethylsiloxane, increased by two to three orders of magnitude with increasing of the shear frequency. The higher $CaCO_3$ content resulted in better shear-hardening behavior, which further enhanced the anti-impact performance of the sandwich structure. When the impact velocity was below 110 m/s, all energy was dissipated by the sandwich structure and the maximum energy dissipation was 20.8 J, represented a 60% increment than the neat Kevlar. Importantly, under the same impact energy, the energy dissipation of the sandwich structure under ballistic impact was 63% higher than under low velocity impact, which must be due to the shear-hardening nature. The mechanism of the excellent protection performance was discussed. The sensitivity to loading rate and reliable energy dissipation of the soft sandwich structure widely broad its practical applications.

1. Introduction

Over the past several decades, because of the increasingly frequent global terrorism and civil conflicts, body armors which can protect a person from the damage caused by weapons or projectiles have become a research hotspot. Traditional personal body armors are made of metals [1], ceramics [2] and transparent glasses [3], thus they are heavy, rigid and bulk. Limited by the shortage of their flexibility and mobility, these traditional body armors can hardly protect arms or legs. Therefore, more and more attentions are focused on reducing the weight and improving the flexibility of personal body armor while ensuring the same protective effect [4–6].

Kevlar, a kind of aromatic polyamide fiber, has been widely used in soft body armors as a base material because of its high strength, toughness, and modulus, light weight and stability [7,8]. In order to get better performance, many researches were conducted on tailoring the structure and composition of Kevlar. To achieve the high protection performance, Hwang et al. [5] increased the friction between yarns of the aramid fabric through the growth of zinc oxide nanowires on the fiber surface so as to enhance the ballistic resistance. Haro et al. [9] synthesized hybrid composite laminates for armor protection, which consist of layers of aluminum alloy and Kevlar fibers impregnated with shear thickening fluid and epoxy resin. Due to the smart structure and composition, the final products presented better protection than the neat Kevlar precursor.

Among various structures of the Kevlar based body armor, the shear thickening fluids (STFs) impregnated Kevlar fiber is the most attracting one. STFs are a kind of smart materials whose apparent viscosity can be dramatically increased when subjected to a high-speed impact loading. They can recover immediately after removing the impact. Due to their reversible and particularly sensitive rate-dependent shear thickening characteristic, the STFs possess high potential in energy dissipation and personal body protection [10–12]. Lee et al. [13] found the ballistic resistance of Kevlar fabric could be enhanced after impregnating with SiO_2-based STFs. To investigate the enhancing mechanism, Lee et al. [14] investigated the effect of the particle size in STFs and Kalman et al. [15] studied the influence of particle hardness in STFs impregnated

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https://doi.org/10.1016/j.compscitech.2017.10.019
0266-3538/

fabrics. The numerical simulation was also conducted by Park et al. [16] to study the friction effects in STFs impregnated Kevlar fabric under the high velocity impact.

Recently, because of the instability of fluidic STFs, some researches have been focused on a new shear-hardening polymer - silly putty (SP), which is a viscoelastic material sensitive to strain rate [17–20]. It behaves like a soft plasticine in nature state but becomes very hard when suffering an external impact. Recently, Liang et al. [21] applied SP in a shock transmission unit which provided a free motion under slowly applied loads and a rigid link under impact loads. Jiang et al. [22] tested the SP composite by falling weight impact and split Hopkinson pressure bar experiments. It was found that SP could store up to 23% of the impact energy and showed solid characters at high strain rate. To broad the application of SP in protection, Wang et al. [23] incorporated SP into polyurethane sponge. The results indicated that the impact force could be reduced by 2 orders even under 26 cycles of continuous dynamic impact loading. In consideration of their high performance, the composite structures composed of Kevlar and SP will be favorable for body armor. Unfortunately, few work based on the Kevlar/SP has been reported.

Sandwich structure is a kind of composite component, which features a light weight core placed between two high strength thin plates or skins. It is extensively used to dissipate energy and protect a system from ballistic threats. The plates, which are still rigid and unsuited to personal wearing, typically include aluminum or other rigid fiber reinforced polymer. The core of the sandwich structure is usually made of the material with low density, high stiffness and energy absorption, such as metallic foam [24], fiber [25], polymer [26] and other light materials [27], which can enhance the strength and energy dissipation of the sandwich structure. Considering the high flexibility, easy sealing and rate-sensitivity characteristics of SP and the high strength, light weight and soft of Kevlar, the sandwich structure combining of Kevlar fabrics with SP core can not only become a comfortable light material but also provide reliable protective and energy dissipation performance as a personal body armor.

In this work, the anti-impact performance of a soft sandwich structure consisting of two layer Kevlar face sheets and a SP core was studied through ballistic and low velocity impact tests. The effect of $CaCO_3$ contents on the mechanical properties of the SP and Kevlar/SP were investigated. The storage modulus of SP under various shear frequency was measured for indicating the sensitivity to strain rate. Ballistic impact tests of the Kevlar/SP were conducted at the velocity ranging from around 90 to 150 m/s. The process of deformation and destruction was recorded by the high-speed video camera at 50,000 fps. Additionally, the low velocity impact test was conducted at the same impact energy as the ballistic impact. The difference of the two impact test results was carefully discussed. At last, the possible mechanism was proposed to analyze the rate dependent protective property of the Kevlar/SP. This sandwich structure with Kevlar face sheets and SP core declared excellent energy dissipation to ballistic threats and this soft wear possessed the huge potential in personal body armors.

2. Materials and methods

2.1. Materials and preparation

Boric acid, dimethyl silicone oil, ethanol, benzoyl peroxide(BPO) (Sinopharm Chemical Reagent Co. Ltd, Shanghai, China) were raw materials to synthesize SP matrix – polyborodimethylsiloxane (PBDMS). The 1250 mesh $CaCO_3$ (Lingdong Chemical Co. Ltd, Shanghai, China) was used as reinforced particles. HTV silicone rubber (type MVQ 110-2 from Dong Jue Fine Chemicals Co. Ltd, Nanjing, China) was the control group in contrast with SP. Kevlar fabric (Junantai Protection Technologies Co. Ltd, Beijing, China) was a type of plain-woven high-performance aramid.

Firstly, the boric acid was heated at 160 °C for 2 h to gain pyroboric acid. Then, pyroboric acid and dimethyl silicone oil (mass ratio 2:15) and 15 ml of ethanol were mixed in a beaker and heated for about 7 h at high temperature. Subsequently, the BPO (as the cross-linking agent) and different contents of $CaCO_3$ particles were added to the above product by the internal mixer (HL-200, Jilin University Scientic and Teaching Instrument Factory, Jilin, China). At last, the mixture was sulfurized for 2 h at 110 °C to obtain SP. The mass fractions of $CaCO_3$ were kept at 0, 20, 35, and 50 wt%, respectively. For simplicity, the SP with $CaCO_3$ particles are defined as SP-$CaCO_3$-X%, where X is the mass fraction of the $CaCO_3$ particles.

Fig. 1(a) and (b) show the schematic of the fabrication procedure and the composition of the sandwich structure. The front and rear face sheets were both single layer Kevlar fabric with an areal density of 200 $g \cdot m^{-2}$ and the edges were stitched by sewing threads to maintain the soft core inside the structure. Five different components of sandwich core (kept at 30 g) were used in this work: HTV silicone rubber (as the control group) and SP with four different contents of $CaCO_3$ particles (as mentioned above). The impacted part was a square with a side length of 127 mm. More parameters of the sandwich structure are shown in Table 1.

2.2. Characterization

Rheological properties of SP and HTV silicone rubber were studied using a torque rheometer (Physica MCR 301, Anton Paar Co., Austria). The dimension of the tested samples was $\Phi 20$ mm × 1 mm. A frequency sweep test was carried out with a parallel plate ($\Phi 20$ mm). The frequency was varied from 0.1 Hz to 100 Hz at 25 °C with a strain of 0.1%. The Kevlar fabrics in the sandwich structure were investigated by the SEM (FEI, type: XL-30 ESEM).

2.3. Ballistic impact testing

The experimental configuration consisted of five components: a gas gun as the launcher, a laser velocimeter to measure the impact velocity of the projectile, a steel frame for the target sample, a projectile catcher, and a high-speed video camera (Fig. 2(a)). According to the NIJ Standard 0101.04 [28] and MIL-DTL-46593B [29], a 44 grain (2.85 g) chisel-nosed steel fragment simulating projectiles (FSP) was used (Fig. 2(b)) and its impact velocity varied from 90 m/s to 150 m/s. A heavy steel frame was fixed on the basement to prevent violent vibration and the target sample was four edges clamped tightly (Fig. 2(c and d)). The high-speed video camera (FASTCAM SA5 1000 k-M3, Photron) was used to capture the deformation and destruction process of the rear face and record the projectile position for calculating the residual velocity. The target sample was placed in close with the muzzle (15 cm) so that the yaw and velocity decay of the FSP could be neglected.

2.4. Low velocity impact testing

Low velocity impact experiment (Fig. 3) was conducted by a drop tower test device (ZCJ1302-A, MTS Co. Ltd, China). A 1.97 kg impactor had the same shape and dimension with FSP expect length. During the impact, the accelerometer collected the accelerometer signals of drop tower and transformed them into electric signals. Finally, through the charge amplifier, the signals were recorded by the oscilloscope.