Composites Science and Technology 127 (2016) 169–176

Contents lists available at ScienceDirect

Composites Science and Technology

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

Dynamic behavior of magnetically responsive shear-stiffening gel under high strain rate

Yunpeng Wang [a], Sheng Wang [b], Chenhui Xu [a], Shouhu Xuan [a], Wanquan Jiang [b], Xinglong Gong [a, *]

[a] *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*

[b] *Department of Chemistry, USTC, Hefei 230026, PR China*

ARTICLE INFO

Article history:
Received 7 January 2016
Received in revised form
2 March 2016
Accepted 7 March 2016
Available online 9 March 2016

Keywords:
Shear-stiffening
Modified split Hopkinson pressure bar
Magnetorheological effect
Mechanisms
Phase transitions

ABSTRACT

The dynamic mechanical behavior of the magnetically responsive shear-stiffening gel (MSTG) was investigated by using a modified Split Hopkinson Pressure Bar (SHPB) system. It was found that the elastic modulus of the MSTG increased with increasing strain rate and magnetic field. The elastic modulus of the MSTG with 45 wt% carbonyl iron (CI) particles reached to 126.6 MPa at the strain rate of 7236 s^{-1}, while it was merely 160 Pa without excitation. Under a 300 mT magnetic field, the elastic modulus also increased from 116.5 MPa (no magnetic field) to 255.5 MPa at the strain rate of 2900 s^{-1}. The shear stiffening performance of the MSTG was stable and its maximum yield strain was 17.2%, which was very important for its practical application. The magnetically strengthened mechanisms of the high strain-rate-dependent mechanical properties were proposed. It was found that the enhanced shear-stiffening behavior was attributed to the phase transitions from viscous-liquid state to elastomeric state to glassy state under impact.

1. Introduction

Shear-stiffening gel (STG), firstly known as Silly Putty, is an intelligent material whose mechanical properties *e.g.*, storage modulus, elastic modulus, and yield stress, were usually markedly strengthened under the external excitation of shear, compression, and tension. Due to this unique strain-rate sensitivity, it attracted growing interests in the past decade. In presence of the mechanical stimuli, the STG could absorb a lot of energy through the micro-fragmentation [1,2] and disentanglement [3,4] of the high weight molecular chains. As soon as the stress is unloaded, the mechanical characters return back to the initial state. Owing to the excellent capacities of energy absorption and impact resistance, STG exhibited broad potential in aircraft, automotive components, damping, as well as for military protection measures [5–9].

Many works have been done to investigate the shear stiffening characteristic of the STG. Cross R [10–12] developed a standard viscoelastic model consisting of two springs and a dashpot to analyze the viscous elastic properties of STG. They found that the stiffness and the relation behaviors were concerned with compression speed. By studying the change in internal energy under impact, the specific heat of STG was determined [13]. Moreover, the influence of the temperature on the rheological property was studied and it was found that the mechanical properties shifted significantly with respect to temperature [14]. Recently, it was reported that the additives played an important role in determine the mechanical properties of the STG. Various additives such as the silica, borax, calcium carbonate, carbon nanotube, ferromagnetic particles and carbonyl iron were used, and the quasi-static analysis and low shear-rate mechanical tests have been carried out to understand the microstructure and mechanisms of the STG [15–18]. Interestingly, the magnetic additives endowed the STG with special magnetically responsive characteristic. Under applying the magnetic field, the shear stiffening effect of magnetic STG (MSTG) increased correspondingly [17,18].

During their practical application, the STGs often experienced high rate impact, thus their mechanical properties at high strain rate were very important for evaluating the protection performance. The SHPB experimental technology was widely used to determine the stress-strain curves at high strain rate varying from

* Corresponding author.
E-mail address: gongxl@ustc.edu.cn (X. Gong).

http://dx.doi.org/10.1016/j.compscitech.2016.03.009
0266-3538/

10^2 s^{-1} to 10^4 s^{-1} in the study of engineering materials, such as metal, alloy, concrete, ceramic, composites [19–21], *etc*. In the research of the soft materials of low strength and low mechanical impedance, some valid modifications have been done on the SHPB apparatus [22–24]. Aluminum bars were used because of their lower impedance [23,25], and a practical loading shaping technique was applied to achieve approximately constant strain-rate elastic waves [25,26]. Jiang W [27] analyzed the high strain rate based mechanical properties of the STG by using SHPB and it was found that the shear stiffening effect was originated from the phase change of the STG. In consideration of their tunable shear stiffening effect under applying the external magnetic field, the MSTG exhibited high potential in body armor. However, their dynamic behavior under high strain rate has not been reported. Moreover, the influence of the magnetic field on the anti-impact mechanical property will be valuable for understanding the shear stiffening mechanism.

In this study, a modified Split Hopkinson Pressure Bar (SHPB) system was employed to investigate the dynamic compressive properties of magnetic shear-stiffening gel (MSTG) at high strain rate. The stress-strain curves and elastic modulus of MSTG at high strain rate varying from 10^2 s^{-1} to 10^4 s^{-1} were determined through SHPB technology. Simultaneously, the influence of the magnetic field on the mechanical properties of the MSTG was investigated. The MSTG was found to have a capacity of “self-healing” and the restorability was excellent. Finally, the possible magnetically enhanced shear-stiffening mechanisms were proposed.

2. Experimental section

2.1. Sample preparation

The materials include boric acid, dimethyl siloxane, ethyl alcohol, benzoyl peroxide (BPO) (from Sinopharm Chemical Reagent Co. Ltd, Shanghai, China) and carbonyl-iron (Type CN, from BASF, Germany). The boric acid, dimethyl siloxane and ethyl alcohol are raw materials to prepare polymer matrix, and the BPO is the vulcanizing agent in the preparation. The carbonyl-iron is used as the magnetic additive. The procedures of MSTG in detail are as follows.

Firstly, boric acid was heated at 160 °C for 2 h to gain pyroboric acid. Secondly, 15% pyroboric acid, 81% dimethyl siloxane, and 4% ethyl alcohol were mixed together in a beaker. Then, this mixture was heated for 5 h and cooled down to room temperature, through which the polymer matrix was gained. Next, the polymer matrix was put in a double-roll mill (Taihu Rubber Machinery Inc., China, Model XK-160) to be homogeneously mixed with carbonyl iron (CI) and BPO. Finally, the mixture was vulcanized at about 100 °C for 1 h. The MSTG was fabricated after the mixture cooling down. The mass fractions of CI in the composite were kept at 15%, 30%, 45%, 60% and 75%, respectively. The MSTG filled with different contents of CI are defined as MSTG-X % for brevity, where X is the mass fraction of CI.

2.2. Low shear-rate rheological tests

The mechanical properties of the MSTG under low shear rate were tested using a rheometer (Physica MCR 301, Anton Paar Co., Austria). The dimension of the specimens was Φ20 mm × 1 mm. Frequency sweeping tests were carried out with a parallel plate (Φ20 mm). The frequency swept from 0.1 Hz to 100 Hz with a strain of 1% at the temperature of 25 °C. In the investigation of the magnetically responsive properties, the frequency sweeping tests were carried out in the magnetic field with magnetic flux density of 120 mT, 240 mT and 480 mT.

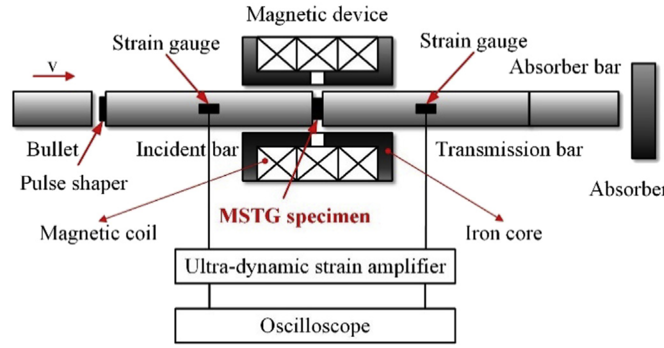

Fig. 1. Schematic illustration of a modified SHPB system.

2.3. Dynamic compression tests with modified SHPB technology

A split Hopkinson pressure bar (SHPB) system is modified for the dynamic compression tests of MSTG. It mainly consists of a bullet, an incident bar, a transmission bar, an absorber bar, an absorber and a magnetic device (Fig. 1). All the bars and the bullet are made of aluminum to match the soft materials' measurement because of its lower mechanical impedance. Their elastic modulus is 71.7 GPa and the density is 2700 kg/m^3. The lengths of the bullet, the incident bar and the transmission bar are respectively 300 mm, 1500 mm and 1000 mm and all with 14.5 mm diameter. A rubber pulse shaper (1 mm × 1 mm) is placed at the front face of the incident bar to guarantee that the rising edge of the incident wave is gentle and the sample has enough time to obtain stress equilibrium. The incident bar and the transmission bar go through the magnetic device, and the MSTG specimen is placed between them. The volume of the specimen is determined by a plastic tube mould with an inner diameter of 7 mm and a length of 2 mm; and the shape of the specimen is kept as a cylinder with a diameter of about 10 mm and thickness of 1 mm. The bullet is shot by a light-gas gun. The velocity of the bullet is calculated through dividing the constant distance of the double photo-electric door by the time crossing it.

An elastic compressive wave is generated by the impact of the bullet in the incident bar. When the shaped wave, travelling along the incident bar, reaches the front face of the MSTG specimen, a part of it reflects into the incident bar and the rest transmits through the specimen and into the transmission bar. The incident wave (ε_i), the reflected wave (ε_r) and the transmitted wave (ε_t) are

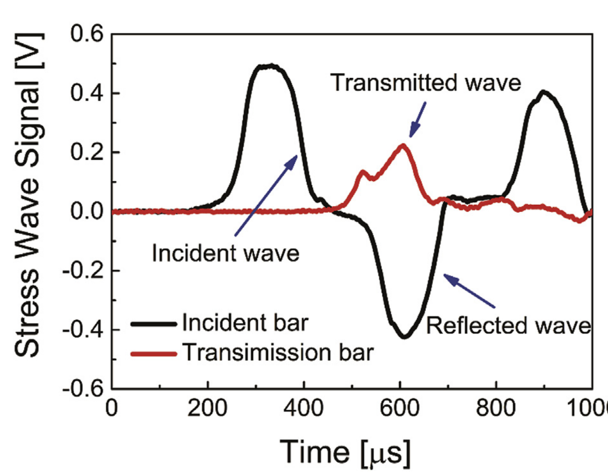

Fig. 2. Typical stress wave signals measured by the Modified SHPB.