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Mechanical properties and constitutive model of aluminum powder/rubber matrix composites compressed at various strain rates

Li Jun-bao, Li Wei-bing*, Wang Xiao-ming, Li Wen-bin, Hong Xiao-wen

ZNDY of Ministerial Key Laboratory, Nanjing University of Science and Technology, Nanjing 210094, China

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ABSTRACT

Quasi-static and dynamic compression tests of aluminum powder/rubber matrix composites were conducted using a universal testing machine and Split Hopkinson Pressure Bar apparatus to evaluate their mechanical properties and establish a constitutive model. Stress–strain curves were obtained for composites containing 0 wt%, 10 wt%, 30 wt%, and 50 wt% Al for strain rates of 0.0083–5500 s^{-1}, and a modified Mooney–Rivlin-based model was proposed to describe the one-dimensional compression behavior of the composites. The 50 wt% Al specimen exhibited different hardening modes than the 0 wt% Al, 10 wt% Al, and 30 wt% Al specimens under quasi-static loading; the middle hardening stage was significantly weakened by the internal stacked arrangement of the aluminum powder, which caused the particles to break during compression. At high strain rate, distinct linear hardening was observed for the 30 wt% and 50 wt% specimens during the late deformation stage as the aluminum particles carried the main compressive load. Moreover, the composites exhibited clear strain-rate sensitivity, with their elastic modulus and engineering stress increasing linearly with increasing strain rate to substantially higher levels than those for the static tests.

1. Introduction

Rubber is a highly elastic polymer that is widely used as a cushioning material for impact loading applications in the aerospace industry and for weaponry armor because of its shock-absorbing properties [1,2]. However, the density and impedance of rubber materials used in engineering applications are very low, and their impact resistance cannot be guaranteed under high-strain-rate loading. Therefore, research on rubber matrix composites has received widespread attention [3–5]. Neto et al. [3] prepared nanocomposite films using casting/evaporation with natural rubber as the matrix and observed a high reinforcing effect even at low cellulose nanocrystal content. Kashani et al. [4] investigated the dynamic mechanical properties of a typical tire tread compound reinforced with one part aramid short fibers. Reynolds and Huntington–Thresher [6] proposed tunable warheads with a composite charge structure using aluminum powder/rubber composites between the outer and inner charge to weaken blast shock waves.

To satisfy the diverse performance requirements of different industries for the widespread use of aluminum powder/rubber composites, a better understanding of their mechanical properties and the establishment of a constitutive model are critical. Many authors have studied the basic properties of these composites [7–11]. Namitha et al. [9] investigated the effects of filler content on the dielectric, thermal, and mechanical properties of aluminum nitride–silicone rubber composites. Vinod et al. [11] studied the heat, ozone, gamma radiation, and flame resistance of aluminum-powder-filled natural rubber composites. However, in-depth research on the mechanical properties and constitutive models of aluminum powder/rubber matrix composites remains lacking. The Split Hopkinson Pressure Bar (SHPB) apparatus is generally used to study the mechanical behavior of materials at high strain rate, and many systematic studies of the mechanical behavior of rubber-like soft materials have been conducted using this apparatus [12–17]. However, the wave impedance of soft materials is low, leading to weak transmitted signals. Some scholars have reduced the difference in the wave impedance between the compression bar and specimen using polymer bars [18, 19] or have used thinner specimens to obtain stronger transmitted signals [20]. However, strong dispersion and attenuation occur when the wave propagates in the polymer bar, and a small aspect ratio increases the friction effect of the specimen, leading to deviation of the stress state in the specimen from the one-dimensional stress assumption [21]. In addition, because of the low wave velocity of soft materials, a longer time is required to reach the dynamic stress equilibrium of the test specimen; however, the traditional SHPB test incident strain pulses are only ~10–20 μs. The development of the pulse shaping technique [22,23] has provided control over the incident

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* Corresponding author.
E-mail address: njustlwb@163.com (W.-b. Li).

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waveform through selection of the appropriate shaper material and dimensions to achieve stress equilibrium; in addition, constant strain-rate loading can be more easily realized.

In this study, the mechanical properties of aluminum powder/rubber matrix composites were investigated using quasi-static and dynamic compression tests conducted on a universal testing machine and SHPB apparatus. The deformation behavior and strain rate effect of vulcanized rubber and rubber composites with aluminum contents of 0 wt%, 10 wt%, 30 wt%, and 50 wt% at strain rates of 0.0083–5500 s^{-1} were evaluated. In addition, a constitutive model based on the Mooney–Rivlin model was established that accurately describes the mechanical response of these composites under quasi-static and dynamic loading.

2. Experimental procedures

2.1. Materials and sample preparation

Specimens containing different proportions of a masterbatch consisting of vulcanized natural rubber and aluminum powder with a particle size of 10 μm as a reinforcing agent filler were prepared. Because of the small specimen size, a mold in an open mill at room temperature was used for refining. First, the vulcanized rubber masterbatches were placed in the roller and completely coated the roller. Then, batches with added aluminum powder were prepared and kneaded evenly at the minimum roller distance, thinned by passing through the roller 4–5 times, and finally refined by uniform mixing. The molding temperature, molding time, post-treatment temperature, and post-treatment time were 170 °C, 1 h, 200 °C, and 4 h, respectively. For the quasi-static tests, a cylindrical mold was used to directly prepare the specimens. To avoid the sticking phenomenon resulting from the thinness of the specimens, 2 mm-thick plate specimens were first prepared and then cut using a knife to prepare the dynamic test specimens. Finally, the specimens were allowed to stand for 1 h to remove the machining residual stress. The weight ratios of the aluminum powder to masterbatch were 1:9, 3:7, and 5:5 for the specimens labeled *C*-10, *C*-30, and *C*-50, respectively; the pure masterbatch specimens were labeled *C*-0. For the quasi-static loading, the diameter and thickness of the specimens were both 10 mm. Appropriate thickness reduction of the specimen was shown to increase the transmitted signal and ensure stress equilibrium in the dynamic test; however, too small of an aspect ratio increased the friction effect on both ends of the specimen; therefore, dynamic loading specimens with diameters and thicknesses of 10 and 2 mm, respectively, were used.

2.2. Quasi-static testing

The quasi-static testing was performed on the WGD-1 MTS universal testing machine made in Song Ying Instrument Manufacturing Co., Ltd, Shanghai. The compression speed of the testing machine was set to 5 mm/min, which corresponds to a strain rate of 8.333×10^{-3} s^{-1}. The engineering stress and strain of the specimen were calculated from the compressive load data obtained from the sensor and the displacement data obtained from the indenter, and an engineering stress–strain curve was constructed. Each test was repeated three times, and the results were averaged.

2.3. Dynamic testing and improvement of SHPB method

The dynamic test was conducted on a SHPB apparatus; a schematic illustration of this system is provided in Fig. 1. The SHPB test set-up consisted of 14 mm-diameter aluminum bullets, an incident bar, a transmission bar, and absorption devices. The bullet used was 300 mm long, and the lengths of both the entrance and transmission bars were 1400 mm. Strain gauges attached to the entrance and transmission bars each record the history of the strain signal. The Wheatstone bridge made of a strain gauge is used to transform the strain signal of the bar into a voltage signal, which is then amplified by an ultra-dynamic resistance strain gauge and inputted into a data acquisition card for processing, and the display connected to the acquisition card displays the voltage-time curve of the two strain gauges. Fig. 2 presents a representative output of the computer data acquisition system.

To ensure stress equilibrium of the specimen and even deformation during the test and to improve the incident pulse shape, cylindrical silicone rubber pads of different sizes were pasted between the bullet and incident bar. A comparison of the waveforms produced using different sized pulse shapers is presented in Fig. 3. The width of the rising front of the waveforms increased from 20.3 to 94.4 and 177.1 μs after the inclusion of the shapers. In addition, the oscillation of the incident waveform was significantly reduced with the shapers. The inclusion of the shapers clearly improved the incident waveform. As shown in Fig. 4, the stress vs. time curves at the two ends of specimen agreed well; specifically, the assumption of dynamic stress equilibrium was experimentally verified.

To enhance the transmission signal, an LC4 ultra-high strength aluminum alloy bar with a density of 2700 kg/m^3 and elastic modulus of 74 GPa was used to reduce the impedance difference between the specimen and transmission bar. In addition, the inclusion of a semiconductor strain gauge with a magnification of 50 × improved the signal-to-noise ratio of the transmitted wave signal. Molybdenum disulfide was also applied as a lubricant on both ends of the test piece to reduce the friction of the end surface resulting from the small aspect ratio of the test piece. Impact tests were conducted at strain rates of 2800–5500 s^{-1}, and each test was repeated three times with the results averaged. Based on the one-dimensional assumption and uniformity assumption, the engineering stress $\sigma(t)$, the engineering strain $\varepsilon(t)$ and the stain rate $\dot{\varepsilon}(t)$ were determined using Eqs. (1)–(3) [24]:

$$\sigma(t) = \frac{S_0}{S_s} E \varepsilon_t(t) \tag{1}$$

$$\varepsilon(t) = \int_0^t \dot{\varepsilon}(t) d\tau \tag{2}$$

$$\dot{\varepsilon}(t) = -\frac{2c_0}{L_s} \varepsilon_r(t), \tag{3}$$

where $\varepsilon_r(t)$ and $\varepsilon_t(t)$ are the reflected and transmitted strain, respectively; E, S_0 and c_0 are Young's modulus, cross-sectional area, and longitudinal wave speed in the incident and transmitted bars, respectively; S_S and L_S are the initial cross-sectional area and length of the specimen, respectively;

3. Results and discussion

Fig. 5 shows the deformation of the specimens after the quasi-static and dynamic tests. As observed in Fig. 5(a) and 5(b), specimens C-0, C-10, and C-30 mostly returned to their original shapes after compression, whereas specimen C-50 became drum-shaped (Fig. 5(a)) and noticeably thinner (Fig. 5(b)) after compression. The measured thicknesses of specimens C-0, C-10, C-30, and C-50 were 9.92, 9.88, 9.64, and 9.02 mm, respectively, after the quasi-static test and 1.96, 1.94, 1.94, and 1.72 mm, respectively, after the dynamic test. We can see that obvious plastic deformation of specimens C-50 exists during compression process under different strain rates.

3.1. Quasi-static testing

Fig. 6 presents the engineering stress–strain curves of the composites for the quasi-static testing. The deformation mode of specimens C-0, C-10, and C-30 was similar: the first stage consisted of linear elastic deformation for strains below 0.4; with continued compression, the material hardening effect became increasingly evident, as indicated by