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High strain-rate failure in carbon/Kevlar hybrid woven composites via a novel SHPB-AE coupled test

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The high strain-rate induced failure characteristics in a carbon/Kevlar hybrid composite subjected to high strain-rate compressive loading were studied using a novel SHPB-AE coupled test. The tests were performed based on a split-Hopkinson pressure bar (SHPB) apparatus and an acoustic emission (AE) technique, respectively. Within the strain-rate range of 1002–1941 s^{-1}, a high strain-rate compressive test was conducted on the cylindrical carbon/Kevlar hybrid composite specimens located between the incident and transmitted bars. A wide bandwidth type AE sensor was connected to the specimen with a fine copper waveguide to monitor the AE signals in real time during the test. Specific types of failure mechanisms were observed with optical microscopy and scanning electron microscopy. First, AE characteristics originating from the specimens were investigated profoundly to distinguish the AE signals from diverse damage or failure sources. AE signals were then analyzed in terms of the AE amplitude, the AE count, the slope of cumulative AE count and the peak frequency. Finally, signals were classified into four types based on the waveform and corresponding peak frequency by a short time Fourier transforms (STFT). As a result, under high strain-rate compressive loading, the strain level at the damage initiation was shortened with increasing strain-rate. The failure process of the carbon/Kevlar hybrid woven composite showed initial matrix fracture and then brittle carbon fiber breakage. Subsequently, multiple failure mechanisms appeared, such as fiber-matrix debonding, fiber pull-out, excessive deformation and breakage in the Kevlar fiber tips including splitting and fibrillation. The application of the novel SHPB-AE coupled test to the carbon/Kevlar hybrid composite was discussed in depth for characterizing the failure process, and it was an effective and relevant methodology to grasp in situ information on the failures under high strain-rate compressive loading.

1. Introduction

Fiber-reinforced composites provide distinct advantages compared to other conventional engineering materials, such as aluminum and steel. The use of advanced fiber-reinforced composites, therefore, are increasing in a wide range of high technology engineering applications because they have high specific stiffness and strength, resistance to fatigue loads, tolerance to temperature extremes, and weight minimization. For examples, fiber-reinforced composites are used in the fuselage skin of airplanes and helicopters, some body panels for cars and truck cabs, fishing rods, tennis rackets, golf club shafts, skis, bows and arrows etc. In recent years, the use of woven composites has particularly increased. Woven composites provide additional resistance to damage growth according to the interlacing architecture of the fiber (weft and warp yarns) bundles and they possess exceptionally high ratios of strain to failure in tension, compression and impact load; however, the main hindrance to the application of woven composites in primary and/or secondary structures is the lack of understanding of their material behavior particularly under high strain-rate compressive loading. Furthermore, it is difficult to observe the failure mechanisms with the naked eye because woven composites fail in a short period of time and their failure mechanisms are various and complex.

Hybrid composites, in general, are referred to as materials that combine two or more reinforced fibers with suitable binding matrix such as resin. Hybridization is one of the most effective ways to adjust the property of individual fiber composite. They provide a

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wide range of physical properties that cannot be obtained from single fiber-reinforced composites. Unidirectional and laminated hybrid composites [1–3] have been investigated extensively while fewer studies have examined woven hybrid composites. Furthermore, there is little literature on the investigation of high strain-rate compressive loading induced failure characteristics in woven hybrid composites.

Fiber-reinforced composites have been characterized and examined under diverse loading environments [4–8]. However, their failure process and damage mechanisms under a high strain-rate loading conditions are less understood. Researchers have investigated the dynamic response of fiber-reinforced composites at high strain-rates mostly using split Hopkinson pressure bars (SHPB). Hufenbach et al. [9] experimentally investigated of dynamic material behavior and failure mechanisms in hybrid 3D-textile reinforced composites under highly dynamic loading, such as crash or impact loads. Thanomsilp et al. [10] investigated the penetration impact resistance of hybrid composites based on commingled yarn fabrics, which are composed of E-glass fibers and thermoplastic fibers blended together within the fiber bundles. They found that the total absorbed energy of the fiber-hybrid composites was significantly higher than for the plain glass composites. Kang et al. [11] characterized the impact behavior and damage tolerance properties of Kevlar multi-axial warp-knit fabric composites, as well as woven and unidirectional composite laminates using the energy approach. Pankow et al. [12] reported that 3D woven textile composites showed an increase in strength in all three directions. The in-plane orientations showed the largest increase in strength, approximately 100%, at elevated rates of loading. Recently, Wang et al. [13] examined the thermal mechanical behavior of recycled polypropylene (PP)-based composites under dynamic loading using SHPB tests. They showed that the neat PP and PP/talc composites presented a brittle behavior at low temperatures, and the addition of ethylene octane copolymer (EOC) inclusions markedly improved the impact resistance of PP and PP/talc. The results also indicated that the impact resistance of PP/talc was improved with the recycling numbers due to a fragmentation of the talc particles during the reprocessing inducing a self-reinforcement.

As aforementioned, much work dealing with impact or high strain-rate loading related problems has focused mainly on the dynamic behavior/responses, impact performance/resistance, damage tolerance and mechanical properties of fiber-reinforced composites via fracture tests and numerical analyses [14–16]. Fiber-reinforced composites, unlike isotropic materials, show various failure mechanisms, and they fails often in a combination of several mechanisms such as matrix cracking, fiber/matrix debonding, inter-fiber failure, ply delamination and fiber breakage [17]. The failure processes and damage mechanisms for fiber-reinforced composites under high-strain-rate were successfully examined via destructive methods; unfortunately, little has been reported on their failure processes and damage mechanisms via destructive-nondestructive coupled techniques, and available data to determine the failure process of woven hybrid composites subjected to a high strain-rate loading are rare, to the knowledge of the authors.

In previous studies, the authors investigated the damage mechanisms of armor structural materials via a three-dimensional finite element analysis and SHPB tests [18]. We also addressed a state of the art SHPB-AE coupled methodology, and successfully investigated how high-strain-rate affected the failure processes and damage mechanisms of armor structural materials [19] and Kevlar-woven composites [20].

This work focuses on the in-depth analysis of the failure processes and failure mechanisms in carbon/Kevlar hybrid woven composites subjected to high-strain-rate compressive loading. Tests were performed using a novel SHPB-AE coupled test [19,20], which can provide information on the microscopic damage sources and the failure process of carbon/Kevlar woven hybrid composites in real time. Following testing, the characteristic AE signals generating from the specific damage mechanisms were identified and classified by comparing with microscopic observations of damage mechanisms in the specimens. The AE amplitude, the AE count, and the slope of cumulative AE count were adopted as damage parameters in the analysis of AE signals. Furthermore, for better understanding of the damage initiation and its evolution in real-time during the loading history, the AE waveform and corresponding peak frequency-based analysis was carried out. For the characterization of microstructures in the materials, optical microscopy and scanning electron microscopy were utilized.

2. Experiments

2.1. Materials and specimen

In this study, preform type carbon/Kevlar woven hybrid composites with a 2 × 2 twill weave pattern (see Fig. 1(a)) were used. The physical properties of two fibers provided by the manufacturer (GCOSTA Inc., Korea) are tabulated in Table 1. Specimens for SHPB-AE tests were prepared by cutting carefully from the carbon/Kevlar preform plate with a diamond wheel cutter to minimize damage in the specimens. Then they were machined into cylinders with an average diameter of 8 mm and an average length of 8 mm as shown in Fig. 1(b). There is a micromachining error of 0.1 mm in the specimens. The axis of the cylindrical specimen is perpendicular to the *x-y* plane and the specimens were impacted in the *z* direction.

2.2. SHPB-AE coupled test

The high strain-rate compression tests were carried out on a split-Hopkinson pressure bar (SHPB) apparatus. The schematic illustration of the SHPB used in this study is presented in Fig. 2. The details of the measurement theory, techniques, and instrumentation on the SHPB test are well described in the references [21,22]. The equations for the stress, strain-rate and strain of the specimen are as follows [23]:

$$\sigma(t) = \frac{A_b}{2A_s} E(\varepsilon_i + \varepsilon_r + \varepsilon_t) \tag{1}$$

$$\dot{\varepsilon}(t) = \frac{C}{L_s}(\varepsilon_i - \varepsilon_r - \varepsilon_t) \tag{2}$$

$$\varepsilon(t) = \frac{C}{L_s}\int_0^t (\varepsilon_i - \varepsilon_r - \varepsilon_t)dt \tag{3}$$

where A_b, A_s and L_s are the cross-sectional area of pressure bar, the original cross-sectional area and the original length of the specimen, respectively; E the Young's modulus of the pressure bar; C the elastic wave speed of the pressure bar; ε_i and ε_r the incident and reflected axial strains on the incident pressure bar, respectively; ε_t is the transmitted axial strain on the transmission bar. In this study, the engineering values calculated from equation (1)–(3) were converted to true values by using the equations [24], such as true stress $\sigma_{true}(t) = \sigma(t)[1-\varepsilon(t)]$, true strain-rate $\dot{\varepsilon}_{true}(t) = \dot{\varepsilon}(t)/[1-\varepsilon(t)]$, and true strain $\varepsilon_{true}(t) = -\ln[1-\varepsilon(t)]$ respectively.

Fig. 2 shows an entire schematic diagram of the SHPB-AE coupled test. The SHPB testing apparatus consists of an air gun,