IMPACT BEHAVIOR OF STEEL AND POLYMER COMPOSITES

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Abstract
Steel-polymer composites are widely used in automotive, aerospace and construction due to their desirable vibration damping properties and weight advantages. One of the main reasons that steel-polymer composites have lower impact energy absorption is due to the occurrence of weak interfacial failures during impact. Using the Charpy impact test, the fracture modes of steel-polymer composites were observed and the absorption energy was obtained for various compositions. By observing the relationship between the interface shear strength and the absorbed energy, the critical interface shear strength required to prevent interfacial failure at impact was found. The mechanical properties of steel-polymer, for strain rates of impact 45 s^{-1}, were characterized using the Hopkinson bar test. The stress-strain curve of the specimen was obtained using a high-speed camera and filtering method. Using the obtained stress-strain curve, the relationship between each material (steel, polymer and steel-polymer composites) was examined. Finally, the stress-strain curves of the steel-polymer composites were calculated using the Zhao constitutive model, for a strain rate of that found in a typical car accident (300 s^{-1}).

1. Introduction

Steel-polymer composites are being exploited in the automotive, aerospace and construction sectors due to their vibration damping properties and weight advantages compared to other metallic materials [1, 2]. The steel-polymer composite is vulnerable to impacts because the interface between the steel and the polymer layer is weak. Therefore, the ability to predict interfacial shear strength is important for optimal utilization of steel-polymer composite materials, i.e., to withstand constant impact energy.

Multiple studies have been conducted using a three-point bending system to characterize the interfacial properties of steel-polymer composites. Researchers have proposed an experimental and theoretical minimum strength to prevent interfacial failure during these tests [3, 4]. However, these testing methods are performed at low strain rates. There are insufficient studies addressing the interfacial strength of steel-polymer composites at high impact level strain rates.

One of the most widely used test methods to investigate impact durability is the Charpy impact test. This test uses a drop impactor on the test specimen to evaluate the energy absorbed during impact. In this study, the Charpy test was used to observe the failure mode of steel-polymer composites, and to measure the energy absorbed by a specimen during impact. Two failure modes of the steel-polymer composite were observed: interface failure and yield. It was found that interfacial failure significantly reduces the impact durability of steel-polymer composites. By observing the interface shear strength and the absorbed energy, the critical interface shear strength required to prevent interfacial failure at impact was found.

Furthermore, the mechanical properties were characterized for a very high strain rate, similar to a real-life impact. Numerous studies have been conducted in an attempt to characterize various materials under very high strain rates [5, 6]. Currently, however, no high strain rate tensile test has been performed on steel-polymer composites. The Hopkinson bar test was used for tensile testing of steel, polymer and steel-polymer composites at high strain rates of up to 10^{2} s^{-1}. The stress-strain curve of the specimen was obtained using a high-speed camera and filtering method. Compared to a tensile test at a low strain rate (10^{-3} s^{-1}), the steel-polymer composites exhibited a strain rate sensitivity similar to steel, where the yield strength and tensile strength were calculated by rule of mixture and were found to be similar to experimental results. Finally, Zhao's constitutive flow model was found to be suitable for predicting the stress-strain curve of steel-polymer composites at higher strain rates.

2. Experimental

2.1 Materials

In this work, Galvanized (GA) steel, electro galvanized (EG) steel, and phosphate light treated (PL) steel from POSCO (Korea) were used. Polymer used in this study was nylon-6 (PA), polypropylene (PP), polyethylene terephthalate (PET), and polycarbonate (PC) from Goodfellow (USA).

2.2 Charpy test

To prepare specimens for the Charpy test, the steel and polymer were cut to an appropriate size (127 mm long × 6.35 mm wide). The two materials were then adhered together to form a sandwich structure. Loctite 401 (Henkel) was used as the adhesive.

To perform the Charpy impact test, a hammer with 14.7 J of potential energy was dropped on the specimen. The absorbed energy was found by dividing the potential energy difference by the thickness of the specimen.

2.3 Hopkinson bar test

The 104 mm × 20 mm dog bone-shaped specimens were used to characterize the high-speed mechanical properties of steel-polymer composites. Galvannealed (GA) steel and PA were adhered together using Loctite to form a sandwich structure.

Dynamic tests were then performed using the Hopkinson bar tester. Fig. 1 shows a schematic of the Hopkinson bar tester, which includes a high pressure gas cylinder, a fast moving bar and frames attached to the specimen. After the cylinder was pressurized with nitrogen up to 4 bar, the nitrogen was released, accelerating the bar until it struck the frame. As the frame moved, the specimen elongated. The speed of the frame was measured at 3.5 m/s, with a strain rate of 40 s^{-1}.

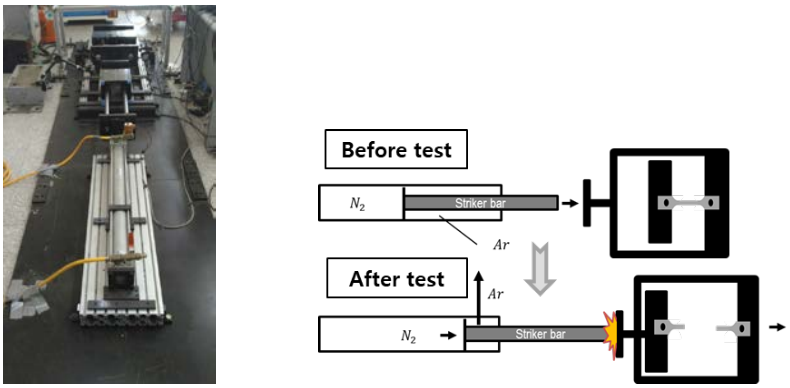

Figure 1. Photo and schematic of the Hopkinson bar tester

The impact force was measured using a piezoelectric load cell. The strain was measured using a high speed digital camera (X-Stream XS-4). During the test, the camera recorded 5,000 images per second, with each image composed of 256 × 256 pixels to give a resulting image resolution of 0.168 mm per pixel. By tracing fiducial marks on the specimen, the strain of the steel-polymer composites was calculated.

3. Results and discussion

3.1 Charpy test results

The absorbed energy of the steel-polymer composites was measured for different compositions (three types of steel: GA, EG, PL; and four types of polymer: PA, PP, PET, PC) using the Charpy test. During the test, two failure modes were observed; interfacial and yield failure. The average absorbed energy, according to the failure modes, is shown in Fig. 2. The absorbed energy showed a large difference depending on the failure mode, regardless of the composition of the specimen. As shown in Fig. 2, specimens that underwent debonding exhibited lower absorbed energy than those showing no debonding. Therefore, it is important to ensure sufficient adhesion between the steel and polymer.

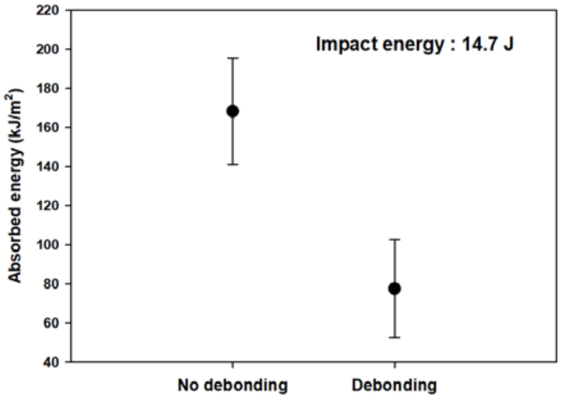

Figure 2. Average absorbed energy according to the failure modes.

Figure 3 shows the relationship between the lap shear strength and the absorbed energy. As the interfacial strength between the two materials increased, the absorbed energy also increased linearly. By correlating this with results from other test specimens, the critical interfacial shear strength required to prevent debonding during impact can be obtained. The minimum strength to withstand the impact energy of the test (14.7 J) was found to be 6.3–6.7 MPa.

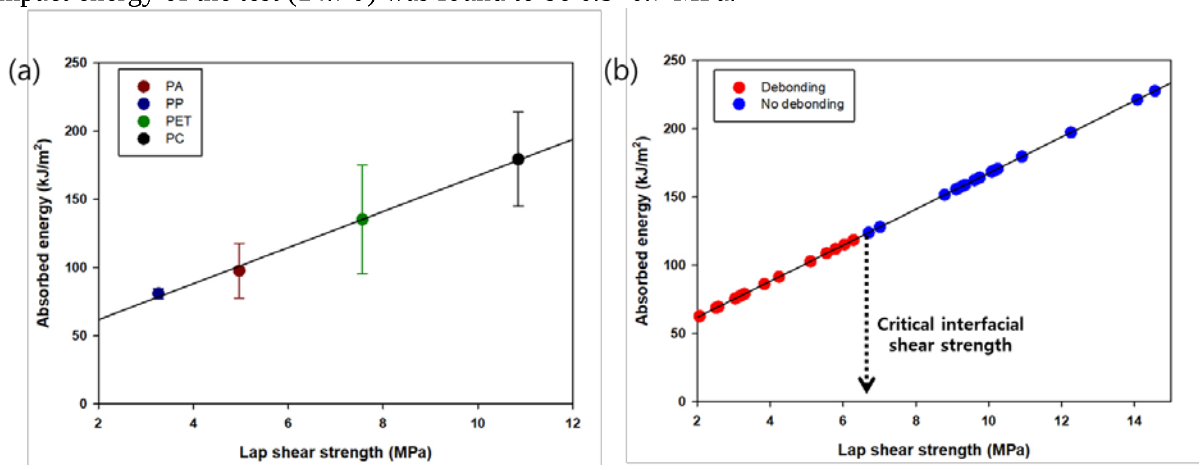

Figure 3. (a) Relationship between lap shear strength and absorbed energy, (b) Critical interfacial shear strength by placing absorbed energy of all Charpy test specimens on linear equation.

3.2 Hopkinson bar test results

3.2.1 Stress-strain curve of high strain rate

The stress and strain of a single layer of GA steel, and for PA and GA steel-PA composites, were measured using the Hopkinson bar tester. As shown in Fig. 4, the flow-stress oscillates with time during plastic deformation due to system ringing [7]. Therefore, it was difficult to determine any mechanical properties during the high strain rate tensile test, as additional filtering was required. The force from the yield point was filtered using a fourth order Butterworth low-pass filter with a cut-off frequency of 145.1 Hz.

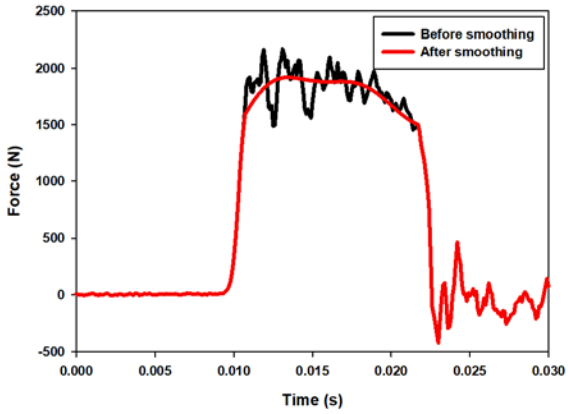

Figure 4. Comparison experimental force-time curve and smoothed data by a low pass filter in case of GA steel-PA composites

Finally, synchronizing the stress and strain with the start time allowed the stress-strain curve for the high strain rate tensile test to be obtained [8]. Figure 5 shows the true stress–true strain curve of the GA steel-PA composites for the high strain rate test, and that the dynamic flow stress of the steel-polymer composites increased compared to the static test.

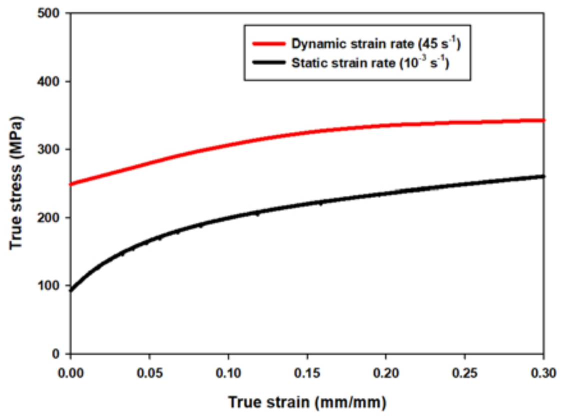

Figure 5. Comparison true stress – true strain curve of high strain rate and static true stress - true strain curve in case of GA steel-PA composites

3.2.2 Mechanical properties of high strain rate

The theoretical strength of the steel-polymer composites (σ_1) was calculated from the sum of the strength of a single steel and polymer layer (σ_s, σ_p), multiplied by the volume fraction of the steel and polymer in the composites (V_s, V_p).

$$\sigma_1 = \sigma_s V_s + \sigma_p (1 - V_p). \tag{1}$$

The experimental yield strength and tensile strength of the steel-polymer composites for a high strain rate were approximately the same as the theoretical strength (Eq. 1), as shown in Fig. 6.

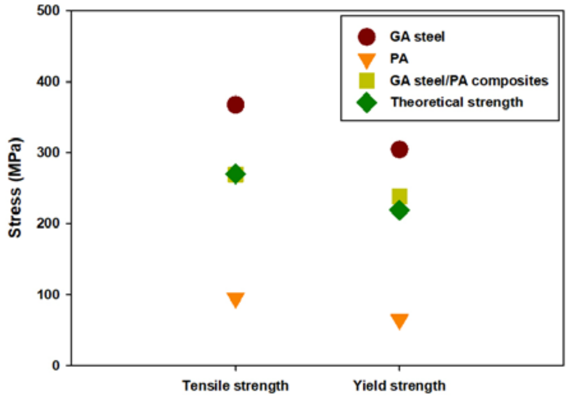

Figure 6. Comparison experimental tensile strength and yield strength of steel-polymer composites at 40 s^{-1} and theoretical strength calculated by rule of mixture.

3.2.3 Prediction of stress-strain curve at higher strain rates

The Zhao constitutive model is an empirical strength model that accounts for the effect of temperature of mild steel on strain rate [9]. The following equation combines internal stress, thermally activated stress and viscous drag stress.

$$\sigma = [A + B\varepsilon_p{}^n + (C - D\varepsilon_p{}^m)log(\acute{\varepsilon}/\acute{\varepsilon}_0) + E\acute{\varepsilon}^k](1 - \mu\Delta T) \tag{2}$$

Where ε_p is effective plastic strain, $\acute{\varepsilon}$ is plastic strain rate, $\acute{\varepsilon}_0$ is reference plastic strain rate (0.00125 s^{-1}), and ΔT is the change in temperature. Because the high strain rate test occurs over a short time, the specimen undergoes an adiabatic process. This results in the specimen increasing in temperature due to the heat emitted during plastic work [10]. The rise in temperature is expressed using the following equation:

$$\Delta T = \beta/(\rho C_p) \int \sigma \, d\varepsilon_p \tag{3}$$

Where ρ is density, C_p is the specific heat at constant pressure and β is the Taylor-Quinney coefficient, which indicates the fraction of heat converted from total plastic work. β was assumed to be 0.9. For the GA steel-PA composites, the material properties were calculated by rule of mixture for a single sheet of GA steel and PA. The calculated values of ρ and C_p for the composite materials were found to be 5.45 g/cm^3 and 0.91 kJ/kg·K respectively. Using the stress-strain curve at various strain rates (0.00125 s^{-1}, 0.0125 s^{-1}, 0.125 s^{-1} and 45 s^{-1}), the coefficients of the Zhao constitutive model were calculated. From this, the stress-strain curves at 45 s^{-1} and 300 s^{-1} were predicted, as shown in Fig. 7. The predicted 45 s^{-1} stress-strain curve closely correlated with the experimental results (fig. 7).

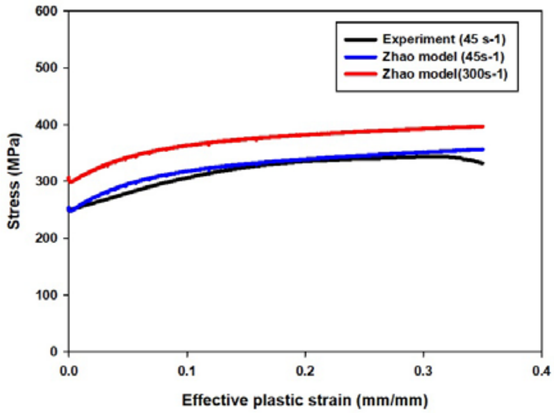

Figure 7. Predicted stress-strain curve (45 s^{-1} and 300 s^{-1}), and tested stress-strain curve(45 s^{-1}).

4. Conclusion

In this study, Charpy impact tests were performed to measure energy absorption and observe failure modes of steel-polymer composites. There were two failure modes; yield and interfacial failure. The specimens that exhibited interfacial failure absorbed less energy than those that yielded. The critical interfacial shear stress, required to prevent debonding, was obtained from the Charpy and lap shear tests. The Hopkinson bar tests were then performed to characterize the steel-polymer composites for high strain rates. To obtain an accurate stress-strain curve at high speed, camera analysis and filtering techniques were used. The resulting mechanical properties of the composites were found at high speed, along with several features of steel-polymer composites. 1. The stress increased, and fracture strain decreased, compared to the static tests. 2. The yield strength and tensile strength of the composites could be calculated using the rule of mixture from the high speed strength results of the individual steel and polymer. 3. A higher stress-strain curve can be obtained using Zhao's model.

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