Nondestructive detection of the interfacial failure of steel-polymer sandwich composites during forming process

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Abstract. Steel-polymer composites have low density, high specific flexural stiffness and vibration damping properties over other metal materials. However, the weak interfaces between steel and polymer sheet are the typical locations where the failure occurs. Furthermore, interfacial failure is a fatal reason of the degradation of mechanical properties. Therefore, predicting interfacial failure of the final product is an important technology in commercialization of steel-polymer composites. In this study, we built forming limit diagram (FLD) based on two different failure modes: failure of the bottom skin steel and interfacial failure between the skin steel and core polymer. Acoustic emission (AE) technique was conducted to observe the interfacial failure moment. Peak frequency was found to be the key feature to distinguish interfacial failure. Peak frequency band that indicates interfacial failure was from 300 kHz to 500 kHz. This peak frequency band made it possible to build FLD considering the interfacial failure.

Keywords: steel-polymer composites, forming limit diagram, acoustic emission, failure modes

1. Introduction
Steel-polymer composites are sandwich structure made of top and bottom skin steel and core polymer as shown in Figure 1. Steel-polymer composites are being widely used in the automotive, aerospace and construction fields due to their high specific flexural stiffness and functional properties [1, 2]. Therefore, the forming limit of steel-polymer composites is important. One of the common tools for characterizing the forming limit of sheet material is forming limit diagram (FLD). As such, some researchers have studied FLD of sandwich composites [3]. They focused on the localized necking of the bottom skin material. Also, numerical simulations have been conducted to predict FLD of sandwich material based on the failure of the skin metal sheet [4]. All these researches neglected interfacial failure during the forming process. However, the formability characteristic of steel-polymer composites is more complicated because it consists of materials with different mechanical properties. Furthermore, the interfacial separation between the skin and the core degrades the performance of steel-polymer composites [5]. Therefore, experimental tool for interfacial failure should be studied. Few researches have been carried out on building FLD considering interfacial failure.
Acoustic emission (AE) technique is widely used for structural health-monitoring systems to detect failure of materials in real time. Ultrasonic waves induced by elastic strain energy when material damages are observed by the AE sensor. Many researchers have carried out on classifying failure modes by observing AE signal features: amplitude, rise time, and peak frequency [6]. In this study, key AE signal feature that classifies the failure modes of steel-polymer sandwich composites was investigated. There are three different failure modes: steel fracture, polymer fracture, and interfacial failure. According to the peak frequency of AE signals, only interfacial failure showed unique characteristics. During the formability test, in-situ AE signals were obtained, and finally, FLD considering the interfacial failure can be obtained.

2. Experiments

2.1. Specimen preparation
Electro galvanized (EG) steel was used as skin material. The thickness of skin steels was 0.6 mm. Polyamide-6 (PA6) polymer was used as core material. The thickness of core polymer was 1 mm. Acetyl type adhesive, Loctite 401 (Henkel) was used to adhere the steel and polymer. Mechanical properties of EG steel and PA6 polymer are presented in Table 1.

|          | Elastic modulus (GPa) | Yield strength (MPa) | Tensile strength (MPa) | Elongation |
|----------|-----------------------|----------------------|------------------------|------------|
| EG steel | 177                   | 178.5                | 302                    | 0.68       |
| PA6      | 1.13                  | 32.7                 | 54.9                   | 5.43       |

2.2. Formability test methods
Hemispherical punch tests were conducted to build forming limit diagram of the steel-polymer sandwich composites. Figure 2 shows the punch test setup. Load and displacement of the punch were obtained by the universal testing machine connected to the hemispherical punch. The diameter of the punch is 50 mm and the diameter of hole where the punch moved was 56.5 mm.

Specimen was fabricated with different shape varying from 10 mm to 100 mm width as shown in Figure 3(a). After specimen placed on the die, the blank-holder was clamped by bolts and nuts. The beads helped specimen not to slip. Speed of the hemispherical punch was 10 mm/min. Each specimen showed different strain paths from simple tension to biaxial tension.
Figure 3. (a) Specimen for the punch test, and (b) specimen with circle grid painted by a stamp

Circle grid with 3 mm diameter was painted on the specimen with a stamp as shown in Figure 3(b). Deformed grids around the failure region was moved to a flat surface using a tape and major strain and minor strain were measured. Forming limit curve was constructed between the safe grids and failed grids

2.3. Acoustic emission test methods
Acoustic emission test was conducted to capture the interfacial failure moment. Figure 4 shows the acoustic emission test setup. M204A wide-broad sensor (Fuji ceramics corporation) was used. Operating frequency of the sensor is from 100 kHz to 600 kHz. To amplify the signal, A1002 preamplifier (Fuji ceramics corporation) was used. Then signals were acquired by DAQ board and analysed by the software (Mistras).

Figure 4. Acoustic emission test setup

2.4. Tests for failure modes
Steel fracture, polymer fracture and interfacial failure can occur during forming process. To distinguish interfacial failure from other failure modes during the punch test, acoustic emission signal features of interfacial failure must be studied. To observe AE signal features of steel fracture and polymer fracture, tensile tests of single steel and single polymer were conducted. For observing AE signal features of interfacial failure, lap shear test and tensile test of steel-polymer composites were conducted. AE sensor was placed on the specimen directly as shown in Figure 5. Additionally, tensile test of steel-polymer composites was conducted. For one type of specimen there was no adhesive between EG steel and PA6 layer. The other type of specimen was adhered with acrylic adhesive. AE signals from tensile test of two types of specimen were collected to observe AE features of interfacial failure.

Figure 5. (a) Tensile test specimen and AE sensor, (b) lap shear test specimen.
3. Results and discussion

3.1. FLD of steel-polymer composites with steel fracture
Steel fracture was detected observing load drop during the punch test. Load-displacement curve of the punch test is shown in Figure 6. While displacement of the punch increased, the load increased linearly until the bottom steel broke. Signal of interfacial failure could not be observed from the load-displacement curve. FLDs of single steel and steel-polymer composites without considering interfacial failure were compared as shown in Figure 7. The minimum point of steel-polymer composites was higher than that of steel due to the thickness effect.

![Figure 6. Load-displacement curve during the punch test (specimen with 100 mm width).](image)

![Figure 7. FLDs of single steel and steel-polymer composites based on the steel fracture](image)

3.2. AE signal features
One of the acoustic emission waves measured by AE system during the tensile test of EG steel was shown in Figure 8(a). Peak frequency of the AE wave was calculated using fast Fourier transform as shown in Figure 8(b). The time when AE signals generated and plotted on X axis and Y2 axis of the stress-time curve as shown in Figure 9.

![Figure 8. (a) AE waves measured during the tensile test of EG steel and, (b) frequency distribution of the AE signal using fast Fourier transform.](image)
As shown in Figure 9, AE signals which have peak frequency of 10–100 kHz and 100–200 kHz were observed at the moment of steel fracture. This indicates that strain energy release from steel fracture generates ultrasonic wave with 10–100 kHz and 100–200 kHz peak frequency. Likewise, AE signals from the fracture of the single PA6 showed 30–70 kHz peak frequency. Lap shear test was also conducted and AE signals from interfacial failure had peak frequency of 10–200 kHz and 300–500 kHz. Comparing the results, signal with peak frequency of 300 kHz–500 kHz was only observed at interfacial separation.

Stress-time and frequency-time curves of tensile tests of steel-polymer composites with and without adhesion were shown in Figure 10(a) and 10(b) respectively. Steel-polymer composites specimen with adhesion showed additional frequency band of 300 kHz–500 kHz when compared to the specimen without adhesion. When the specimen with adhesion went into the fracture, the interfacial separation at the side of the specimen occurred due to different necking behavior of EG steel and PA6 as shown in Figure 11. This results confirm that AE signals of 300 kHz–500kHz peak frequency band are key features to distinguish the interfacial failure from the other failure modes.

Figure 9. Peak frequency bands of tensile test of single steel.

Figure 10. Peak frequency bands of tensile test of steel-polymer sandwich composites (a) with adhesion and (b) without adhesion.

Figure 11. Interfacial separation after the tensile test of steel-polymer composites with adhesion.
4. Conclusions
In this study, the formability of steel-polymer sandwich composites was investigated. Acoustic emission technique was used to define key features of interfacial failure signal. Single steel and polymer tensile tests were compared with lap shear test. Furthermore, tensile test of steel-polymer composites were carried out with and without adhesion. It was shown that peak frequency of 300 kHz~500 kHz was only found in interfacial failure.

5. References
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