Formability simulation of steel-polymer sandwiched composites considering the adhesion strength

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Abstract. Developed to increase the energy efficiency of automobiles, steel-polymer sandwiched composites are attracting attention due to their lightweight and multi-functionality and are being actively researched recently. In order to apply those composites to industrial fields, their formability must be investigated in order to prevent the degradation of mechanical properties of the composites during the forming process in various shapes. Therefore, experimental studies have recently been conducted to evaluate the formability of the composites. However, there are few studies to predict the formability of the composites considering the mechanical properties of core polymer and interfacial properties. In this study, formability tests were carried out for evaluating the forming limit diagram of the composites. Also, the formability test of the composites was simulated considering the viscoplastic properties of the core polymer using Arruda-Boyce model and the interfacial properties using the cohesive zone model. Finally, the effect of the interfacial adhesion on the formability of the composites was investigated, from which an optimal condition was explored for the interfacial adhesion strengths that can ensure the formability of the composites for specific applications.

1. Introduction

Steels have been widely used in various field due to their good mechanical properties and low production cost. However, they have been require to be replaced because of their heavy weight. For that reason, automotive industries have developed new structural materials with lightweight to enhance energy efficiency. Steel-polymer sandwiched composites have been researched to reduce the weight of structural materials while lightweight maintaining their performance. For example, the sandwiched composites with a volume fraction of polymer of 30% theoretically show that the flexural rigidity remains 97%, but the weight decrease by 75% compared to the steel of the same volume. In addition, these composites have showed improved damping and soundproof properties compared to pure steel structure.

In order to apply the composites to industrial fields, their formability must be investigated. Various experimental studies have recently been conducted to evaluate the formability of the composites [1]. Although there were studies evaluating the formability of the composites using the deep drawing test, there were some disadvantages that the used materials were limited. Also, in the case of the steel-polymer sandwiched composites, most fractures are caused by delamination at the interface. Therefore, formability of steel-polymer sandwiched composites should be investigated considering the interfacial properties. Also, there were studies to evaluate the forming limit of the composites through simulation. However, they did not consider the delamination at the interface and did not match the actual forming limit.
For simulating the formability of the composites, a mechanical model is required to accurately simulate the interfacial properties and the mechanical properties of steel and polymer. For example, a ductile damage criterion was used in simulation for the steel. Also, during forming of the steel-polymer sandwiched composites, the core polymer undergoes the plastic deformation. Generally, the mechanical properties of the polymer are affected by the tensile rate and temperature. Therefore, in order to accurately simulate the mechanical properties of polymer, a mechanical model for the polymer that should reflect the viscoplastic properties of the polymer. In addition, for simulating the interfacial properties, the cohesive zone model is necessary.

In this study, the formability test of the sandwiched composites was simulated considering the viscoplastic properties of the core polymer and the interfacial properties using the cohesive zone model. Among various effective traction-separation law [2], a linear softening relationship was used [3]. Finally, the effects of the adhesion strength on the formability of the composites were investigated, and the optimal conditions for the adhesion strength to ensure the formability of the composites were investigated.

2. Theoretical background

2.1. Formability

The formability is the ability of materials such as metals to undergo the plastic deformation without being damaged. Generally, the formability of the material is affected by its deep drawability, ductility and so on. There are various indices to show the formability of the material, but the forming limit diagram is typically used. The forming limit diagram, also known as the forming limit curve, is used in sheet metals. Through repeated measurement, the shape of the curve could be obtained experimentally. Alternatively, the forming limit diagram could be generated by mapping the shape of a failure criterion into formability limit domain. The example of the forming limit diagram is shown as Figure 1.

![Figure 1. Example of forming limit diagram (ASTM E2218-15)](image)

2.2. Ductile damage model for steel

A ductile criterion is a phenomenological model for predicting the onset of damage due to nucleation, growth, and coalescence of voids [4]. The model assumes that the equivalent plastic strain ($\varepsilon_D^{pl}$) at the onset of damage is a function of stress triaxiality ($\eta$) and strain rate [5] (see Equation (1)).
Figure 2 illustrates the characteristic stress-strain behaviour of the material undergoing damage. In the context of an elastic-plastic material with isotropic hardening, the damage manifests itself in two forms: softening of the yield stress and degradation of the elasticity. The solid curve in the Figure 1 represents the damaged stress-strain response, while the dashed curve is the response in the absence of damage. In Figure 2, \( \sigma_{y0} \) and \( \varepsilon_{eq0}^{pl} \) are the yield stress and equivalent plastic strain at the onset of damage, and \( \varepsilon_f^{pl} \) is the equivalent plastic strain at failure. That is, when the overall damage variable reaches the value \( D=1 \). The overall damage variable, \( D \), captures the combined effect of all active damage mechanisms and is computed in terms of the individual damage variable. The value of the equivalent plastic strain at failure, \( \varepsilon_f^{pl} \), depends on the characteristic length of the element and cannot be used as the material parameter for the specification of the damage evolution law. Instead, the damage evolution law is specified in terms of equivalent plastic displacement or in terms of fracture energy dissipation.

\[
\varepsilon_D^{pl}(\eta) = \varepsilon_f^{pl} \frac{\sinh[k_0(\eta^- - \eta)] + \varepsilon_f^{pl} \sinh[k_0(\eta - \eta^+)]}{\sinh[k_0(\eta^- - \eta^+)])}
\]

(1)

Figure 2. Stress-strain curve with progressive damage degradation [6]

2.3. Viscoplastic model for polymer

Arruda-Boyce model [7] was selected as a model to simulate the viscoplastic behavior of the polymer, and the viscoplastic behavior of the polymer could be simulated by deriving the material constants of the polymer (see Figure 3).

Figure 3. A rheological model of polymer [8]
2.4. **Cohesive zone model for interfacial properties**

To describe the delamination behavior of the interface, a cohesive zone model was used. The adhesive layer between the steel and the polymer was represented by cohesive elements, whose delamination behavior was characterized by a traction-separation law in Figure 4.

![Figure 4. The traction-separation law [3]](image)

3. **Experimental**

3.1. **Mechanical properties**

Tensile tests were carried out for evaluating the mechanical properties of steel, polymer, and the hybrid composite using a universal tensile machine. In addition, in order to obtain the material constants of polymer, tensile test and unloading test of polymer were carried out under various strain rate conditions.

3.2. **Interfacial properties**

For evaluating the interfacial properties of the adhesive layer between steel and polymer, four types of tests were carried out. For evaluating the failure stress of mode I and mode II, the butt joint test and lap shear test were carried out. Also, for evaluating the fracture toughness of mode I and mode II, double cantilever beam test and end-notched flexure test were carried out [9].

3.3. **Formability simulation**

A commercial finite element analysis software (ABAQUS/explicit, Simulia Inc., USA) was used for simulation. A three-dimensional model was built with the same specifications as the formability test by Nakazima [10]. The forming limit diagram was derived using the strain at the fracture of the specimen. The results obtained from the simulation were verified by comparing with the results obtained through Nakazima tests.

4. **Results and discussion**

Since the polymer did not fully recover in the unloading test, the plastic properties should be used in simulation. Experiments were conducted to confirm that the recovery of polymer was affected by strain rate. The results were shown in Figure 5. Also, through the tensile tests at various strain rates, the material constants of the polymer were obtained for simulation. Four experiments were performed to consider the properties of the adhesive layer. The failure stress in each mode served as a criterion for the initiation of interfacial failure. And the fracture toughness in each mode was the basis of the final fracture at the interface.
Figure 5. Stress-strain curve for polymer (PA6) according to tensile rate

In this study, 4 kinds of tests such as butt joint test, lap shear test, double cantilever beam test and end-notched flexure test were conducted to measure the interfacial properties between steel and polymer. Through these tests, the failure stress and the fracture toughness in mode I and model II were obtained. The results are shown in the table below.

|                     | Mode I | Mode II |
|---------------------|--------|---------|
| Failure stress (MPa)| 1.85   | 5.36    |
| Fracture toughness (N/mm) | 0.36 | 0.8     |

The forming limit of the steel/polymer/steel hybrid composites could be predicted through the simulation. The simulation results in Figure 6 showed that the forming limit of the hybrid composites were highly accurate when compared with the experimental results.
Finally, the effect of the interfacial adhesion on the formability of the hybrid composites was investigated in shown as Figure 7, from which an optimal condition was explored for the interfacial adhesion strengths that can ensure the formability of the hybrid composites for specific applications. The forming limit of steel-polymer sandwiched composites increased as the adhesion increased. Under actual experimental conditions, the forming limit of the composites was determined by delamination, and this tendency was more shown as the adhesion was lower. However, assuming that the failure stress at mode I and mode II were 10 times stronger than the actual, the forming limit of the composites was very close to that in a perfect bonding condition where delamination did not occur. Therefore, in order to derive the forming limit of the composites, it is necessary to consider the interfacial properties because most fracture of the specimen occurs. In addition, it is understood that the adhesion at the interface must be strengthened for stable forming of the composites.
5. Conclusion
In this study, we set the analytic model for steel, polymer, and interface, and used them to confirm the forming limit of steel-polymer sandwiched composites through the simulation. The simulation results verified the accuracy through comparison with the experimental results. When the forming limit of the composites was derived while changing the adhesion, it was confirmed that the forming limit increased as the adhesion increased. In most cases, the fracture at the interface occurred earlier than the fracture of the specimen, and the strain at delamination was further reduced as the adhesion decreased. Thus, for stable forming of the steel-polymer sandwiched composites, it is necessary to strengthen the interfacial properties.

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