Material characterization of high strength sound-deadening sheets and its application on a square cup drawing simulation

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Abstract. In this study, the mechanical properties of a high strength sound-deadening sheet (SDS) in the stretch deformation mode was characterized, and it successfully apply to the formability prediction of the square cup drawing tests. The high strength SDS was fabricated with dual phase (DP) 590 steel sheets as outer skins and polymeric adhesive layer as a core by a roll bonding process. Uniaxial and biaxial mechanical characteristics were evaluated by the uniaxial tension tests and the in-plane biaxial tension tests, respectively, while the forming limit was investigated by the punched dome tests. Then, based on the experimental data, the mechanical properties of SDS was characterized, viz., hardening curve, yield function and forming limit curve. Square cup drawing was carried out using the SDS, and its deformation and failure behaviour were successfully predicted via the finite element simulation performed by inputting characterized mechanical properties.

Keywords: High strength sound-deadening sheet, DP590 steel sheet, Polymeric adhesive, Formability prediction, Square cup drawing test

1. Introduction

Recently, as the demand for improvement of a ride quality mainly influenced by the vibration and noise, various vibration-reduction methods are applied to the automotive body. One of them is to utilize a sound-deadening sheet (SDS) manufactured by bonding two sheets with a thin layer of a polymeric adhesive which has viscoelastic characteristic [1]. If the thickness of the polymer core is very thin that is generally less than 20% of the total thickness, it is assigned to SDS, while 40% to 60% is classified as a lightweight sandwich sheet with a low density polymer core [2]. The mechanical vibration applied to the SDS causes the repetitive elastic deformation of the polymer and finally converts to the thermal energy [3]. Thus, if the SDS is utilized instead of the base sheet in the automotive applications, the improvement of the ride quality will be expected. Several decades ago, to suppress the transmission of vibration and noise from the oil pan to passengers, methods of applying SDS to automotive dashboard [4] or oil pan [5] were already proposed, and there have been many studies on not only wrinkles [6,7] but also shear deformation between two sheets. Especially, because the shear deformation which usually occurs in the bending mode can cause a delamination without a failure of the base sheets, most previous investigations focused in this phenomenon [8–10]. Although, the beneficial effect of thicker adhesive
layer on the stretch formability of the lightweight sandwich sheet was reported in the several previous studies [11–13], only few studies have investigated the stretch forming behavior of the SDS [2]. According to the author’s previous works [14], the high strength SDS was fabricated by inserting a thin polymer adhesive between high-strength steel sheets to simultaneously consider both vibration reduction and structure stiffness, and a forming limit curve (FLC) of the SDS was determined by a punched dome tests.

The aim of this follow-up study is to examine anisotropic behaviors of the high strength SDS, and then, based on the experimental data, the mechanical properties of SDS was characterized. Finally, a square cup drawing test was performed, and its deformation and failure behavior was predicted by the finite element (FE) simulation performed by inputting characterized mechanical properties.

2. Experimental procedure

2.1. Materials
The base sheet in this study was high strength dual phase (DP) 590 steel sheets which have a ferrite matrix containing martensite as a second phase with 0.7 mm thickness. The SDS was fabricated by inserting acrylic polymeric adhesive between two base sheets, and the bonding section of the SDS is shown in Figure 1.

![Figure 1. Bonding section of SDS](image)

The mechanical properties of the SDS and base sheet measured from the uniaxial tension tests along RD, DD and TD in addition to the in-plane biaxial tension (BT) test are presented in Table 1 (see the parentheses in case of base sheet). Differences in the mechanical properties between the SDS and base sheet were not significant.

|         | Young’s modulus, $E$ (GPa) | Yield stress, $\sigma_{YS}$ (MPa) | Ultimate tensile stress, $\sigma_{UTS}$ (MPa) | Uniform elongation, $\varepsilon_u$ (%) | Total elongation, $\varepsilon_f$ (%) | Lankford value $r$ |
|---------|-----------------------------|-----------------------------------|---------------------------------------------|---------------------------------------|-------------------------------------|-------------------|
| RD      | 210.3                       | 347.6 (350.8)                     | 635.9 (649.8)                               | 18.5 (19.2)                           | 27.0 (27.5)                         | 0.84 (0.87)       |
| DD      |                             | 361.9 (348.3)                     | 630.8 (639.2)                               | 19.1 (19.0)                           | 27.4 (27.4)                         | 0.91 (0.93)       |
| TD      |                             | 357.9 (351.6)                     | 636.2 (655.9)                               | 18.1 (19.0)                           | 26.6 (27.4)                         | 1.05 (1.10)       |
| BT      |                             | 396.6 (387.4)                     | 613.4 (616.2)                               | 5.4 (5.7)                             | -                                   | 0.88 (0.89)       |
2.2. Yield function
A non-quadratic anisotropic yield function under plane stress conditions, Yld2000-2d [15], is defined as:

$$\phi = \phi' + \phi'' = 2\bar{\sigma}^m$$

(1)

where $\bar{\sigma}$ is effective stress and exponent $m$ is 6 for steel with a BCC structure:

$$\phi' = |X'_1 - X'_2|^{\alpha_1}, \quad \phi'' = |2X'_1 + X'_2|^\alpha_2 + |2X'_1 + X'_2|^\alpha_3$$

(2)

where $X'_i$ and $X''_i (i = 1, 2)$ are the principal values of the deviator matrices obtained from the linear transformation $L$ associated with the Cauchy deviatoric stress $\sigma$:

$$X' = L' \sigma, \quad X'' = L'' \sigma$$

(3)

where

$$L' = \begin{bmatrix} 2/3 & 0 & 0 \\ -1/3 & 0 & 0 \\ 0 & 2/3 & 0 \end{bmatrix}, \quad L'' = \begin{bmatrix} -2 & 8 & -2 \\ 1 & -4 & -4 \\ 4 & -4 & 1 \end{bmatrix}$$

(4)

In Eq. (4), $\alpha_1 - \alpha_8$ are eight anisotropy coefficients, and they were calculated using the Newton-Raphson procedure from the experimental data in Table 1 according to the numerical method proposed by Barlat et al. [15]. The calculated anisotropy coefficients of the SDS and base sheet are listed in Table 2 (see the parentheses in case of base sheet).

| Table 2. Anisotropy coefficients of SDS and base sheet |
|-----------------------------------------------|
| $\alpha_1$ | $\alpha_2$ | $\alpha_3$ | $\alpha_4$ | $\alpha_5$ | $\alpha_6$ | $\alpha_7$ | $\alpha_8$ |
| 0.965 | 0.977 | 0.940 | 0.962 | 0.991 | 0.885 | 0.950 | 0.986 |
| (0.928) | (1.047) | (0.918) | (0.971) | (0.994) | (0.893) | (0.988) | (1.092) |

Additionally, yield surfaces of the SDS and base sheet were plotted in Figure 2, and there were no significant differences between them.

![Figure 2. Yield surface for SDS and base sheet](image)

2.3. Forming limit curve
According to the author’s previous works [14], punched dome tests were performed to evaluate the a forming limit of the SDS. Determined forming limit curve of the SDS was compared with that of base
sheet, as shown in Figure 3. Even though the minor strain of the SDS was slightly delayed compared to the base sheet, which was caused by the positive effect of the inserted adhesive on the lubrication, entire trend of the forming limit curves was not different.

![Figure 3. Forming limit curve for SDS and base sheet](image)

2.4. Square cup drawing test setup
Square cup drawing test of SDS were performed to simultaneously evaluate both the stretchability and drawability using a universal sheet metal testing machine of Erichsen GmbH, model 142-40. Apparatus of test tool sets is shown in Figure 4(a). The tests were conducted on square shape specimen with size of 100mm by 100mm, as shown in Figure 4(b). Punch speed and sheet holding force were 0.5mm/s and 150kN, respectively. Upper and lower contact area of the specimens were lubricated by the Teflon film of 0.1mm thickness.

![Figure 4. Apparatus of square cup drawing test: (a) test tools and (b) shape of a specimen](image)

3. Simulation procedure
The FE simulation of the square cup drawing test was conducted using the commercial software LS-DYNA, version R10 [16]. The SDS specimen was regarded as a one continuum body with 1.4 mm thickness, and the characterized SDS mechanical properties were inputted. FE meshes of the square cup drawing tests are shown in Figure 5. Four-node quadrilateral shell elements were used for the all parts. The upper die was meshed using 3,392 elements and the lower die was meshed using 1,440 elements with a mesh size of 5.0 mm by 5.0 mm. The punch was discretized into 1,332 elements, each 5.0mm by 5.0mm. The corner regions of the upper die and punch were finely split to 20 elements. The specimens were discretized into 40,000 elements, each 0.5 mm by 0.5 mm. A surface-to-surface contact method was applied to handle the contact between the punch, die and the specimen. The friction coefficient was
chosen to be 0.15 by assuming a conventional friction condition in sheet metal forming [17]. The upper die, lower die and punch were treated as rigid bodies, whereas the specimen was modelled with deformable bodies. MAT_133_BARLAT_YLD2000 was adopted for the material model of the specimen.

![Figure 5. Finite element meshes of square cup drawing test](image)

**4. Results and discussions**

Failure behaviour of the square cup drawing tests were successfully predicted by the FE simulation, as shown in Figure 6. When a first crack was observed in the test and simulation, the forming was stopped and the comparison between the test and simulation was performed. Crack position of tests indicated by red arrow are same to those of simulation, and the time of crack occurrence was coincided because the overall shape and height of the specimen was not significant difference in the test and simulation when the first crack was observed. Also, cross-sections of the simulation on the AA’ line and BB’ line were compared with the experimental one, and there were no significant differences.

![Figure 6. Comparison between experimental and simulation results](image)
5. Summary
In this study, the mechanical properties of the high strength SDS was successfully characterized, and it was not significantly differed to that of the base sheet. As an example for SDS application on the stretching and drawing, a square cup drawing tests were carried out. Although SDS regarded as a one continuum body in the FE simulation, the characterized mechanical properties of SDS well simulated the square cup drawing tests.

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