Determination of forming limits of high strength sound-deadening laminated sheet

Hyeonil Park1,2, Se-Jong Kim1, Jinwoo Lee1, Daeyong Kim*1

1Materials Deformation Department, Korea Institute of Materials Science, 797 Changwondaero, Changwon, Gyeongnam 515508, Republic of Korea
2Department of Mechanical Engineering, Pusan National University, 2 Busandaehak-ro 63beon-gil, Busan 609-735, Republic of Korea

*daeyong@kims.re.kr

Abstract. High strength sound-deadening laminated sheet consists of high strength steel sheets and a viscoelastic polymeric adhesive with high vibrational damping characteristics. In this study, to evaluate formability of sound-deadening laminated sheet, forming limit curves (FLC) were determined. The high strength sound-deadening laminate sheet was fabricated with dual phase (DP) 590 steel sheets as outer skins and polymeric adhesive as a core by roll bonding process. The punched dome tests (Nakajima tests) were performed with varying specimen width. On the specimen prior to deformation, a stochastic pattern was applied to the surface using a white and black spray. Until the fracture occurs, the strain distribution was measured in the stereo image using digital image correlation (DIC) system. FLC of the laminated was successfully determined by capturing limit strains near fracture as well as calculating them according to the ISO standards. FLC of the laminated sheet is slightly higher than that of DP590 sheet but is not significantly different.

1. Introduction
Recently, as the basic driving performance of the world's vehicles has been leveled up, the riding quality has become an important purchase requirement. Particularly, the vibration and noise are one of the variables that have a great influence on the riding quality, and researches are underway to reduce the vibration and noise of the automotive body during driving in various directions. The sound-deadening laminated sheet manufactured by inserting a thin polymeric adhesive between two steel sheets was introduced as one of them. It has excellent vibration and noise attenuation characteristics due to the polymeric adhesive inserted between the base sheets [1]. The polymeric adhesive is a thin layer with viscoelastic properties, which is effective for vibration damping because it can reduce the vibration by converting the mechanical vibration energy to thermal energy [2]. The damping of laminated sheet is affected by the design properties such as the thickness of the steel sheet and that of the polymeric adhesive, material properties such as the stiffness of the steel sheet and the glass transition temperature of the polymeric adhesive, and operating properties such as frequency and temperature [3]. The parts such as dash panels, oil pan and front floors have been successfully built with the laminated sheet and it will be used extensively in the automotive industry in the future.

However, the behaviour of laminated sheet differs significantly from that of homogeneous steel sheets in the forming process and the understanding of the contact state between the steel sheets during
the forming process is very difficult [4]. Especially, in the drawing or bending process, some areas can be delaminated without failure of the base sheet because of slip between the base sheets depending on large viscoelastic deformation of the polymeric adhesive. So, many researches on the delamination behaviour of the laminated sheet during drawing and bending are underway [5–7].

Furthermore, it is also generally known that in the case of a sandwich sheet in which a relatively thick polymeric adhesive (about 20% to 60% of the base sheet) is inserted, the sliding of the inserted polymeric adhesive affects the formability [8–10]. However, in case of the sound-deadening laminated sheet manufactured by inserting thin-walled polymeric adhesives (less than about 10% of the base sheet), only few studies have investigated the effect of the thin adhesives on the formability of the laminated sheets [11]. In this study, the high strength sound-deadening laminated sheets were manufactured by bonding two DP590 steel sheets with an acrylic based polymeric adhesive with a thin thickness of about 0.05 mm, and the punched dome tests (Nakajima tests [12]) were performed to evaluate the formability of the manufactured laminated sheet.

2 Experimental procedure
2.1 Materials
The base material of laminated sheet in this study is dual phase (DP) 590 high strength steel sheets which have a ferrite matrix containing martensite as a second phase with 0.7 mm thickness supplied by POSCO. The mechanical properties of the DP590 steel sheet measured from the tensile tests along the rolling direction (RD) are listed in table 1.

| Table 1. Mechanical properties |
|-----------------------------|
|                            | E     | YS    | UTS   | εUTS  | εfracture | R-value |
| Steel sheet (DP590)         |       |       |       |       |           |         |
|                            | 210.3 | 351.4 | 649.8 | 19.2  | 27.5      | 0.88    |
| Adhesive (Acrylic)          | 0.72  | 9.97  | 0.45  | 3.12  | 1.66      | 0.32    |

Since the adhesive strength between the polymeric adhesive and the base sheets is influenced by the surface condition of the base sheet, the contact surface of the two base sheets were cleaned. The two base sheets with a clean surface treatment were bonded by inserting the acrylic polymeric adhesive and cured at room temperature under the roll bonding process. The bonding section of the manufactured laminated sheet were observed by the optical microscope as shown in figure 1. The uniaxial tensile tests along the RD were performed on the manufactured laminated sheet and the results were compared with the results of base sheet. The flow curves and the strain variations in the longitudinal and width direction are shown in figure 1. The difference in mechanical properties between the base material and the laminated sheet was not significantly different because the thickness of the adhesive was very thinner than that of the base steel sheet, and the strength of the adhesive was weak. Also, the bidirectional (normal and shear) peel tests were perform to measure the mechanical properties of the inserted polymeric adhesive as listed in table 1. The measured polymeric adhesive E, T and UD are the slope of the adhesive strength-delamination displacement curve, the maximum adhesive strength and the perfect delamination displacement, respectively. The normal mechanical properties which are \( E_N \), \( T_N \) and \( UD_N \) were measured by a U-peel test in which the bonding specimen of the existing T-peel test [13] was modified to a U-shape. The shear mechanical properties that are \( E_S \), \( T_S \) and \( UD_S \) were measured by the single lap joint test standardized by ASTM [14].
2.2 Test setup
The Nakajima tests were performed to evaluate the formability of the material using a universal sheet metal testing machine of Erichsen GmbH, model 142-40. The apparatus of the testing machine is shown in figure 3(a) and the tool sets are shown in figure 3(b). The diameter of the hemispheric punch was 100mm and the radius of the bead was 5mm. During the test, when the upper die pressed the lower die, the beads of the upper and lower dies held the specimen, and the punch was moved upwards to stretch the specimen. The cross-head speed and the holding force were 0.5mm/s and 150kN respectively for all tests. In order to decrease the friction between the specimen and tools, the graphite grease on both sides of the Teflon film of 0.1mm thickness was applied to the contact area between the tools and specimen. The specimens were manufactured in accordance with the ISO 12004-2 standard [15]. For steel materials, the RD should be perpendicular to the parallel part of the specimen, and the length of the parallel part of the specimen should be longer than 25% of the punch diameter. To account for the formability in various forming mode, the specimens with 6 types of width were manufactured, as shown in the figure 4. Three specimens each of the laminated sheet and the base sheet were tested with each width condition respectively.

2.3 Determination of forming limits
The fracture based forming limit curve (FLC) was obtained by curve fitting the major-minor strain values of the fracture point for each width condition. Also, in order to calculate the necking based FLC defining the necking point, the following procedures referenced by the ISO standard [15] were carried out. The three sections were created perpendicular to the crack and the distributions of the major-
minor strains were measured along these sections. The average strains of the several points on both sides of the crack along the sections were calculated using the evaluation of the inverse best fit parabola on the “bell-shaped curve” and the necking based FLC conditions were obtained from the curve fitting of the calculated average strains with respect to each width condition.

Figure 3. Configuration of the equipment for the punched dome tests: (a) DIC system and testing machine, (b) tool sets

Figure 4. Geometry of the specimens for the Nakajima tests

3 Results
The effective strain distribution of the base sheet and the laminated sheet before fracture and the deformed shape of that after fracture for each width condition are shown in figure 5. The fracture occurred at the center of specimen (the red arrow in figure 5) due to the good lubrication condition under all specimens and the crack was parallel to the direction of rolling. The fracture based FLC and the necking based FLC of the laminated sheet and the base sheet are shown in the figure 6. The necking based FLC was 25% lower than fracture based FLC because it fitted smoothly with a “bell-shaped curve” and defined necking conservatively. Overall, the FLC of the laminated sheet was somewhat higher than that of the base sheet. Especially, the difference of the biaxial mode (the specimen width of 200mm) was larger than the other modes. There are following two possible reasons for this. First, the thicker material thickness of the laminated sheet affected the formability improvement. Second, the viscosity behavior of the inserted polymeric adhesive had a positive effect.
on the lubrication between the base sheets. It is necessary to analyze in detail the reasons for the difference of formability by methods such as simulation in the future.

Figure 5. Effective true strain (log.) distribution and the crack appearance of the deformed specimen: (a) the laminated sheet, (b) the base sheet.

Figure 6. Comparison of the FLC between the laminated sheet and the base sheet

4 Summary
The sound-deadening laminated sheets were manufactured by roll bonding two DP590 steel sheets with the acrylic polymeric adhesive. In order to evaluate the formability of the sound-deadening laminated sheet, the Nakajima tests were performed with varying specimen widths and the strain distributions on each specimen during the test were measured by the DIC system. Finally, the fracture based FLC and necking based FLC were obtained and comparison of the FLCs between the laminated sheet and the base sheet was carried. The necking based FLC conservatively evaluated the formability of the material compared to the fracture-based FLC. Overall, the FLC of the laminated sheet was
somewhat higher than that of the base sheet was not significantly different. Especially, the difference of the biaxial mode (the specimen width of 200mm) was larger than the other modes.

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