*International Journal of Automotive Technology*, Vol. 7, No. 4, pp. 485–492 (2006)

1229–9138/2006/028–12

# SERRATION MECHANISM OF AA5182/POLYPROPYLENE/AA5182 SANDWICH SHEETS

K. J. KIM*

CAE Team, Ssang Yong Motor Company, 150-3 Chilgoi-dong, Pyungtaek-si, Gyeonggi 459-711, Korea

*(Received December 26, 2005; Revised April 19, 2006)*

**ABSTRACT**–The AA5182/polypropylene/AA5182 (AA/PP/AA) sandwich sheets have been developed for application to automotive body panels in future lightweight vehicles with significant weight reduction. It has been reported that the AA5182 aluminum sheet shows Lüders band because of dissolved Mg atoms that cause fabrication process problem, especially surface roughness. The examination of serration behavior has been made after the tensile deformation of the AA/PP/AA sandwich sheets as well as that of the AA5182 aluminum skins at room and elevated temperatures. All sandwich sheets and the AA5182 aluminum skin showed serration behavior on their flow curves. However, the magnitude of serration was significantly diminished in the sandwich sheet with high volume fraction of the polypropylene core. According to the results of the analysis of the surface roughness following the tensile test, Lüders band depth of the sandwich sheet evidently showed lower than that of the AA5182 aluminum skin. The strain rate sensitivity, m-value, of the AA5182 aluminum skin was –0.006. By attaching these skins to the polypropylene core, which has relatively large positive value of 0.050, m-value of the sandwich sheets changed to the positive value. The serration mechanism of the sandwich sheets was quantitatively investigated in the point of the effect on polypropylene thickness variation, that on the strain rate sensitivity and that on the localized stress state.

**KEY WORDS :** Aluminum sandwich sheet, AA5182 skin, Polypropylene core, Serration behavior, Lüders band, Strain rate sensitivity

## 1. INTRODUCTION

The lightweight vehicles have become the center of attention, and the effort to replace from a steel sheet to a lighter material for automotive body panels has been made. Accordingly, 5xxx aluminum alloy sheets have been currently applied to some high performance automobiles, and various metal-plastic laminates and sandwich sheets have been developed in order to reduce the vehicle weight and/or improve the sound-deadening properties of the materials (Veenstra, 1998; Shin *et al.*, 1999). The AA5182/polypropylene/AA5182 (AA/PP/AA) sandwich sheet consists of two 5182 aluminum skin with a thermoplastic polypropylene core in between in order to achieve the lightest weight per unit area when flexural rigidity is the design criterion. Since the sandwich sheet is made by roll bonding polypropylene with low density for a core and aluminum skins sheet with relatively high strength together, it has great potential materials in applying to automotive body panels due to its lightweight materials (Veenstra, 1998; Shin *et al.*, 1999; Kim, 2005).

The main element for 5xxx aluminum alloys, which are excellent in strength and formability comparing to commercially available other aluminum alloys is Mg. However, Lüders band was observed on the surface of these 5xxx aluminum alloys sheet resulted from forming operation, and serration behavior or serration phenomena was observed on the stress-strain flow curve resulted from tensile test (Robinson and Shaw, 1992, 1994; Han *et al.*, 1996). Such Lüders band causes roughness on surface, and thus its application for automotive panels causes a severe problem. Usually, serration behavior is described by Portevin-Le Chatelier effect, which resulted from the repeated process of lock and release as follows. When diffusivity of solute atoms in an alloy element is full enough during deformation, dislocations are locked by solute atoms, and these dislocations with solute atoms are released abruptly to continue deformation (Han *et al.*, 1996). Serration behavior could be reduced or exterminated according to the change of the initial strain rate that can alter mobility of dislocations, and/or the change of temperature that can vary diffusivity of solute atoms. Although there have been many studies on serration behavior of the 5xxx aluminum alloys (Robinson and Shaw, 1992, 1994; Han *et al.*, 1996; Park and Morris, 1993; Ling and

---

*Corresponding author.* e-mail: kjkimfem@smotor.com

McCormick, 1993), that on serration behavior of the AA/PP/AA sandwich sheet have not yet been examined. Since polypropylene does not show any serration on its flow curve, the magnitude of serration in the AA/PP/AA sandwich sheet would decrease as the volume fraction of polypropylene core increases. In the present study, therefore, serration mechanism of AA/PP/AA sandwich sheets was carefully examined. The examination of serration behavior has been made following the tensile deformation of the AA/PP/AA sandwich sheets and the 5182 aluminum skin at room and elevated temperatures. The strain rate sensitivity of the 5182 aluminum skin, polypropylene core and the AA/PP/AA sandwich sheets were also examined for comparison. The surface roughness of the specimens of the 5182 aluminum skin and AA/PP/AA sandwich sheets were measured after tensile test. The serration reduction of the sandwich sheets was quantitatively investigated in the point of the effect on the variation of polypropylene thickness and the strain rate sensitivity.

## 2. EXPERIMENTAL PROCEDURES

5182 aluminum alloy (AA5182) skins rolled prior to annealing at 350°C for 2 hrs were chosen as skin materials in the present study because of their mechanical properties and formability. Polypropylene has a density of 0.9 g/cm$^3$, relatively low cost and good high temperature resistance compared to other commercially available plastics. A schematic diagram of the AA/PP/AA sandwich sheet is shown in Figure 1. The sandwich sheet was prepared by roll bonding of two aluminum skins with a pre-rolled polypropylene sheet in between at 140°C. Film type ethylene vinyl acetone (EVA) adhesives were inserted between the aluminum skin and the polypropylene core in order to achieve the appropriate bond strength. Four AA/PP/AA sandwich sheets with different core dimensions were employed in the present study in order to examine the effects of core thickness on serration behavior of the sandwich sheet. The specifications of four AA/PP/AA sandwich sheets used in the present study are summarized in Table 1.

Table 1. specifications of the AA/PP/AA sandwich sheets.

| Designation of sandwich sheet | | 1.0SW | 1.2SW | 2.4SW | 3.4SW |
|---|---|---|---|---|---|
| AA5182 Skin | Thick. (mm) | 0.2 | 0.2 | 0.2 | 0.2 |
| Polypropylene core | Thick. (mm) | 0.6 | 0.8 | 2.0 | 3.0 |
| Sandwich sheet | Thick. (mm) | 1.0 | 1.2 | 2.4 | 3.4 |

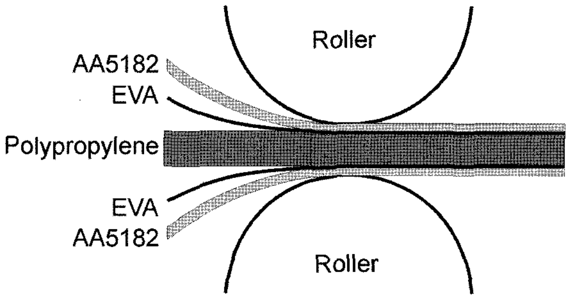


Figure 1. Schematic diagram of roll bonding process for Al/PP/Al sandwich sheet.

In order to examine serration behavior of the AA/PP/AA sandwich sheet, both tensile and strain rate sensitivity tests were carried out. Sheet type tensile specimens with a sub-size gage length of 25 mm were prepared from 5182 aluminum skin and the polypropylene core as well as the AA/PP/AA sandwich sheets. Tensile tests were carried out on an Instron machine with initial strain rates of $5\times10^{-4}$/sec~$5\times10^{-2}$/sec following as the test method of ASTM E8. Tensile tests were also carried out on the 1.2SW sandwich sheet specimens at 80°C, 120°C and 160°C in order to observe the variation of serration behavior at elevated temperatures. For tensile tests at elevated temperatures, a split type tube furnace was used and the tensile specimens were kept at the test temperature for 20 min. before test. Strain rate sensitivity specimens were used from 5182 aluminum skin and the polypropylene core as well as the AA/PP/AA sandwich sheets with the same size and machine of tensile tests. Strain rate sensitivity tests were conducted by strain rate change method. A tensile load was applied with the strain rate change from $5\times10^{-4}$/sec~$5\times10^{-2}$/sec and the stress caused by an abrupt strain rate change was measured. In order to compare the surface roughness of the 5182 aluminum skin and sandwich sheet specimens after tensile tests, roughness caused by Lüders band were measured.

## 3. EXPERIMENTAL RESULTS

### 3.1. Serration Behavior Following as Temperatures

Tensile tests were carried out on the AA/PP/AA sandwich sheets as well as the AA5182 skin and the polypropylene core at room temperature. The typical stress-strain curves obtained from AA5182 skin, polypropylene core and 1.2SW sandwich sheet are shown in Figure 2(a). In case of AA5182 skin, serration behavior was showed on almost all strain sections and many Lüders band were observed on the test specimens. Although the 1.2SW sandwich sheet showed serration behavior on their flow curves, the magnitude of serration was significantly diminished in the sandwich sheet. The stress-strain curve

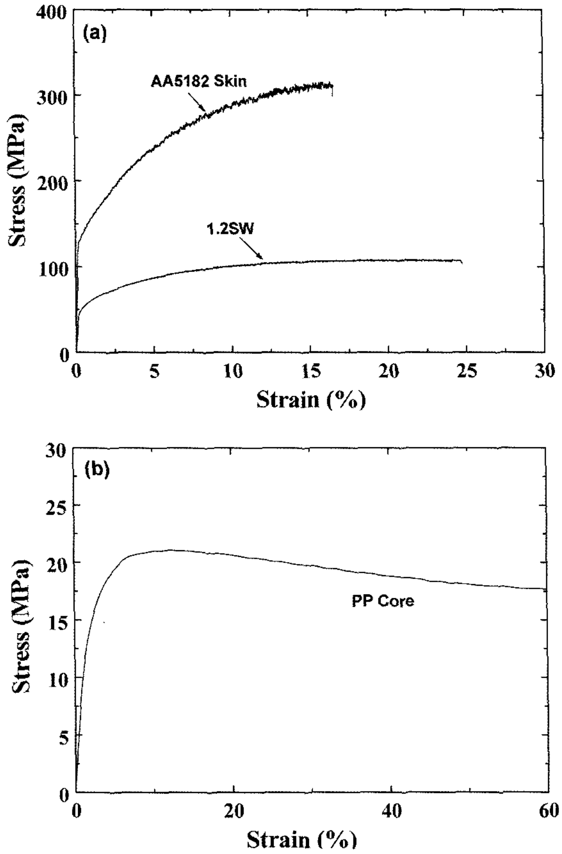


Figure 2. Tensile stress-strain curves of (a) AA5182 skin and 1.2SW sandwich sheet and (b) polypropylene core.

of the polypropylene core was quite different from that of the AA5182 skin as shown in Figure 2(b). The flow curve reached the maximum stress soon after yielding and showed work softening behavior. Although it was not completely shown in the stress-strain curve, the tensile elongation of the polypropylene core was more than 500%.

In order to examine serration behavior of the AA/PP/AA sandwich sheet affecting on temperatures, it is necessary to perform tensile tests at elevated temperatures. In the present study, the tensile properties of the 1.2SW sandwich sheets were examined at 80°C, 120°C and 160°C, respectively. Figure 3 shows the stress-strain curves of the 1.2SW sandwich sheet obtained at four different temperatures. Serration behavior of the sandwich sheets decreases or exterminates with the increase of the temperature as shown in Figure 3. In detail, serration behavior of almost all sections of strain in the 1.2SW sandwich sheet can be observed at room temperature and that is observed after the critical strain (initial strain sowing serration behavior) of 17% at 80°C. However serration behavior of that did not occur at 120°C and 160°C, indicating that when the diffusivity of solute atoms in an alloy element is full enough during deformation caused by elevated temperature, dislocations lose the chance to lock many solute atoms, and these dislocations are released from the solute atoms freely with the increase of the strain (Han *et al.*, 1996). Therefore, according to the change of temperature, the critical strain of serration behavior increases as the diffusivity increases. As expected, the yield and ultimate tensile strengths of the sandwich sheets decreased with the rise in temperature and the tensile elongation of those increased with the rise in temperature as shown in Figure 3.

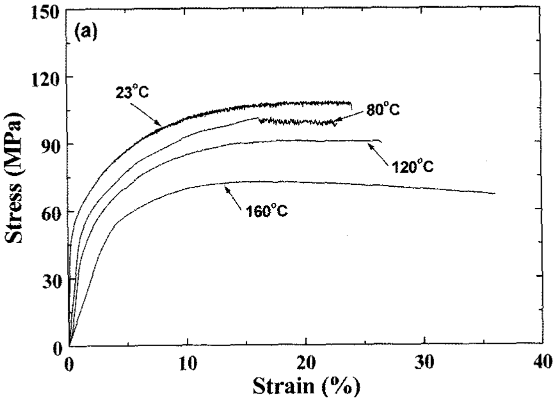


Figure 3. Stress-strain curves of the 1.2SW sandwich sheets.

### 3.2. Strain Rate Sensitivity

In order to clarify the diminution reason of the serration magnitude and to analyze the stress amplitude (serration amplitude) quantitatively, strain rate sensitivity tests were carried out. An initial strain rate (test speed) of $5 \times 10^{-4}$/sec was initially applied to the specimens of the AA5182 skin and the sandwich sheet until 5% tensile strain and the strain rate of $5\times10^{-2}$/sec was applied to specimens of those after 5% tensile strain, then it was restored to the original state of the strain rate after 8% tensile strain. The same strain rates were applied to the polypropylene core, but the strains of the abrupt strain rate change were determined at 10% and 15%, respectively for the strain rate variation at perfect plastic regions for the polypropylene core. The stress caused by an abrupt strain rate change was measured. Figure 4 shows the strain rate sensitivity on the stress-strain curves of AA5182 skin, polypropylene core and 1.2SW sandwich sheet. While the value of the strain rate sensitivity of AA5182 skins is negative, that of the polypropylene core and the sandwich sheet is positive, respectively.

### 3.3. Lüders Band Observation

Since serration behavior of sandwich sheets was much smaller than that of the AA5182 skin, it was expected the

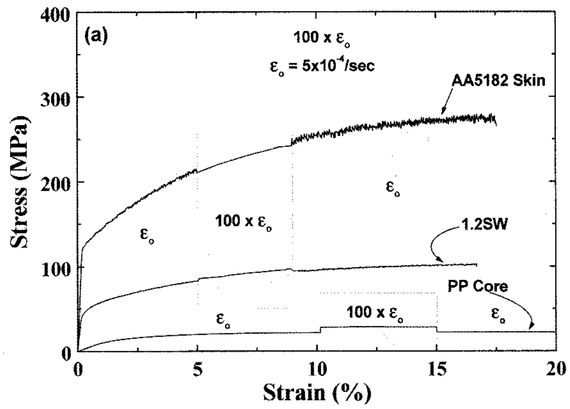
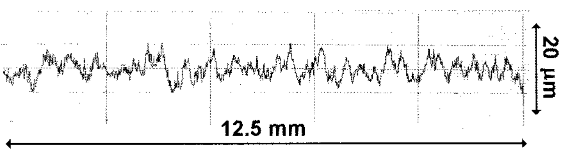
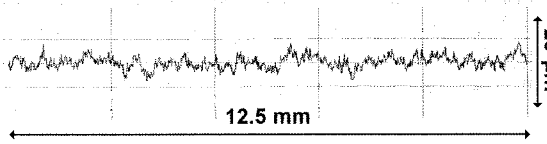


Figure 4. Strain rate sensitivity on stress-strain curves of the AA5182 skin, polypropylene core and 1.2SW sandwich.



(a) AA5182



(b) 1.2SW

Figure 5. Surface roughness of the AA5182 skin and 1.2SW sandwich sheet.

number and the depth of Lüders band would reduce. The surface roughness difference caused by Lüders band between AA5182 skin and the sandwich sheet was examined. Figure 5(a) and (b) shows the measured results of the surface roughness of the AA5182 skin and 1.2SW sandwich sheet. The surface of the AA5182 skin is rougher than that of the 1.2SW sandwich sheet, which indicates that the surface roughness of the sandwich sheet caused by Lüders band was decreased with adhesion of polypropylene core.

Type the contents of the section here. Type the contents of the section here. Type the contents of the section here. Type the contents of the section here. Type the contents of the section here. Type the contents of the section here. Type the contents of the section here.

## 4. DISCUSSION

To consider the serration behavior in sandwich sheets there are four aspects that are relevant, namely, stress amplitude, thermal dependency, negative strain rate sensitivity and Lüders band (localized deformation band). The correlation among these will be considered.

### 4.1. Variations of Serration Behavior Following Tensile Variables

In general, the flow curve of metals can be estimated by the differential expression of the flow stress for the explanation of flow localization (Semiatin and Jonas, 1983). The differential of the flow stress (***dσ***) which is dependent on the strain ($\varepsilon$), the strain rate ($\dot{\varepsilon}$) and temperature (***T***) is defined as Equation (1). In present study, tensile variables affecting serration behavior showing unstable flow localization are thoroughly discussed according to the following Equation (1),

$$d\sigma = \left(\frac{\partial\sigma}{\partial\varepsilon}\right)_{\dot{\varepsilon},T} d\varepsilon + \left(\frac{\partial\sigma}{\partial\dot{\varepsilon}}\right)_{\varepsilon,T} d\dot{\varepsilon} + \left(\frac{\partial\sigma}{\partial T}\right)_{\varepsilon,\dot{\varepsilon}} dT \qquad (1)$$

The main purpose of tensile tests was to analyze the tensile parameters that control serration behavior of the AA/PP/AA sandwich sheet and to find out the effect and the difference on tensile variables between the 5182 aluminum skin and sandwich sheets.

In case of room temperature tensile tests with various strain rates, the critical strain ($\varepsilon_c$) of the AA5182 skins increased from 0.7% to 4.4% as the initial strain rate increases from 5x10$^{-4}$/sec to 5x10$^{-2}$/sec and the results are summarized in Table 2. As mentioned previously, these phenomena can be explained with the interactions between solute atoms and dislocations as follows. If the strain rate was too fast, since the diffusivity of dissolved Mg solute atoms was not full enough to follow the speed of moving dislocations lock and release between solute atoms and dislocations could not be activated and thus the critical strain increases as the strain rate increases. The critical strain of the 1.2SW sandwich sheets increased from 1.7% to 9.0% as the initial strain rate increased from 5x10$^{-4}$/sec to 5x10$^{-2}$/sec and it was higher than that of the AA5182 skin all the range of tested strain rate as shown in Table 2. Each of data indicates the average of the results obtained from more than five specimens.

In case of tensile tests at elevated temperatures, the critical strain of the 1.2SW sandwich sheets at 80°C was 17%, moreover, serration behavior was not shown over 120°C. Therefore, the process variables affecting surface roughness problem which occurs while working and forming to manufacture the desired shape of the AA/PP/AA sandwich sheets should be effectively controlled by temperature than strain rate.

The degree of serration behavior can be commonly compared using critical strain and it is defined Equation (2) as follows (Han *et al.*, 1996; Huang and Gray III, 1990),

$$\rho_m C_v = K_1\dot{\varepsilon}\exp(Q/RT) \qquad (2)$$

Table 2. Initial strain showing serration behavior, critical strain ($\varepsilon_c$).

| Specimens | Critical strain (%) | | |
|---|---|---|---|
| | at $5\times10^{-4}$/sec | at $5\times10^{-3}$/sec | at $5\times10^{-2}$/sec |
| AA5182 Skin | 0.7 | 1.7 | 4.4 |
| 1.2SW Sandwich | 1.7 | 4.0 | 9.0 |

where, $\rho_m$, $C_v$ and $\dot{\varepsilon}$ are the density of mobile dislocation, vacancy concentration and the strain rate, respectively and $K_1$, $Q$, $R$ and $T$ are constant, activation energy, gas constant and temperature, respectively. Both vacancy concentration and the density of mobile dislocation are given by the following Equation (3) and Equation (4).

$$C_v = A\varepsilon^m \tag{3}$$

$$\rho_m = B\varepsilon^\beta \tag{4}$$

From the relationship between Equation (3) and Equation (4), $m+\beta$ parameter can be determined as the following Equation (5),

$$\varepsilon_c^{(m+\beta)} = K_2\dot{\varepsilon}\exp(Q/RT) \tag{5}$$

Figure 6 compares the strain rate dependent parameter, $m+\beta$ of the AA5182 and 1.2SW sandwich sheet acquiring from Equation (5) using the critical strain versus the strain rate with the AA3004, the AA8090 and the AA2090 aluminum rolled alloys published in other reports (Park and Morris, 1993; Huang and Gray III, 1990). The $m+\beta$ of the AA5182 skin and 1.2SW sandwich sheet is 2.42 and 2.79, respectively. The strain rate dependent parameter of the AA5182 skin is nearly same to the AA8090-T4. That of the AA2090-T8 which was naturally aged for 4 years being appeared no serration behavior was 3.45 (Huang and Gray III, 1990) and it was most highest among other alloys. The comparisons indicate that because $m+\beta$ of the sandwich sheet is higher than that of the AA5182 skin it is another evidence that serration behavior of the sandwich sheet is fairly suppressed comparing with the AA5182 skin.

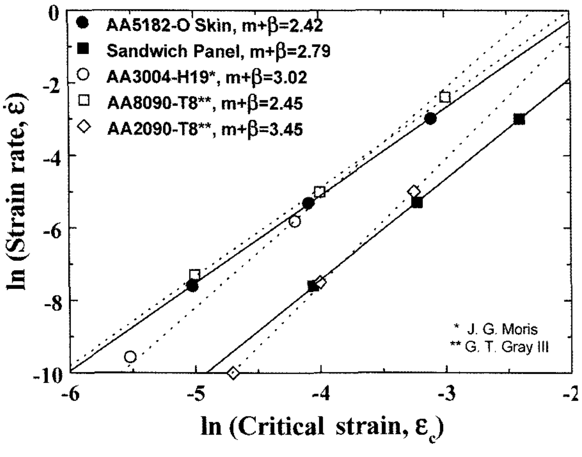


Figure 6. Comparison on the strain rate dependent parameter, $m+\beta$ of the AA5182 and 1.2SW sandwich sheet with various rolled sheets.

4.2. Analysis of Strain Rate Sensitivity

The flow stress of the AA5182 skins decreased as the strain rate increased, whereas that of the AA/PP/AA sandwich sheets was increased as the strain rate increased as previously shown in Figure 4. It is caused by the strong dependency of the polypropylene core, because the flow stress of the polypropylene core was evidently increased as the strain rate increased. In addition, serration behavior of the sandwich sheets was significantly diminished comparing to the AA5182 skin and the occurrence frequency of serrated flow is decreased as the strain rate increased. As the formation of Lüders band is relevant to the flow localization following repetitions of stress fluctuations, serration behavior is closely related to the strain rate sensitivity. The values of the strain rate sensitivities of the metal sheets is commonly positive, on the contrary, if the metal sheets showed serration behavior on their flow curves, the value of the strain rate sensitivities would be negative. The experimentally measured strain rate sensitivities of the AA5182 skin, the polypropylene core and the 1.0SW, the 1.2SW, the 2.4SW and the 3.4SW sandwich sheets are summarized in Table 3. For all sandwich sheets the values of the strain rate sensitivities are positive from the fact that those of the AA5182 skin and the polypropylene core are –0.006 and 0.050, respectively. It is known that the metal sheets, which show serration behavior, have a negative value of the strain rate sensitivities because of the repetition of localized softening and propagation caused by Lüders band (Huang and Gray III, 1990; Park and Shin, 1995). Accordingly, these results indicate that since strain rate sensitivities of the sandwich sheets are all positive values, and those of the sandwich sheets are increased as the volume fraction of the polypropylene core increased it is another evidence that serration behavior of the sandwich sheet is fairly suppressed caused by high strain rate sensitivity of the polypropylene core. Therefore, the strain rate sensitivity increases with increasing the thickness of the sandwich sheet. It is natural that the strain rate sensitivity of the sandwich sheets should increase with increasing the volume fraction of the polypropylene core because only the volume fraction of the polypropylene core sheet increased without increasing the thickness of the aluminum skin sheet.

Table 3. experimentally measured strain rate sensitivities.

| Specimens | Strain rate sensitivity (= $\Delta\ln\sigma/\Delta\ln\dot{\varepsilon}$) | |
|---|---|---|
| AA5182 skin | −0.006 (at 5% T. S.) | −0.006 (at 8% T. S.) |
| PP core | – | −0.050 (at 10% T. S.) |
| 1.0SW | 0.004 (at 5% T. S.) | −0.002 (at 8% T. S.) |
| 1.2SW | 0.010 (at 5% T. S.) | −0.007 (at 8% T. S.) |
| 2.4SW | 0.021 (at 5% T. S.) | −0.015 (at 8% T. S.) |
| 3.4SW | 0.025 (at 5% T. S.) | −0.026 (at 8% T. S.) |

*T. S.: tensile strain.

### 4.3. Serration Behavior of Sandwich Sheets and Lüders band Formation

Since the serration behavior of the sandwich sheet and its surface roughness decreased as shown in Figure 5, the Figure 7 shows comparisons for the load-displacement curves of the sandwich sheet, the 5182 aluminum skin sheet and the polypropylene core sheet in order to explain the deformation mechanism of the serration behavior. In these curves, the 1.2SW represents the load-displacement curve of the sandwich sheet manufactured by the same method as before and AA5182+AA5182 represents that of the simply overlapped two 5182 aluminum skin sheets without adhesion. In addition, AA5182+PP represents that of the overlapped 5182 aluminum skin sheet and the polypropylene sheet without adhesion. In case of AA5182+ AA5182, the load drop amplitude with displacement was the largest compared to that of the single 5182 aluminum skin sheet or other sheets. When overlapped two 5182 aluminum skin sheets are gripped and tensile-loaded, two aluminum skin sheets have no influence over each other due to be gripped without adhesion and the load drop amplitudes of them increase. The load drop amplitude of the 1.2SW sandwich sheet which consists of two 5182 aluminum skin sheets and the polypropylene core sheet with adhesion is much smaller than that of AA5182+ AA5182 sheet. The load drop amplitude of AA5182+PP is similar to that of a single 5182 aluminum skin sheet because it is gripped and tensile-loaded without adhesion.

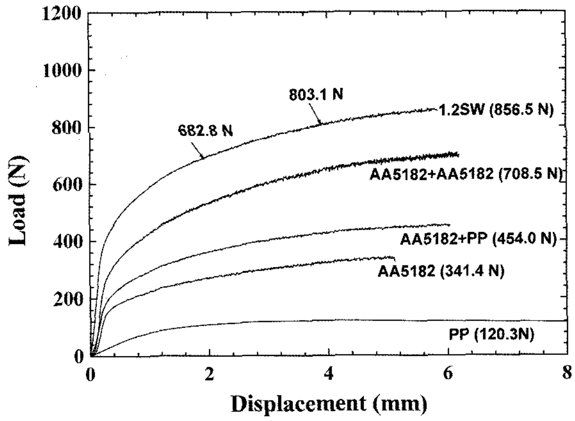


Figure 7. Load-displacement curves of various sheets.

As shown in Figure 7, the maximum tensile loads of the 1.2SW sandwich sheet and the 5182 aluminum skin sheet are 856.5 and 341.4N, respectively. In case of the 1.2SW sandwich sheet, the sum of the maximum tensile load of the upper/lower skin sheet (341.4N×2 piece = 642.8N) and the polypropylene core sheet (120.3N) becomes 803.1N. Namely, the difference between this sum and the actual maximum tensile load of the 1.2SW sandwich sheet is 53.4N. It resulted from the high adhesion strength of the 1.2SW sandwich sheet. The surface roughness by Lüders band of the sandwich sheet decreased compared to the 5182 aluminum skin sheet as shown in Figure 5. In addition, the load drop amplitude due to the serration behavior of the 1.2SW sandwich sheet after tensile test at the load-displacement curves decreased compared to overlapped two 5182 aluminum skin sheets as shown in Figure 5. These results are caused by following reasons. Typically, it has been considered that the formation of Lüders band would be a kind of planar slip [13]. That is, the local deformation by the interaction between dislocations and solute atoms is created on the specimen surface having planar slip shape and this leads to the stress drop and again work hardening occurs at the sill part of Lüders band and Lüders band propagates to the neighbor band and this procedure is repeated. At this time, Lüders band with no more work hardening is softening more and more and then it makes the unstable deformation behavior and reaches the abrupt reduction of the cross section area to the fracture. In addition, through the investigation of Figure 5, the number of valleys of the 5182 aluminum skin sheet and the 1.2SW sandwich sheet were 105 and 133, respectively. Namely, the frequency of valleys in 1.2SW sandwich sheet was higher by 27% than that in 5182 aluminum skin sheet. In addition, the surface roughness of the 5182 aluminum skin sheet and the 1.2SW sandwich sheet were 5.1 $\mu$m and 3.9 $\mu$m, respectively. Therefore, the surface roughness of the 1.2SW sandwich sheet was lower by 31% than that of the 5182 aluminum skin sheet. In case of the 1.2SW sandwich sheet, the surface roughness decreased and the frequency of valleys increased compared to the 5182 aluminum skin sheet, moreover, the degree of decreasing surface roughness and the frequency of increasing valleys were similar. That is, because the sandwich sheet is adhered with the polypropylene core sheet, the polypropylene core sheet, which has high strain rate sensitivity, accommodates the deepening of Lüders band, and this makes Lüders band to propagate to other bands though the skin sheet has enough work hardening. Therefore, the frequency of valleys of sandwich sheet is denser and more frequent than that of the 5182 aluminum skin sheet.

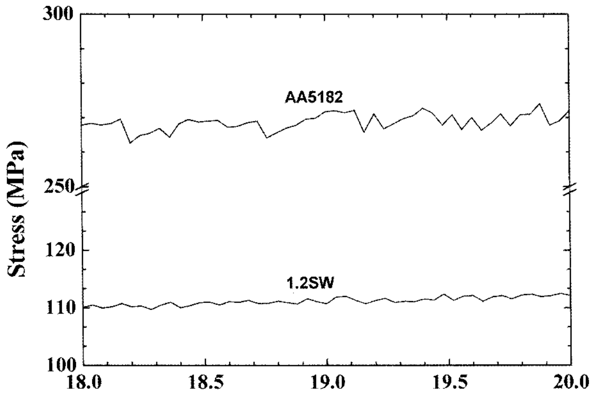
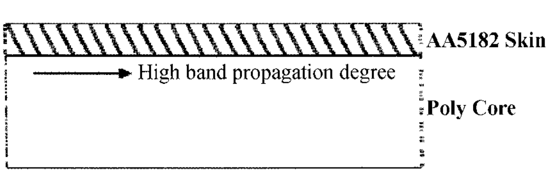
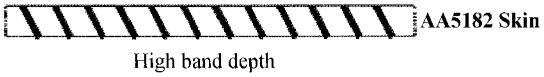


Figure 8. Amplified stress-strain curves of AA5182 skin and 1.2SW sandwich sheet.



(a) Cross section part of sandwich sheet



(b) Cross section part of AA5182 skin

Figure 9. Idealized slip line of (a) cross section part of sandwich sheet and (b) cross section part of AA5182 skin.

Figure 8 shows the amplified stress-strain curves of the 5182 aluminum skin sheet and the 1.2SW sandwich sheet (the tensile strain: 18–20%, the stress: 100–300 MPa). The stress amplitude of the serration behavior in case of the 1.2SW sandwich sheet severely decreased compared to that in the 5182 aluminum skin sheet, but on the other hand, the frequency for the stress amplitude of the serration behavior in case of the 1.2SW sandwich sheet was observed to be high compared to the 5182 aluminum skin sheet. These results were similar tendency to the frequency of valleys from the measured results of the surface roughness.

Figure 9 shows the idealized model of the slip system, which occurs by deformation in the thickness section (cross section) of the 5182 aluminum skins and 1.2SW sandwich sheets. It synthesizes the measured results of the serration behavior with the surface roughness in 5182 aluminum skin sheet and 1.2SW sandwich sheet. The deepening of valleys on the surface roughness of the 5182 aluminum skin sheet is suppressed by the stability of the polypropylene core sheet and the interface region between the 5182 aluminum skin sheet and the polypropylene core sheet. In addition, the band depth of the sandwich sheet is low but the band propagation in polypropylene core sheet occurs more frequently than that in the 5182 aluminum skin sheet by propagating its band to the other place to receive the deformation continuously.

## 5. CONCLUSIONS

In order to investigate serration mechanism of the AA/PP/AA sandwich sheets, stress amplitude, thermal dependency, strain rate sensitivity and Lüders band (localized deformation band) were examined in the present study as well as those of the 5182 aluminum skin and the polypropylene core at room and some cases at elevated temperatures and the correlation among these was performed. The following conclusions could be made from the present study.

(1) The magnitude of serration was significantly diminished in the AA/PP/AA sandwich sheet comparing to the AA5182 skin with high volume fraction of polypropylene core. The reduction degree of serration behavior of the AA/PP/AA sandwich sheet could be experimentally measured and quantitatively evaluated as follows; tendency of the flow stress increase as the strain rate increases, high strain rate dependency parameter (*$m+\beta$* of the AA5182 skin and the 1.2SW sandwich sheet is 2.42 and 2.79, respectively), positive strain rate sensitivity (The AA5182, polypropylene core and 1.2SW sandwich sheet is –0.006, 0.050 and 0.007, respectively), the reduction of the surface roughness by Lüders band on the sandwich sheets.

(2) The process variables affecting the problem of surface roughness which occurs while working and forming to manufacture the desired shape with the AA/PP/AA sandwich sheets should be effectively controlled by temperature than that by strain rate.

(3) The serration behavior and surface roughness were reduced with increasing the thickness of the sandwich sheet because of two reasons. One is that the polypropylene core sheet with increasing its thickness can endure most portions of the load in the sandwich sheet. The other is that the load which is applied to the 5182 aluminum skin sheet is dispersed by means that some portions of load is absorbed in the adhesion load.

## REFERENCES

Han, G., Choi, I. D. and Kang, S. B. (1996). Effect of the factors on the formation of Lüders line in Al-Mg alloys. *J. Korean Inst. Met. & Mater.* **34**, **4**, 470–477.

Huang, J. C. and Gray III, G. T. (1990). Serrated flow and negative rate sensitivity in Al-Li base alloys. *Scripta Metall*, **24**, 85–90.

Kim, K. J. (2005). Plastic strain ratios and planar anisotropy of AA5182/Polypropylene/AA5182 sandwich sheets. *Int. J. Automotive Technology* **6**, **3**, 259–268.

Ling, C. P. and McCormick, P. G. (1993). The effect of temperature on strain rate sensitivity in an Al-Mg-Si alloys. *Acta Metall. Mater.* **41**, **11**, 3127–3131.

Park, D. and Morris, J. G. (1993). The portevin-Le Catelier effect in an Al-Mn-Mg alloy. *Scripta Metall.*, **29**, 365–369.

Park, S. C. and Shin, K. S. (1995). Serration behavior of 2090 Al-Li alloys. *J. Korean Inst. Met. & Mater.* **33**, **6**, 743–749.

Robinson, J. M. and Shaw, M. P. (1992). The influence of specimen geometry on the Portevin-Le Chatelier effect in an Al-Mg alloy., *Mat. Sci. & Eng.* **A159**, 159–165.

Robinson, J. M. and Shaw, M. P. (1994). Observations on deformation characteristics and microstructure in an Al-Mg alloy during serrated flow. *Mat. Sci. & Eng.* **A174**, 1–7.

Semiatin, S. L. and Jonas, J. J. (1983). Formability and workability of metals. *ASM Series in Metal Processing*, Ohio, 51–116.

Shin, K. S., Kim, K. J., Choi, S. W. and Rhee, M. H. (1999). Mechanical properties of aluminum/polypropylene/aluminum sandwich sheets. *Metals and Materials* **5**, **6**, 613–618.

Veenstra, E. W. (1998). Aluminum-plastic-aluminum sandwich sheet for maximum weight reduction in body panels. *SAE Paper No.* **930706**, 1–10.