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ANALYTICAL AND NUMERICAL STUDIES OF FORMABILITY OF METAL/POLYMER/METAL SANDWICH SHEETS

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Abstract. The aim of this study is to analyze formability of three-layer metal/ polymer/metal sandwich sheets. For this purpose, forming limit curves (FLCs) of sandwich sheets with particular configurations were determined using two different approaches, namely an anisotropic GTN model and a modified M–K model. Both GTN and M-K models use mechanical properties of separate layers instead of an equivalent property for the whole sandwich sheet. Effects of thickness, material, and sequence (with respect to the forming punch) of the metallic skin layers on the FLCs of the sandwich sheets were also studied. The results showed that, all of the considered parameters had significant effects on formability of the sandwich sheets. Furthermore, it was found that, the sandwich sheets can have their formability improved by increasing the thickness of the layers and appropriately selecting the layering sequence.

Key words: GTN model, M-K model, Nakazima test, formability, forming limit curve, sandwich sheet.

1. INTRODUCTION

Sandwich sheets are composed of metallic, polymeric or composite layers bonded together by gluing or hot- or cold-rolling [1]. Because of their advantages such as lightweight, good formability, sound and vibration damping and heat isolation, the sandwich sheets are attractive candidates for applications in different industries, e.g. automobile and aerospace. One major demand in application of sandwich sheets, especially in automotive industry, is high formability. Many works have been done to assess the formability of sandwich sheets, some of which will be reviewed in the following.

Dicello [2] and Link [3] experimentally studied the formability of steel/ polypropylene/steel sheets. They conducted different types of experiments such as deep drawing, hole expansion, cutting, and hemispherical punch stretching on sandwich sheets with different thicknesses of layers. The results of these experiments showed that, the sandwich sheets present superior formability over single-layer steel sheets. Similar investigations on three-layer aluminum 5182/polypropylene/

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aluminum 5182 sheets resulted in analogous conclusions [4]. Sokolova *et al.* [5] analyzed formability of sandwich sheets whose skin layers were made from dissimilar materials (aluminum and steel). They conducted Ericson and deep drawing tests on the sheets, finding lower formability for sandwich sheets with dissimilar skins rather than those of two steel skins. In a similar study, the effect of polymeric core layer thickness on the formability of steel/polymer/steel sheets were studied [6]. It was observed that, die geometry and the thickness of the core layer have significant effects on the sheet fracture. Harhash and Palkovski [7, 8] studied the behavior of the steel/polymer/steel sheets during cylindrical cup drawing. They constructed FLC of the sheet using surface strain calculations. Kami *et al.* [9] studied the formability of Bondal sheets (a three-layer steel/polymer/steel sandwich sheet) by conducting different types of experiments such as Nakazima, uniaxial tensile and bulge tests.

In addition to the above-mentioned experimental studies, many attempts have been made to analyze the formability of sandwich sheets following numerical and theoretical approaches. Kim *et al.* [10] calculated FLCs of aluminum/ polypropylene/ aluminum sheets using a M-K model whose properties were equivalent to those of the considered sandwich sheet. Similar investigations were done by Somayajulu [11]. Later on, Kim *et al.* [12] developed a M-K model for determining FLCs for sandwich sheets. The developed M-K model accepted mechanical properties of each layer separately. The authors assessed the effect of layer thickness and material on FLC of the sandwich sheets. The possibility of improving formability of sandwiches by adopting layers of dissimilar materials have also been studied. Kami *et al.* [13] predicted FLC of the Bondal sheet using an anisotropic GTN model.

In the present research, the developed M-K model by Kim *et al.* [12] and the anisotropic GTN model developed by Kami *et al.* [14] were used to assess formability of symmetric and non-symmetric metal/polymer/metal sandwich sheets with skin layers of different thicknesses and materials (aluminum and steel).

2. THE GTN AND M-K MODELS

Kim *et al.* [12] formulated a M-K model for predicting FLC of anisotropic multilayer sheet materials. They made some additional assumptions to the M-K model, which is normally used for single layer sheets. Kim *et al.* [12] assumed iso-strain condition upon which equal strains are assumed for all layers with no delamination occurring in between the layers. Furthermore, they assumed that, initially, each layer thickness shares the same imperfection ratio f_0 with the whole groove. Mathematical form of this assumption is as follows [12]:

$$\frac{h^{b,i}}{h^{a,i}} = \frac{h^{a,i} - d_0^i}{h^{a,i}} = \frac{\sum_{i=1}^{N} h^{b,i}}{\sum_{i=1}^{N} h^{a,i}} = \frac{\sum_{i=1}^{N}\left(h^{a,i} - d_0^i\right)}{\sum_{i=1}^{N} h^{a,i}} \equiv f_0 , \tag{1}$$

where h is the layer thickness, $d_0\left(=1-f_0\right)$ is the initial defect size and the superscripts a, b and i ($i = 1:N(=3)$) refer to homogenous region, imperfection region, and identification number of each layer, respectively. A schematic of the developed M-K model for a three-layer sandwich sheet is illustrated in Fig. 1. Detailed description of the M-K model can be found in [12].

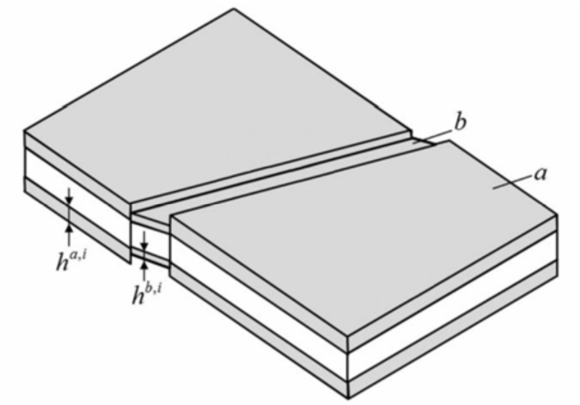

Fig. 1 – Schematic of M-K model for a three-layer sandwich [12].

For numerical determination of FLCs for sandwich sheets, Nakazima tests were simulated via finite-element method on six specimens (a circular specimen with the diameter of 190 mm along with notched specimens of 30, 90, 110, 130, 140 mm in width). Used in these simulations was the GTN damage model formulated by Kami *et al*. [14] with the following potential function:

$$\Phi = \left(\frac{\bar{\sigma}}{Y}\right)^2 + q_1 f^* \left[2\cosh\left(-q_2 \frac{3p}{2Y}\right) - \frac{q_3}{q_1} f^*\right] - 1, \tag{2}$$

where $\bar{\sigma}$ is the Hill'48 equivalent stress [15], is the hydrostatic pressure, Y is the yield stress of the matrix material and f^* is a porosity parameter which depends on the current void volume fraction, f. The parameters q_1, q_2 and q_3 are material constants. Implemented in the form of a VUMAT subroutine, the GTN model was used in the numerical simulations of the Nakazima tests to find the onset of fracture. Then, the limit strains were calculated using the proposed method by Kami *et al*. [14].

3. FORMING LIMIT CURVES OF SANDWICH SHEET

Kami *et al.* [9] constructed experimental FLC of a Bondal sheet by conducting Nakazima and hydraulic bulge tests (see Fig. 2). The Bondal is a sandwich sheet with DC06 skins and a viscoelastic core layer, where the skins and the core layer are 0.6 mm and 0.05 mm thick, respectively. Here, in order to evaluate the ability of the M-K and GTN models to predict limit strains of sandwich sheets, FLC of the Bondal was calculated by these two models. Mechanical properties of Bondal sheet layers and the GTN model parameters of DC06 skins are listed in Table 1.

Table 1

Mechanical properties of Bondal sheet layers
and the GTN model parameters of DC06 skins [9, 13]

Material	Young Modulus, [GPa]	Yield stress, [MPa]	Tensile strength, [MPa]	Lankford coefficient		
				r_0	r_{45}	r_{90}
DC06	210	152	279	2.027	1.751	2.467
Polymer	8.8	15	61	-	-	-
-	GTN parameters					
-	f_0	f_N	S_N	$\bar{\varepsilon}_N^p$	f_C	f_F
DC06	0.0005	0.0008	0.1	0.3	0.0219	0.1677

Fig. 2 depicts the FLCs obtained by the GTN and M-K models. This figure shows that, the GTN model predicts the strains in the middle and right side of the experimental FLC with good accuracy. But, it fails to predict the limit strains on the left side of the experimental FLC. It might be resulted from the GTN calibration procedure adopted by Kami *et al*. [9] who used the hydraulic bulge test results for calibrating the GTN model. On the other hand, Fig. 2 shows that the FLC calculated by the M-K model coincides the experimental forming limit strains only two points. This poor prediction by the M-K model might be originated from the fact that, the f_0 is just based on the limit strain associated with the plane strain point of the experimental FLC. However, from Fig. 2, one may conclude that the GTN model provides more accurate FLCs compared to the M-K model.

In order to study the effect thickness and material of layers of sandwich sheets on their formability, the FLCs of symmetric and non-symmetric sandwiches were calculated using the M-K and GTN models. Configurations of the symmetric and non-symmetric sandwiches are presented in Table 2. In this table, top skin refers to the skin sheet in contact with punch (in the Nakazima tests).

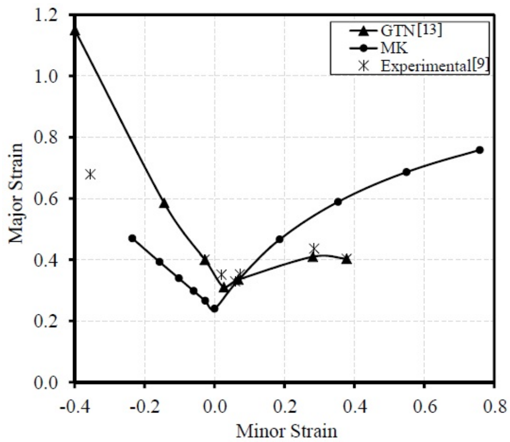

Fig. 2 – Comparison between M-K and GTN models
in prediction of experimental FLCs.

Table 2

Thickness and material of the metallic layers comprising the sandwich sheets.

Sandwich sheet	Sheet name	Material-thickness (mm) of top skin	Material-thickness (mm) of bottom skin
Set #1	AA11	A-0.3	A-0.3
	SS11	S-0.3	S-0.3
	AS11	A-0.3	S-0.3
	SA11	S-0.3	A-0.3
Set #2	AS12	A-0.3	S-0.6
	SA12	S-0.3	A-0.6
	AS21	A-0.6	S-0.3
	SA21	S-0.6	A-0.3

In Table 2, each sandwich sheet is designated as a four-character code in which the characters (from left to right) represent top skin material, bottom skin material, top skin thickness and bottom skin thickness, respectively. Furthermore, A, S, 1 and 2 stand for aluminum AA5754 alloy, mild-steel, thickness of 0.3 mm, and thickness of 0.6 mm, respectively. As Table 2 shows, the sandwich sheets are divided into two sets, set #1 and set #2. Accordingly, the sheets in set #1 have skins of equal thickness, while those in set #2 have different skin thicknesses. All sandwich sheets in Table 2 are equipped with a polymeric core layer of 0.6 mm in thickness. Mechanical properties and GTN parameters of the skins for the sandwiches categorized in set #1 and set #2 are presented in Table 3.

Table 3

Mechanical properties and GTN parameters of the skins for the sandwiches categorized in set #1 and set #2 [16]

Material	Young modulus [GPa]	Yield stress [MPa]	Ultimate strength [MPa]	Lankford coefficient		
				r_0	r_{45}	r_{90}
Mild-steel	198	148	389	2.20	1.90	1.60
AA5754	70	100	230	0.87	0.76	0.71
-	GTN parameters					
-	f_0	f_N	S_N	$\bar{\varepsilon}_N^p$	f_C	f_F
Mild-steel	0.001	0.039	0.1	0.21	0.0601	0.1810
AA5754	0.001	0.034	0.1	0.32	0.0028	0.0977

4. RESULTS AND DISSCUSSIONS

Total thickness of all sandwich sheets categorized in set #1 was 1.2 mm, with their skin thickness ratio being equal to one. These sandwich sheets are considered to evaluate the effect of layers material arrangement on the formability of the sandwiches. FLCs of the set #1 sandwiches were calculated by numerically simulating Nakazima tests using the GTN model, as shown in Fig. 3. As this figure shows, SS11 had the highest forming limit, while the lowest forming limit belonged to SA11. The figure implies that, the alteration of layers material has a significant effect on the FLC. So that, by replacing the bottom skin of AA11 sheet with mild-steel (AS11), its formability is improved. On the other hand, when the top skin of AA11 is replaced with mild-steel (SA11), a significant reduction in formability of the sandwich sheet is observed. As in case of AA11 sheet, the minimum limit strain on the FLC is equal to 0.138, which is 26.09% lower than that of AS11 (0.174) and 33.33% higher than that of SA11 (0.092).

The changes in the limit strains of the sandwiches with skin material are explained by the fact that, during Nakazima tests, the bottom skin experiences more tension. Figure 4 depicts major strain evolution at the critical elements of the bottom and top skins of SA11 sheet. The critical element is the first element of the skin sheet, which is deleted due to fracture. According to Fig. 4, the critical element of the bottom skin has incurs higher strain throughout the deformation. Therefore, the critical element of the bottom skin tends to be fractured prior to the critical element of top skin, i.e. the necking and subsequent fracturing initiates from the bottom skin sheet. Mild-steel sheet is of higher formability than 5754 aluminum alloy sheet [16]. Hence, when the mild-steel sheet is used as the bottom skin, a higher overall formability is achieved. Accordingly, Fig. 3 illustrates that, AS11 has higher formability than SA11. The results illustrated in Fig. 3 are compatible with those reported by Sokolova *et al*. [5].

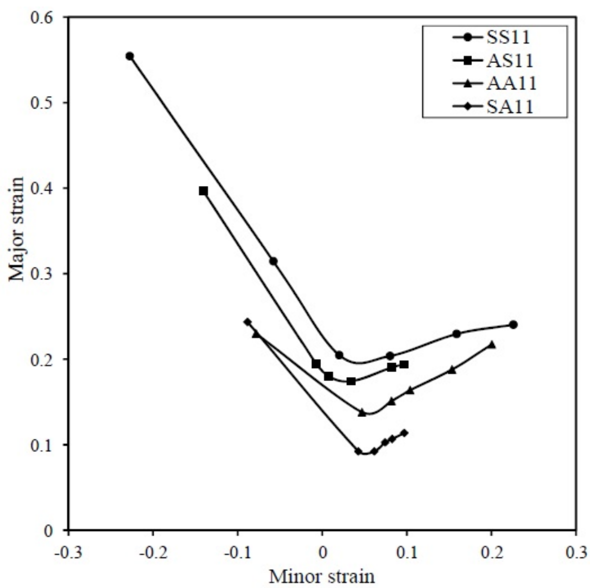

Fig. 3 – The FLCs of the sandwich sheets of set #1,
as calculated using GTN model.

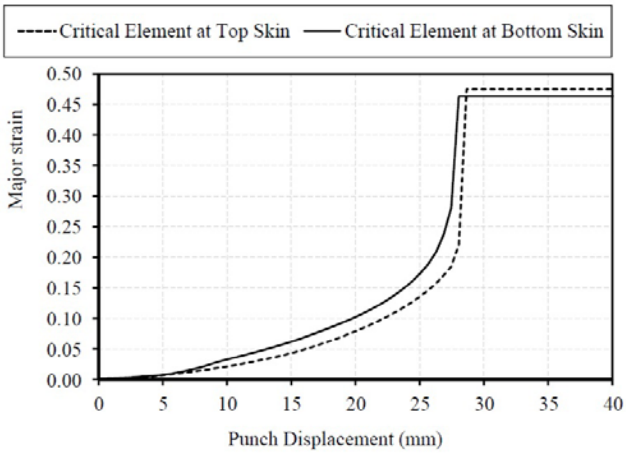

Fig. 4 – Distribution of major limit strains at (a) the bottom
and (b) the top skins of the SA11 sheet, as obtained using finite-element simulation
of a 110 mm wide Nakazima sample.

Figure 5 shows the FLCs of the set #1 sandwiches, as calculated using the M-K model. Comparing Figs. 3 and 5, one may notice that the predictions provided by the M-K and GTN models are qualitatively consistent with one another. Accordingly, both of the models predict that, set #1 sheets provide higher formability in the following order: SS11 > AS11 > AA11 > SA11. Nevertheless, the values of limit strain calculated by the M-K model differed considerably from those calculated by the numerical simulations based on GTN model.

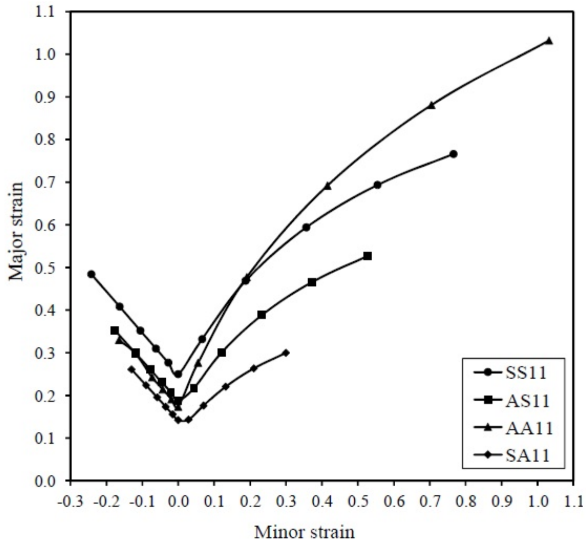

Fig. 5 – The FLCs of the set #1 sandwich sheets,
as calculated by M-K model.

FLCs of the sandwich sheets in set #2 were also calculated using the GTN model. Categorized in set #2 were the sandwich sheets composed of AS and SA with skin thickness ratio of 2 (or 0.5). FLCs of these sheets are illustrated in Fig. 6. This figure indicates that, formability of AS sheets is higher than that of SA sheets, which is in agreement with the results presented in Figs. 3 and 5. Moreover, Fig. 6 shows that, AS12 and AS21 have almost the same formability (this holds true also for SA12 and SA21 sheets), implying that, in particular configurations of the sandwich sheet (e.g. AS), overall thickness of the sheet (rather than thickness ratio of the layers) is the dominant formability-controlling parameter. It should be noted that, this conclusion is just based on the results obtained at thickness ratio of 2 (or 0.5), and different results may be observed at higher thickness ratios.

FLCs of the set #2 sandwiches were further constructed using the M-K model, as plotted in Fig. 7. According to this figure, one may easily conclude that, the M-K model predicts higher formability for AS sheets rather than SA ones. This conclusion is consistent with that provided by the GTN model. Moreover, according to Fig. 7, AS12 and AS21 ended up with almost the same FLCs. Despite the large difference between the FLCs of SA12 and SA21 on the right side of the curves, those coincide one another on the left side of FLCs. The difference between the right branches of the FLCs of the SA12 and SA21 sheets is caused by the different values of f_0 used for calculating the FLCs (0.99586 and 0.9897 for SA12 and SA21 sheets, respectively).

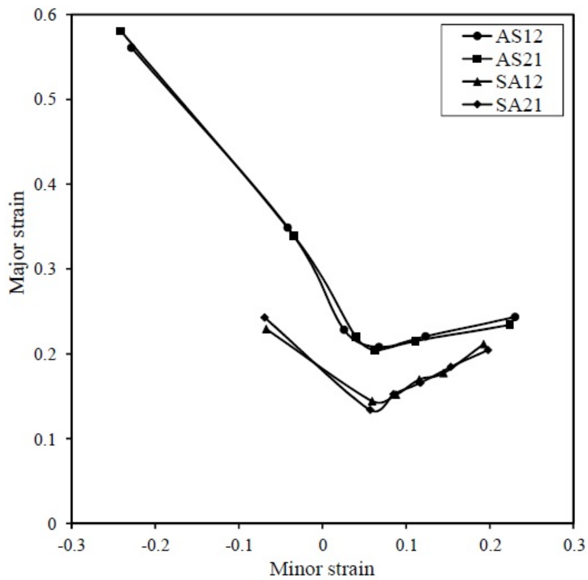

Fig. 6 – FLCs of the sandwich sheets of set #2,
as calculated using GTN model.

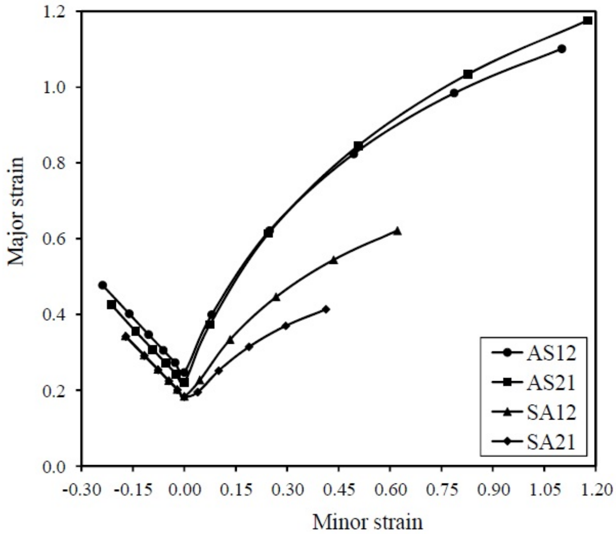

Fig. 7 – FLCs of the sandwich sheets of set #2,
as calculated by the M-K model.

5. CONCLUSIONS

In this research, effects of thickness and material of skin sheets on formability of metal/polymer/metal sandwich sheets were investigated. According to the obtained results, the following conclusions are drawn:

1 – The FLCs calculated by the M-K and GTN models were considerable different from one another. However, both of the models ended up with similar results about the quality of the contribution of the skin thickness and material to formability of the sandwich sheets.

2 – Once the bottom skin of AA-type sheets was replaced by mild-steel (AS-type sheet), its formability was improved. Contrarily, by replacing the top skin of AA-type sheets with mild-steel, its formability decreased. When the GTN model served as basis, minimum limit strain of the FLC of AA11 sheet was found to be 0.138, i.e. 26.09% lower than that of the FLC of AS11 (0.174) and 33.33% higher than that of the FLC of SA11 (0.092).

3 – Concerning AS12, AS21, SA12 and SA21 sheets, the dominant sheet formability-controlling factor was found to be the arrangement of skin material rather than the skin thicknesses. Moreover, for sandwich sheets of the same type (i.e. AS-type or SA-type), sheet formability was found to be controlled by overall thickness of the sandwich rather than thickness ratio of its layers.

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