Int J Mater Form (2009) Vol. 2 Suppl 1:407–410
DOI 10.1007/s12289-009-0502-0

FLD DETERMINATION OF AL 3105/POLYPROPYLENE/AL 3105 SANDWICH SHEET USING NUMERICAL CALCULATION AND EXPERIMENTAL INVESTIGATIONS

M. H. Parsa[1*], M. Ettehad[2], S. Nasher Al Ahkami[3]

[1]Associate Professor, School of Metallurgy and Materials Eng., University college of Engineering, University of Tehran, Iran, P.O.Box 11155/4563
[2,3]Graduate Student, School of Metallurgy and Materials Eng., University College of Engineering, University of Tehran, Iran, P.O.Box 11155/4563

ABSTRACT: Sandwich structures are gaining increase application in aeronautical, marine, automotive and civil engineering. Since such sheet can be subjected to stamping processes and their deformation limited by various defects, knowing beforehand the limiting amount of deformation is very important. For achieving this goal, sandwich sheet of Al 3105/Polymer/Al 3105 were prepared using thin film hot melt adheres. FLD of sandwich sheet was predicted using simulations by considering GTN damage model. Also FLD of prepared sheets evaluated through experimental investigations.

KEYWORDS: Sandwich sheets, Forming Limit Diagrams, FLSD ,Continuum Damage Models, GTN damage model

1 INTRODUCTION

In recent years, many metal-plastic sandwich sheets have been developed and due to their advantages, sandwich structures are gaining increasing applications in aeronautical, marine, automotive and civil engineering [1]. Typically a sandwich structure consists of two thin, stiff and strong face sheet metal separated by a thick, low density core polymeric material. Besides desired properties like high flexural stiffness and good sound and vibration damping, formability of these composites are one of the main concern that should be improved before any attempt to substitute monolithic metal sheets with metal-plastic sandwich materials [2,3]. For numerical investigation of forming behavior, forming limit diagrams are required. FLDs can be obtained experimentally or numerically. It has been shown that the experimental determined forming limit diagram (FLD) in strain state is definitely depended on the forming history and strain path. Since numerous parameters such as core/face sheet thickness ratio, materials type of face sheet and core, and interface behavior affect the sandwich behavior during forming processes. From another way much effort has been recently made to predict the material formability during sheet metal forming processes using numerical simulation methods.

The goal of this work is to apply the micro-mechanical Gurson-Tvergaard-Needleman (GTN) damage model which address ductile fracture mechanisms i.e. nucleation, growth and coalescence of micro voids as a sheet metal failure criterion for FLD prediction of sandwich sheet [4]. In the following sections, first a short review of the Gurson-based material constitutive model is presented. Next identification of model parameters will be dealt by means of experimental and numerical procedures. Finally the accordance between experimental and numerical results on FLD determination will be discussed.

2 THEORETICAL ANALYSIS

Dilatational plasticity theory developed by Gurson can take into account degradation of the load carrying capacity due to the presence of porosity in isotropic materials which stands for three steps in ductile fracture mechanisms i.e. micro void and crack nucleation, growth and coalescence to form macro cracks in sample. Therefore it is a desirable and computational effective mathematical model for the ductile fracture process.

2.1 GTN DAMAGE MODEL

Based on an upper-bound solution for deformation around a single spherical void in rigid plastic isotropic material, the modified Gurson yield function by Tvergaard is given by Equation (1) [5].

$$\Phi = \left(\frac{\sigma_{eq}}{\sigma_0}\right)^2 + 2q_1 f^* \cosh\left(\frac{3q_2\sigma_H}{2\sigma_0}\right) - \left(1 + q_3 f^{*2}\right) \quad (1)$$

* Corresponding author: mhparsa@ut.ac.ir

The above flow potential Φ characterizes the porosity in term of a single scalar internal variable, f^*(the modified void volume fraction). The parameters q_1, q_2 and q_3 were introduced by Tvergaard to compatible the prediction of the Gurson model with his numerical studies of materials containing periodically distributed circular cylindrical and spherical voids. According to Tvergaard, the rate of increase in the micro void volume fraction is given by equation (2).

$$\dot{f} = \dot{f}_N + \dot{f}_G \quad (2)$$

Where $\dot{f}_N$ and $\dot{f}_G$ are, the nucleation and the growth rate of micro voids respectively. The increasing rate of the micro void volume fraction due to the growth of existing micro voids is given by equation (3).

$$\dot{f}_G = (1 - f_v)Tr(\dot{\varepsilon}_{pl}) \quad (3)$$

The term $Tr(\dot{\varepsilon}_{pl})$ is the first invariant of the plastic strain rate tensor. The nucleation part of micro void volume fraction rate is expressed by equation (4).

$$\dot{f}_N = \left(\frac{f_N}{S_N \sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\varepsilon_{eq} - \varepsilon_N}{S_N} \right)^2 \right] \right) \dot{\varepsilon}_{eq} \quad (4)$$

Where f_N is the volume fraction of void-forming particles. ε_N is the mean plastic strain value for void nucleation and S_N is the corresponding standard deviation. In the GTN damage model void coalescence can be described by introducing critical damage volume, fc, which related to loss of stress carrying capacity due to the neighboring voids interactions. Then modified micro void volume fraction can be described as equation (5).

$$f^*(f) = \begin{cases} f \\ f_c + k(f - f_c) \end{cases} \quad (5)$$

Where k is calculated from equation (6)

$$k = \frac{f_u^* - f_c}{f_f - f_c} \quad (6)$$

f_f is void volume by macroscopic fracture and $f_u^* = f^*(f_f)$ is modified specified void volume by macroscopic fracture.

2.1.1 GTN MODEL PARAMETER IDENTIFICATION

Model parameters are obtained by examining the fracture surface of the used material and measurement of electric potential during plane-strain test and simple tensile test [4]. The final model parameters are given in Table 1.

Table 1: *GTN damage model parameters*

f_c	f_f	S_n	ε_n	f_n	q_1	q_2	q_3
0.05	0.15	0.1	0.08	0.01	1.5	1	2.25

2.2 FLD DETERMINATION USING GTN DAMAGE MODEL

Forming limit diagram for different polypropylene core volume fraction were determined using GTN damage model after evaluation of parameters. Like experimental tests, different width samples were simulated to cover all strain conditions in the deformed sandwich sheets. Elements which pass critical volume fraction f_f were deleted to show macro crack formation and growth in sandwich sheets.

3 EXPERIMENTAL PROCEDURE AND MEASURED PROPERTIES

3.1 MATERIALS

The 2mm and 1.2mm thickness AA/PP/AA sandwich sheet samples consist of two AA3105 aluminium skins and a commercially available grade of isothactic polypropylene with $1.8 * 10^8$ molecular weight as core material. In order to investigate the effect of core thickness on the formability of sandwich sheets, the thickness of aluminium face sheet varied as 0.5 and 0.7 mm respectively. Sandwich with 0.5mm face sheets has the same flexural stiffness of 1mm aluminium mono sheets while shows nearly 30% weight saving. True stress-strain curve of constituent materials obtained using screw driven Instron universal testing machine with cross headed velocity of 5mm/min is shown in Figure 1.

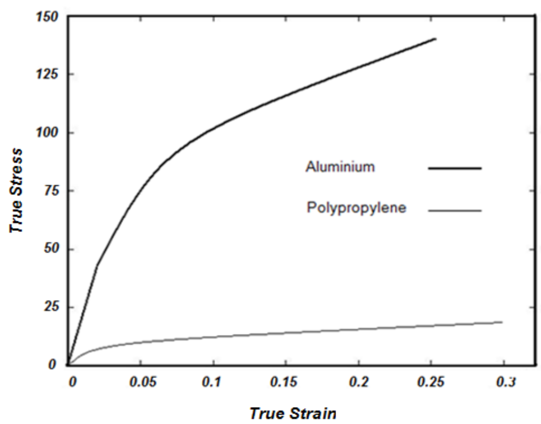

Figure 1: *True stress-strain curves*

3.2 SANDWICH SHEET CONSTRUCTION

Thin film PP-g-MAH was inserted as an adhesive agent between aluminium face sheet and polypropylene core. Total compound were compressed at 190°C for 10 minutes with hydraulic hot press.

3.3 INTERFACE CHARACTERIZATION

In order to investigate and characterize interface adhesion between core and face sheet, experimental T-peel (ASTM D 1876) and single lap-joint (ASTM D 4896) and numerical simulation were carried out using Cohesive Zone Model (CZM) elements implemented in commercially available FEM software. Table 2 presents the fracture parameters i.e. the energy and stress for interface debonding in tension (G_n^c, t_n^c) and shear (G_s^c, t_s^c) modes.

Table 2: *Fracture parameters in tension and shear mode*

Fracture parameter	$G_n^c(J/m^2)$	$t_n^c(MPa)$	$G_s^c(J/m^2)$	$t_s^c(MPa)$
magnitude	350	8	10.5	550

The high values of stress and energy required to overcome the debonding resistance prevent the delamination phenomena at interface during conventional sheet metal forming processes. SEM image from the interface of polypropylene core and aluminium face sheet after T-Peel test shows fibrillation and thereby, the interface remains almost intact after plastic deformation of these sandwich materials [6].

3.4 FLD BY PUNCH-STRETCHING TEST

The punch-stretching test was carried out on hydraulic press with 50mm hemispherical diameter punch and constant speed of 1 mm/s at room temperature. Different widths, varying from 20 up to 120 mm samples were clamped at their edges and stretched until cracks observed on the surface of the samples. Thin film Teflon was inserted between punch and specimen to eliminate friction during FLD tests. In all the specimens, the strains were calculated from the measurements of deformed grids which were etched on the specimens before the test with standard electrolytic etching techniques.

4 RESULTS AND DISCUSSION

4.1 EXPERIMENTAL FLD

Figure 2 shows the FLD of the sandwich materials with 0.2mm and 1mm polypropylene core and 0.5mm aluminium face sheet. In nearly all strain state the sandwich sheet has higher formability in comparison to aluminium sheet. In drawing side, i.e. $\rho < 0$, the slope of the FLD of aluminium mono layer is higher than sandwich sheet and thereby in uniaxial case the forming limit of mono layer and sandwich sheet approach each other.

The higher FLD of sandwich material is related to higher strain rate sensitivity factor (m factor) because of the existence of polypropylene core with high m-factor and also relatively higher initial defect factor. The strain rate sensitivity factor has desirable effect on the FLD. The strain rate hardening for a material with m>0 exerts a stabilizing effect that allows the material to deform in a quasi-stable manner, thereby delaying the onset of localized necking and increasing the forming limit in sandwich sheets. Contrary to this, as the experimental result of uniaxial tension of sandwich sheets shows, deformation of these materials depends on the volume fraction of polymer core that have lower strain-hardening exponent than monolithic aluminium face sheet. Thereby the lower FLD of monolithic aluminium related to lower strain rate sensitivity factor and lower initial defect factor that compensated by higher strain hardening exponent. The higher FLD of sandwich sheets with 0.2mm polymer core than sandwich with 1mm core thickness is due to the positive effect of strain hardening.

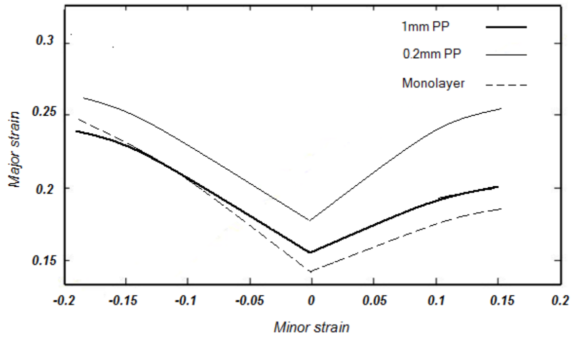

***Figure 2:** FLD of 2mm, 1.2mm sandwich sheets and 0.5mm aluminium constituent face sheet.*

Figure 3 shows the effect of aluminium face sheet thickness on FLD for 2mm sandwich sheet thickness. As it can be seen from the figure, as the thickness of the face sheet increase, the FLD diagram shifts to higher value which is more intense in drawing state.

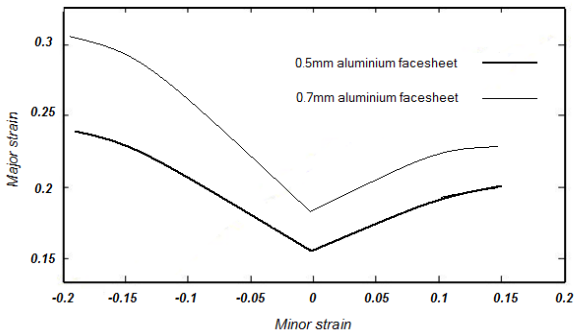

***Figure 3:** FLD of 2mm sandwich sheet with different aluminium face sheet thickness.*

4.2 NUMERICAL FLD

Figure 4 shows the final geometry of experimental and numerical model with 20mm width. The geometry, shape and position of macro crack formation predicted by GTN damage model incorporated in FEM code at the surface of both lower and upper face sheets are in good agreement with experimental specimen. The cross section view from experimental specimen shows that the interface between polypropylene core and aluminium face sheets remains intact after deformation.

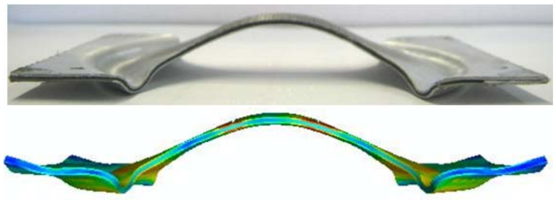

Figure 4: *Geometry of experimental and modelled FLD specimen.*

In Figure 5 the predicted FLD diagram in strain space for 2mm sandwich sheets with 0.5mm aluminium face sheet is compared with experimental one. FEM simulations had been carried out by implementation of GTN damage model for instability modelling during plastic deformation. As it is clear from the figure the compatibility between experimental and simulated FLD is noticeable especially in balanced biaxial strain state. Since the constitutive equations 3 and 4 related to micro void volume changes due to nucleation and growth and the volume fraction of micro voids remain intact in purely shear stress at low hydrostatic stress state, therefore GTN damage prediction shows high deviation from reality in drawing region, i.e. $\rho < 0$.

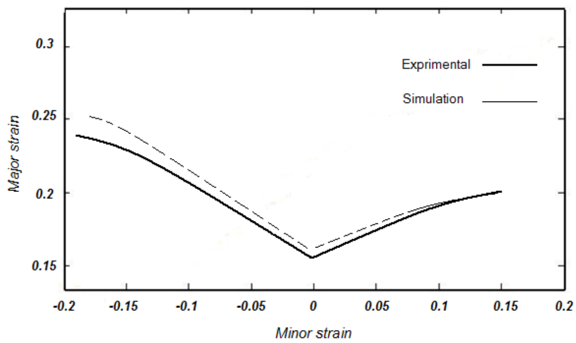

Figure 5: *Experimental and numerical FLD for 2mm thickness sandwich.*

Finally in order to explain numerically the positive effect of thicker aluminium face sheet on FLD for same sandwich sheet thickness, hydrostatic stress values were examined. For the same punch motion before macro crack formation in sandwich sheets, the hydrostatic stress values in upper aluminium skin of 0.5mm and 0.7mm are numerically determined as 45MPa and 27MPa respectively. The thinner the aluminium face sheet, the higher deviatoric and hydrostatic stress state will be due to the I-beam effect. Since the polypropylene core acts as a web and aluminium face sheet act as flanges in sandwich materials. Due to direct relation between hydrostatic stress and micro void growth, thinner aluminium face sheets experiences sever micro voids growth and interactions. The void volume fraction contours with maximum 0.1 values (red region) for crack formation in FLD specimens shown in Figure 6 prove mentioned logic.

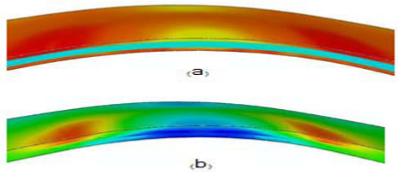

Figure 6: *void volume fraction contour a) 0.5mm face sheet, b) 0.7mm face sheet.*

5 CONCLUSIONS

In this paper, GTN damage model was incorporated with FEM code in order to predict instability in plastic deformation in sandwich sheet materials with different polymer core thickness ratios. The predicted FLD using simulation results show good agreement with experiments especially in balanced biaxial strain state. Where imposed higher hydrostatic stress on specimen and thereby the weakness of GTN damage model to account micro void growth in deviatoric stress space has minor effect in FLD prediction. It was shown that the polymer core has both positive and negative effect on FLD of sandwich sheets. The former is related to positive effect of higher strain rate sensitivity of polymer core and higher defect factor of specimen but the later is related to lower strain hardening that the polymer core imposed in sandwich materials. Additionally, the higher hydrostatic stress state imposed on thinner aluminium face sheets with the same sandwich thickness lowered FLD of sandwich sheets with thin metal skins.

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