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A Novel Methodology to Determination of Forming Limit Curve in Two-Layer Metallic Sheets Based on Numerical Models

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Abstract

Forming limit curve (FLC) is a suitable method to determine the formability of metallic sheets in sheet metal forming operations. The aim of this research is to present a simulation-based approach for prediction of the forming limit curve in two-layer metallic sheets. In this paper, the formability of two-layer (Al3004-St12) metallic sheets, with aluminum inner layer which was in contact with the punch and steel outer layer which was in contact with the die were numerically investigated. Two different criteria, including the acceleration (i.e. the second time derivatives) of thickness and major strain extracted from the strain history information of FE software, were applied to accurately determine the start of localized necking in forming limit curves. This is to say that the localized necking will be started when the acceleration of the thickness or major strain gets its maximum value. The published experimental information for Al/St two-layer metallic sheets had been used to evaluate the simulation results. It was shown that the presented methods were in good agreement with the experimentally observed data. Using the presented methods, the influences of some process parameters on the FLC were investigated. It was shown that process parameters such as, thickness of each layer, friction coefficient between blank and punch, friction coefficient between blank and die/blank holder and lay-up had significant influence on the FLC of two-layer metallic sheets. The results illustrated that the FLC is dependent on mentioned parameters, so the two-layer metallic sheet formability can be increased by improvement of these factors in forming limit tests.

Keywords: *"Forming limit curve", "Two-layer metallic sheet", "FEM", "Criterion".*

Introduction

Nowadays, two-layer metallic sheets are a useful solution to produce multi-functional products. Generally, with different material combinations, two-layer metallic sheets can have advantageous characteristics such as increasing formability of the low formable component, improving the corrosion and wear resistance and finally reducing weight and cost of manufactured products. These kinds of sheets can be used in many domestic and industrial applications, such as in aerospace, chemical and the automobile industry [1-4]. Therefore, understanding the forming limit behavior of a two-layer metallic sheet has an essential role in the design of sheet metal forming operations. The formability of the metallic sheets is limited by the occurrence of necking in sheet metal forming operations. Forming limit curves (FLCs) are applied to predict the formability of metallic sheets. To find the FLC experimentally, some sheet metal specimens of constant length and variable width subjected to different strain conditions by using a hemispherical punch. After the presentation of the forming limit curves concept by Keeler and Backofen [5] and then Goodwin [6], many researcher have tried to develop some models for determination of FLCs.Ito et al. [7] determined the forming limit curve of sheet metal theoretically using the three-dimensional mode analysis. The numerical results showed that the strain limit determined using this method provides upper limit lines for the bifurcation lines suggested in the past for any linear strain-path directions. Zimniak [8] determined the FLC by perturbation theory using the FEM simulations. His study demonstrated that the modification of the perturbation theory by a new stress-strain relationship and six-component Barlat yield criterion provides a suitable estimation of the onset of localized necking to determine the forming limit curve. Butucet al. [9] theoretically studied on the forming limit curves using a new general code to predict the forming limit strains. They used the Yld96 criterion to describe the shape of the yield locus and observed a good correlation between the computed limit strains and the experimental FLCs. Aghaie-Khafri and Mahmudi[10] presented an analytical method for determination the forming limit curves obtained during sheet metal forming processes for sheets having planar isotropy. Campos et al. [11] determined the forming limit curve for the AISI 304 stainless steel during linear strain paths using the Marciniak–Kuczynski (M–K) method. Safikhaniet al. [12] presented the forming limit curves both in strain and stress spaces using the strain gradient theory of plasticity in conjunction with M–K model. Zhang et al. [13] presented a suitable necking criterion for the determination of FLCs of the aluminum alloys which was in good agreement with the experimental test results. Rezaee-Bazzazet al. [14] calculated the FLCs, using the analysis suggested by Jones and Gillis (JG). They found that although the method determines the influence of material parameters reasonably well, the computed FLCs were higher than the experimental forming limit curves. Albakriet al. [15] presented a novel hybrid numerical/experimental approach that can be applied to make forming limit curve under specified strain rate loading paths in sheet metal

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forming operations. Ji He et al. [16] tried to understand and evaluate such anisotropic hardening effect on the forming limit prediction under stretch-bending condition. They predicted the “bending-ratio-dependent” phenomenon in forming limit curve in both stress/strain space with the proposed method. Their analysis demonstrated that the Bauschinger effect provides positive effect in delaying the necking instability, predicting higher formability for sheet metals under stretch-bending. Zhalehfaret al. [17]investigated the influence of strain path change on the forming limit curve of 5083 aluminum alloy sheet experimentally and theoretically using ductile fracture criteria. Zhang et al. [18] used the Marciniak–Kuczynski method with Barlat's 1989 anisotropic yield surface to predicate forming limit to study the effect of the normal stress and material anisotropy. Their analyses showed that normal stress increases the forming limit described both in strain and stress spaces.

In1979SemiatinandPiehler carriedout theearliestresearch onmulti-layermaterials [19].Yoshida and Hino [20] investigated the formability of sheet metal laminates both numerically and experimentally. They found that the FLCs of the laminates lied between the FLC of their components. Weiss et al. [21] tried to determine the forming limit curve of the laminate in two different temperatures to specify the effect of temperature on the forming behavior of sheet metal laminates. Tseng et al. [22] studied the possibility of employing FLC to the fracture and formability determination of clad metal sheets. They studied forming limits of these kinds of sheets with different thickness combinations through punch stretching tests. Their research illustrated that there are an important differences in formability of clad metal sheets with different thickness combinations. Liu et al. [23] developed an AA5052/polyethylene/AA5052 sandwich sheet and investigated its formability. Their study demonstrated that: AA5052/polyethylene/AA5052 sandwich sheet has a better formability than monolithic AA5052 sheet. Aghchaiet al. [24]investigated the influences of the material properties of the components of the two-layer sheets such as strain rate sensitivity coefficient, strain hardening exponent, grain size and stiffness coefficient on the FLC of two-layer sheets with the M–K method which had been verified with an experimental approach. Their study demonstrated that the forming limits of two-layer sheet lies between the forming limits of its components depend on their material properties.

Inthisresearch, two differentnumericalmodelswereused to determinetheformabilityof two-layer metallic sheets.Thesemethods contained:

(1) Accelerationof the major strain ($\frac{d^2\varepsilon_1}{dt^2}$) and

(2) Acceleration of the thickness strain ($\frac{d^2\varepsilon_3}{dt^2}$)

to predicttheforminglimitoftwo-layer sheets.These two criterions have been employed for the first time to determine the FLCs of two-layer metallic sheets. The published experimental information has been applied to validate the results of the proposed methods. Furthermore, in present work, the influences of process parameters on the FLC of two-layer metallic sheets were investigated through numerical simulations.

FE simulations to predict FLCs

The biaxial stretch-forming test was simulated in three-dimensional (3D) using ABAQUS/Explicit FE program [25] to estimate the formability of the Al/St two-layer metallic sheets. All the analyses were realized using an explicit finite element approach. The die was fixed and the punch and the blank holder could move through the axis of the punch, in the Z direction. Moreover, the blanks were meshed by using S4R elements. The coefficient of friction between different contact surfaces has been presented in Table 1and alsothe FEM model included of a punch, blank holder, die and the blank is shown in Figure 1.The blanks were prepared with aluminum inner layer which was in contact with the punch and steel outer layer which was in contact with the die and different in width. The total blank thickness was considered to be 2.1mm where included of a 0.6mm steel layer and 1.5mm aluminum layer in thickness as it mentioned in [24].The specimens were simulated according to ISO 12004-2 standard [26]. The mechanical properties of each layer used in this research are presented in Table 2 [24]. The tensile test properties had been used in the following simulations.

The influences of parameters such as thickness of each layer, friction coefficient between blank and punch, friction coefficient between blank and die/blank holder and lay-up have been studied by FE simulations.

Table 1: Coefficient of friction between contact surfaces

Surface of contact	*Coefficient of friction*
Between blank & punch surface	0.08
Between blank & blank holder surface	0.1
Between blank & die surface	0.1

Table 2: Material and mechanical properties of St and Al sheets from tensile tests [24]

Material	*Strain hardening exponent, n*	*strain rate sensitivity coefficient, m*	*Strength coefficient, K (MPa)*
St 12	0.25	0.02	544
Al 3004	0.25	0	302

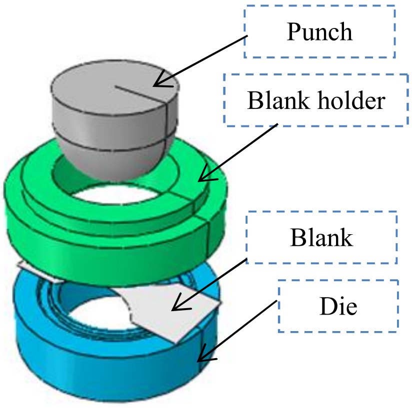

Fig. 1: Modeling in ABAQUS software

Analytical necking criterion

Selecting appropriate necking criterions are important to determine the onset of localized necking in sheet metal forming operations. As mentioned earlier, in this research two different necking criteria, namely the acceleration of the major strain and the acceleration of the thickness strain were used to detect the onset of necking in sheet metal forming process. These criteria are described here.

The acceleration of the major strain criterion

This criterion is based on the acceleration (or second derivative) of the major strain in the blank and defined as follow:

$$\ddot{\varepsilon}_{11} = (d^2\varepsilon_{11})/(dt^2) \quad (1)$$

which ε_{11} is the major strain. At the end of the simulation, the major strain history was extracted from the output file of the FE model and analyzed. Here, a 105mm × 180mm × 2.1mm specimen included of a 0.6mm steel layer and 1.5mm aluminum layer in thickness was simulated and the major strain curve and its first and second derivatives were then plotted (Figure 2). The onset of necking could be predicted from the second derivative curve (Figure 2-c).

The acceleration of the thickness strain criterion

The procedure to predict the forming limit curve by this criterion is the same as that of the acceleration of the major strain criterion. The acceleration (or second derivative) of the thickness strain in the blank is defined as:

$$\ddot{\varepsilon}_{33} = (d^2\varepsilon_{33})/(dt^2) \qquad (2)$$

which ε_{33} is the thickness strain. These two criterions are introduced here as a necking criterion to determine the FLC in two-layer metallic sheets for the first time.

A comparison between the strain histories of the major and thickness strain is presented in Figure 3. Therefore, the maximum value of their acceleration curves happens at the same time and so the resulting FLC would be similar. Therefore, it is only natural that the two criteria show the same results.

Figure 4 shows the major strain and thickness strain distributions from a 130mm wide specimen. The strain distributions show almost similar and the necking position is quite the same. Figure 5 shows the same two distributions from an 80mm wide specimen. The same phenomenon could be seen here, too.

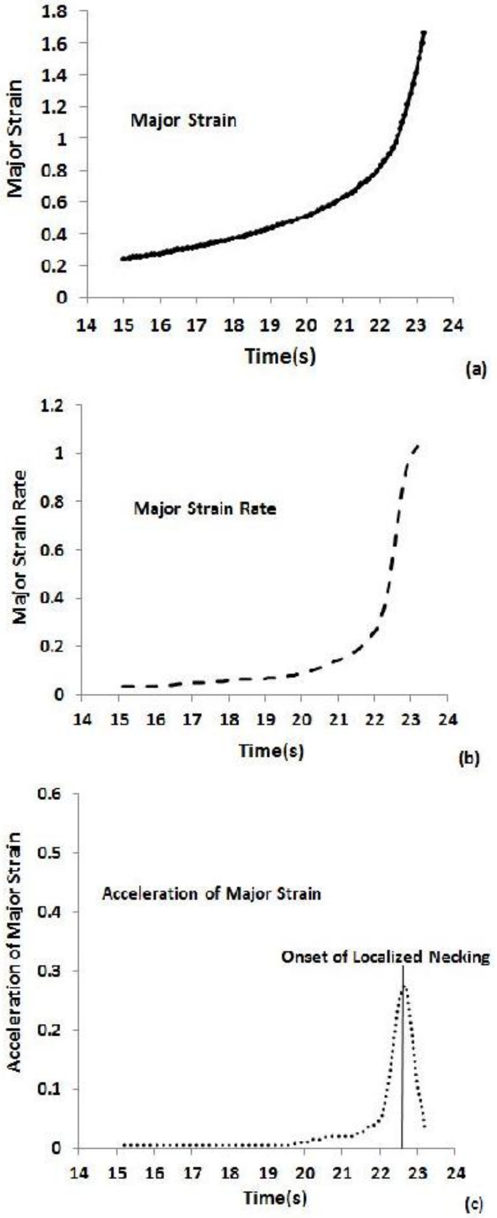

Fig. 2: (a) Major strain history information, (b) Major strain rate history information and (c) Acceleration of the major strain history information

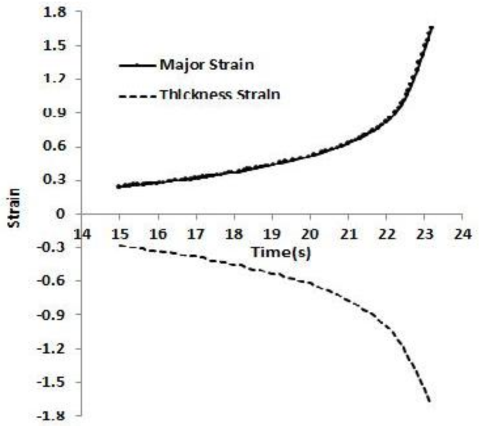

Fig. 3:Comparison between the strain histories of Major and Thickness strain

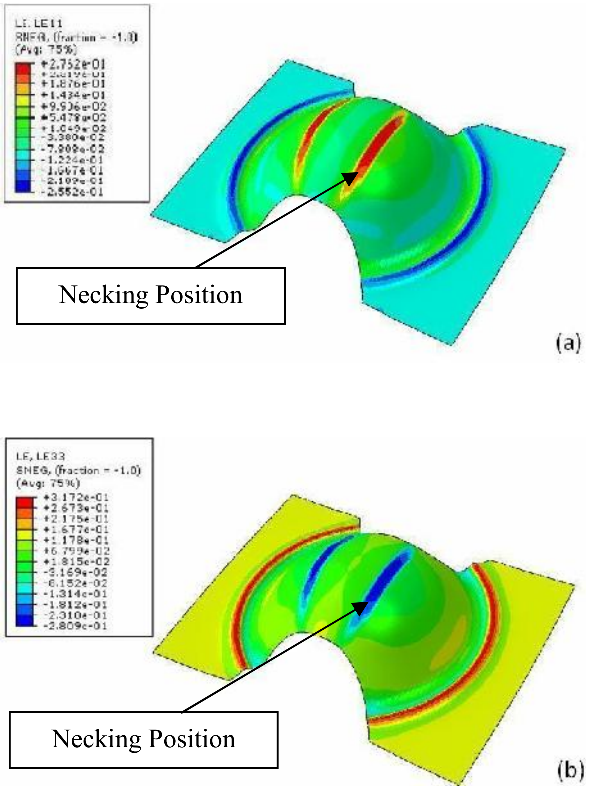

Fig. 4: Strain distributions from a 130mm wide specimen: (a) Major strain,(b) Thickness strain

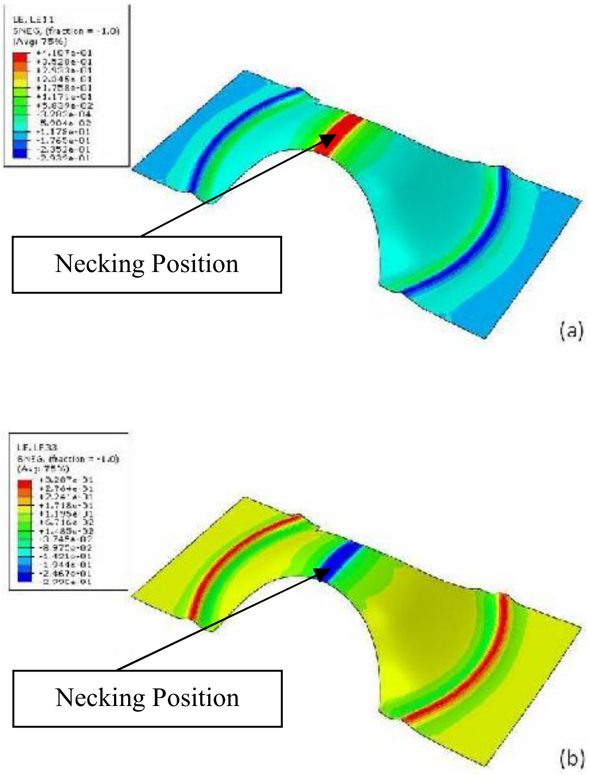

Fig. 5: Strain distributions from an 80mm wide specimen: (a) Major strain,(b) Thickness strain

Results and discussion

This study presents the results of simulated hemispherical die stretching for Al/St two-layer metallic sheets. The simulations were designed to produce FLCs. Two different criteria, including the acceleration of thickness strain and major strainextracted from the strain history of simulations, were used to accurately detect the start of necking in FLCs. This is to say that necking starts when the acceleration of the thickness strain and major strain reaches its maximum value. Knowing the onset of necking, one can measure the major and minor strains at the critical area and produce the corresponding FLC. Results from the proposed methods and those from published experimental information are compared to demonstrate the efficiency of the proposed methods.

Forming limit curve verification

In order to validate the simulation-based approach proposed in the present work, the predicted FLCs have been compared with the forming limit curve obtained experimentally [24]. In reference [24], a series of punch stretching tests were performed to evaluate the FLC in forming limit tests. Polyurethane adhesive had been used in order to join the two layers together. Different regions of FLCs were obtained by tensile tests and stretch-forming with hemispherical punch experiments. In the experimental procedure, the aluminum side of the two-layer metallic sheet was in contact with the punch. Figure 6 shows a comparison between the predicted FLC and the experimental data for Al3004 and St12 one-layer sheets and Al3004-St12 two-layer metallic sheets.

It is clear from the Figure 6 that these models are in good agreement with the published experimental data for Al3004 and St12 one-layer sheets and Al3004-St12 two-layer sheets.

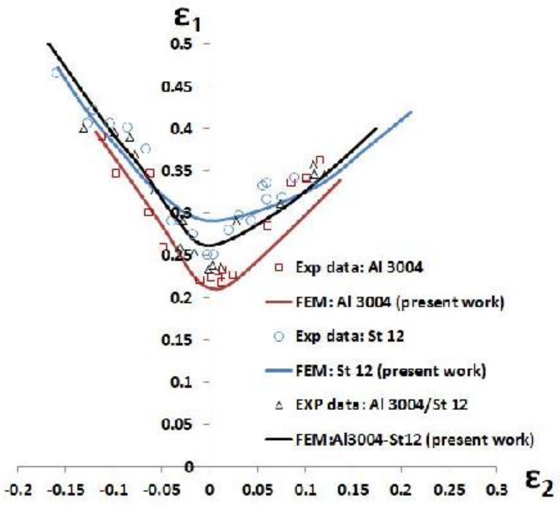

Fig. 6: Comparison of FLCs between the predicted FLC and the experimental data [24] for Al3004 and St12 one layer sheets and Al3004-St12 two-layer sheets

Parametric study

A comprehensive parametric study was carried out and the influences of process parameterson the FLC of two-layer metallic sheets were studied. The influence of blank thickness on the FLC of two-layer metallic sheets is shown in Figure 7. As the Figure7 shows, with increase in steel thickness in a constant total blank thickness, the FLC will be increased that it means the formability of two-layer metallic sheet will be improved. In other hand, the FLC of the two-layer metallic sheet is better than the lower formable component (e.g., the aluminum layer), thus using the two-layer metallic sheet improves the formability of a blank which has a low formability.

Figure 8shows the influence of friction coefficient between blank and punch on the FLC of the two-layer metallic sheets. It can be seen that increasing the friction coefficient increases the FLC. It is seen that there is a positive co-relation between the FLC and friction coefficient between blank and punch.

The influence of friction coefficient between blank and die/blank holder on the FLC of the two-layer metallic sheets is shown in Figure 9. It is clear from the graph that, the FLC decreases as the friction coefficientincreases.

The Figure 10 shows the influence of lay-up on the formability of two-layer metallic sheets. As the Figure 10 shows, there is an increase in the FLC when the Aluminum side is in contact with the punch. That is to say, when the aluminum layer is in contact with the punch the formability of the blank will be improved.

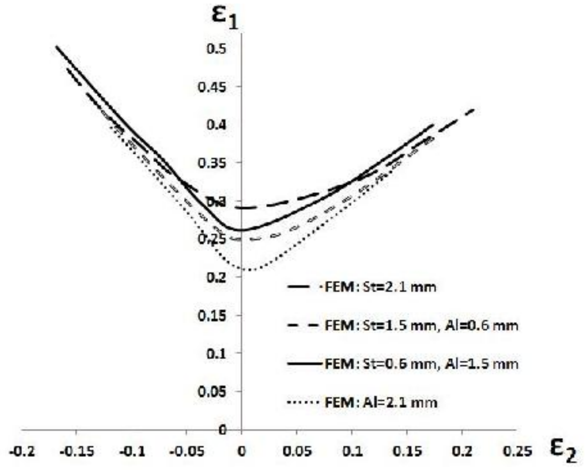

Fig. 7: Influence of thickness of each layer on the FLC

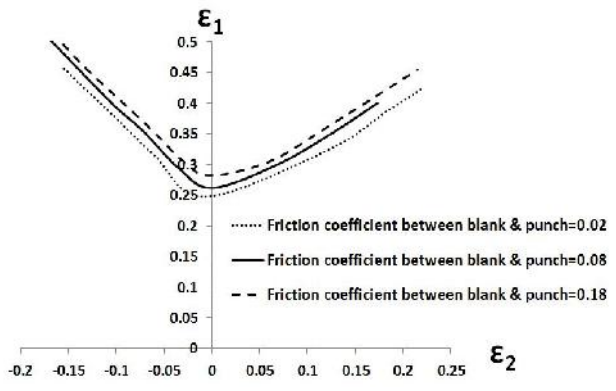

Fig. 8:Influence of friction coefficient between blank & punch on the FLC

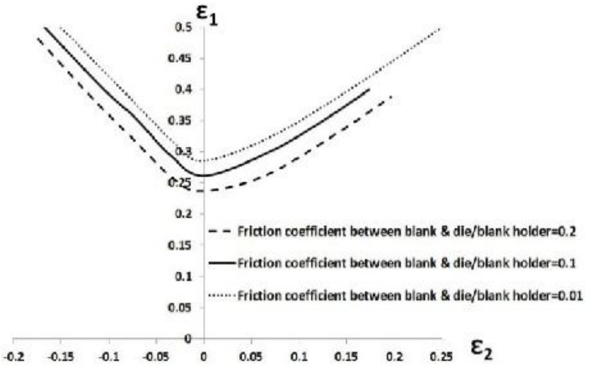

Fig. 9:Influence of friction coefficient between blank &die/blank holder on the FLC

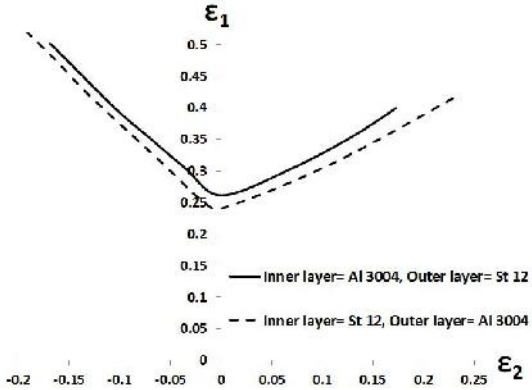

Fig. 10:Influence of lay-up on the FLC

Conclusions

In this paper, two numerical models were used to analyze the FLCs of two-layer metallic sheets. Moreover, the influences of process parameters on the formability of two-layer metallic sheet were investigated through numerical simulations, which have been verified with published experimental data.The following are the conclusions obtained:

1. A new simulation-based method to predict the FLC of the two-layer metallic sheets was introduced and validated through comparison of its results with published experimental data.
2. The FLC of the two-layer metallic sheet is located between the FLC of its components and its precise location depends on thickness of the components.
3. Increase in the thickness of a layer with more formability by assuming that the total blank thickness is constant, increases the formability of two-layer metallic sheet.
4. The FLC of two-layer metallic sheets increases with increase in the friction coefficient between blank and punch but decreases with increase in the friction coefficient between blank and die/blank holder.
5. It’s clear from the studies that there is an increase in the FLC when the layer with less formability is in contact with the punch.

So the FLC of the two-layer metallic sheets can be increased by improvement of the process parameters in punch stretching tests.

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