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Numerical and Experimental Analysis of Subtle Surface Distortion in Sheet Metal Forming

***Jian Cao[1], Wonoh Lee[1], Ying Huang[1] and Hui-Ping Wang[2]**

[1] Northwestern University
2145 Sheridan Road
jcao@northwestern.edu
www.mech.northwestern.edu/fac/cao

[2] General Motors Corporation
GM R&D Center
hui-ping.wang@gm.com

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ABSTRACT

Flange operations on automotive panels often result in subtle distortion on the show panel that affects the appearance and function of the part. These defects can be considered as a type of long wavelength buckling caused by an uneven stress distribution in the sheet blank. Figure 1 shows a typical setup in a flanging operation and a shrink-flanged part. As can be seen from Fig. 1(b), surface distortion is most likely initiated during the unloading stage provided that the applied pad pressure is sufficient during the loading stage.

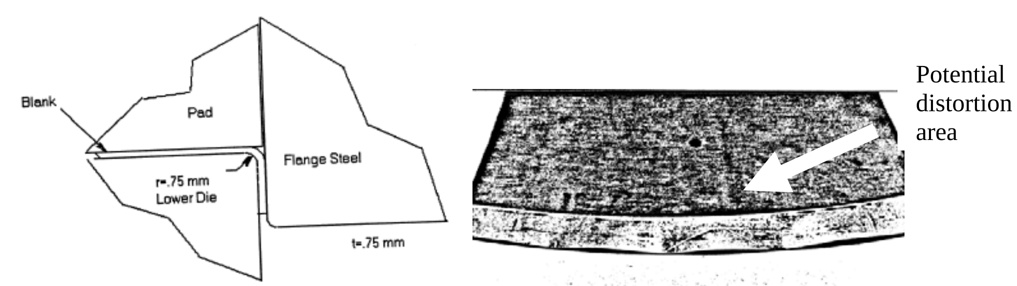

Fig. 1 [Left-a] Schematic of a flanging operation; [Right-b] A shrink-flanged part [1]

Our approach for predicting the subtle surface distortion will be based on the instability of an absolutely ideal surface, whose material behavior follows a combined kinematic/isotropic hardening law, subjected to an uneven stress load. The surface under examination could be a curved one. Surface distortion occurs when the trivial solution is no longer the lowest energy mode. Both experimental work and simulation work will be presented here. Experiments will be conducted using the die shown in Fig. 2. High strength steels will be used as the testing material. The experiments will be conducted for both shrink flanging and stretch flanging and for sheets with and without in-plane pre-stretching.

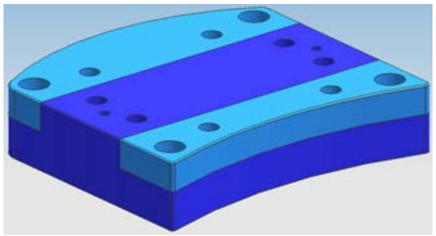

Figure 2. Schematics of the bottom flanging die used in the experiments.

The numerical prediction will use a combination of numerical simulations and the analytical model. The minimum energy state being the stable state is the base for our buckling predictor here. The Lagrangian strain tensor at a distance x_3 from the middle surface of the sheet that has a curvature can be approximated by

$$\varepsilon_{\alpha\beta} = E_{\alpha\beta} + x_3\kappa_{\alpha\beta} \quad (1)$$

where $E_{\alpha\beta}$ and $\kappa_{\alpha\beta}$ represent the stretching and bending strain given by

$$E_{\alpha\beta} = \frac{1}{2}\left(u_{\alpha,\beta} + u_{\beta,\alpha}\right) + b_{\alpha\beta} w \quad and \quad \kappa_{\alpha\beta} = -w_{,\alpha\beta} \quad (2)$$

$b_{\alpha\beta}$ is the curvature tensor of the middle surface in the prebuckling state and w is the out-of-plane displacement. If a constitutive law with the form $\dot{\sigma}_{\alpha\beta} = \bar{L}_{\alpha\beta\kappa\gamma}\,\dot{\varepsilon}_{\kappa\gamma}$ is used, where the instantaneous modulus $\bar{L}_{\alpha\beta\kappa\gamma}$ is defined in the reference [12], the membrane stress resultants $\dot{N}_{\alpha\beta}$ and the bending moment resultants $\dot{M}_{\alpha\beta}$ can be defined as

$$\dot{M}_{\alpha\beta} = \int_{-t/2}^{t/2} \dot{\sigma}_{\alpha\beta}\, x_3 dx_3 = \frac{t^3}{12}\bar{L}_{\alpha\beta\kappa\gamma}\,\dot{\kappa}_{\kappa\gamma} \quad (3)$$

$$\dot{N}_{\alpha\beta} = \int_{-t/2}^{t/2} \sigma_{\alpha\beta} dx_3 = t\,\bar{L}_{\alpha\beta\kappa\gamma}\dot{E}_{\kappa\gamma} \quad (4)$$

The strain energy due to buckling can be expressed as

$$\Delta U = \int_S \left(\int \dot{M}_{\alpha\beta} d\dot{\kappa}_{\alpha\beta} + \dot{N}_{\alpha\beta}\, d\dot{E}_{\alpha\beta}\right) dS$$
$$= \frac{t^3}{24}\int_S \bar{L}_{\alpha\beta\kappa\gamma}\dot{w}_{,\kappa\gamma}\dot{w}_{,\alpha\beta}\, dS + \frac{t}{2}\int_S \bar{L}_{\alpha\beta\kappa\gamma} b_{\alpha\beta} b_{\kappa\gamma}\dot{w}^2\, dS \quad (5)$$

The work done by the external in-plane membrane forces is descried by equation (6).

$$\Delta T = \frac{1}{2}\int_S \left(N_{11}\dot{w}_{,1}{}^2 + N_{22}\dot{w}_{,2}{}^2\right) dS \quad (6)$$

When $\Delta T = \Delta U$, the system reaches a critical buckling point. A mapping to a curved section will be conducted for this flanging application.

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