Direct Design Method Based on Ideal Forming Theory for Hydroforming and Flanging Processes

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Abstract. Conventional practices to predict preform shapes in hydroforming and flanging processes are based on FEM analysis and/or experiment, which require many trials. In an effort to effectively improve the design procedure by overcoming the indirect nature of the conventional design tools, a direct design method based on the ideal forming theory has been previously developed as a newly added design tool in the design procedure. Here, the direct design method based on the ideal forming theory was applied to the preform design for hydroforming and flanging operations. In order to account for anisotropy, the anisotropic strain rate potential which simultaneously accounts for the anisotropy of yield stress as well as the anisotropy of plastic strain ratio was used as a part of the constitutive equation.

INTRODUCTION

In order to improve conventional trial-and-error based practices for optimizing forming processes, a direct design method, called the ideal forming theory, has been previously developed [1 - 4]. In this theory, materials are prescribed to deform following the proportional true strain path (or the minimum plastic work path for isotropic materials having smooth yield surfaces) and then the initial blank shape is obtained from a one-step backward calculation in which the final sheet product shape is specified. The theory can be used to determine an ideal initial blank shape or preform shape needed to achieve a specified final shape while resulting in optimum strain distributions. Because of its assumed deformation path, the result of the theory does not completely comply with real forming so that it is used to guide the iterative design procedure based on analytic methods.

The direct design method usually has been applied for flat blanks in stamping processes for blank design [5] or rapid evaluation of strain distributions [6], while the method also has been applied for non-flat blanks recently [7]. In this work, the method was applied to design a preform for hydroforming of hollow structures utilizing the method developed for non-flat blanks. Also, the one-step forward method based on the direct design method was developed for flanging operation applications. Application examples of industrial parts for hydroforming and flanging processes are presented in this work to show the efficiency and robustness of the proposed direct design method.

IDEAL FORMING DESIGN THEORY FOR NON-FLAT BLANK

When materials are discretized with meshes and the surface traction is approximated by point forces, the plastic work is a function of the initial position vectors $\bar{X}$ and the final position vectors $x$:

$$ W = W \left[ e_c(x_{i=1,2,3}, \bar{X}_{i=1,2}) \right].$$

In Eq. (1), $e_c$ is the effective plastic strain, while $\bar{X}$ and $x$ are based on the local and global Cartesian coordinate systems, respectively. For the initial configuration $\bar{X}$, the 1 and 2 axes are aligned to the tangential surface of the preform shape envelope and
the 3-axis is normal to the surface as shown in Fig.1.

In Eq.(1), the value of the effective strain $\varepsilon_e$ is dependent on the deformation paths of material elements and so is the plastic work. In the ideal forming theory, the minimum plastic work path is imposed for each material. The minimum plastic work path for materials having smooth yield surfaces is equivalent to the proportional true strain path, whose principal directions are restricted to be aligned with specific material directions for anisotropic materials. However, in this design theory, the principal directions are allowed to be arbitrary. When the proportional true strain path is imposed, the effective strain in Eq.(1), obtained from the effective strain-rate by substituting the rate of deformation tensor with the true strain tensor, becomes a function of $\mathbf{x}$ and $\mathbf{X}$. Note that the effective strain is obtained from the flow theory by applying the deformation theory based on the minimum plastic work path [8].

The preform shape is obtained by optimizing the plastic work on the prescribed non-flat envelope surface; i.e.,

$$\frac{dW}{d\mathbf{X}} = \int \sigma_e(\varepsilon_e) \frac{\partial \varepsilon_e}{\partial \mathbf{X}} dV_o = \mu |\mathbf{n}| \mathbf{s} \cdot \mathbf{F}$$

where $\sigma_e$ is the effective stress, $V_o$ is the material volume, $\mu$ is the Coulomb friction coefficient, $\mathbf{f}_n = (\partial W/\partial \mathbf{x}) \cdot \mathbf{n}$ (the unit normal vector and $\mathbf{n}$: final configuration, $\mathbf{n}$: the unit normal vector to define the node sliding direction; i.e., $\mathbf{s} = (\mathbf{n} \times \mathbf{u}) \times \mathbf{n} \times (\mathbf{n} \times \mathbf{u}) \times \mathbf{n}$ where $\mathbf{u}$ is the displacement vector. Eq.(2) is the modified extremum work criterion to account for the Coulomb friction effect in the ideal forming theory and the extremum work criterion is recovered for Eq.(2) when the friction is ignored with $\mu = 0$.

In order to solve Eq.(2), it is required to use a strain-rate potential, $\varepsilon_e$. In this work, the following anisotropic strain-rate potential, Srp98, for the plane stress state was applied to account for the anisotropy of sheet metals [9]:

$$\psi = \alpha_1 \hat{\varepsilon}_1 a + \alpha_2 \hat{\varepsilon}_2 a + \alpha_3 \hat{\varepsilon}_3 a = 2k\hat{\varepsilon}_e a$$

where $\hat{\varepsilon}_1$, $\hat{\varepsilon}_2$, $\hat{\varepsilon}_3$ are the principal values of the isotropic plasticity equivalent (IPE) strain rate $\hat{\varepsilon}$, which is obtained from the plastic strain rate, $\dot{\mathbf{e}} = \mathbf{L} \dot{\mathbf{e}}$. In Eq.(3), $\dot{\varepsilon}_1$, $\dot{\varepsilon}_2$, $\dot{\varepsilon}_3$ are the function of $\alpha_X$, $\alpha_Y$ and $\alpha_Z$, which are another set of anisotropic coefficients.
For isotropic materials, all the anisotropic coefficients become identical, typically with the value of 1.0. The exponent $a$ in Eq.(3) is used to match the shapes of strain-rate potentials with those calculated from polycrystal models. For FCC and BCC polycrystals, the exponents are 4/3 and 3/2, respectively. The value $k$ in Eq.(3) is a constant to accommodate the difference between the reference strain-rate state being used to define the effective strain rate with that being used for the stress-strain hardening curve.

**PREFORM DESIGN FOR HYDROFORMING PROCESSES**

In the preform optimization for hydroforming processes, the preform shape is assumed straight with a uniform cross section as an extruded part. Therefore, if the constraint that all initial positions stay on the initial surface envelope is imposed, Eq.(2) can be replaced with the following equation utilizing the penalty constraint method, especially when the friction condition is ignored:

$$
\frac{\partial}{\partial X_{i,2,3}} \left[ W(X) + \sum_{i=1}^{nnode-nsect} \frac{1}{2} C(X^i_3-X^i_{nsect})^2 \right] = 0
$$

(5)

where $X_{i,3}^{i=1-nsect} = 0$ and “nsect” is the total number of nodes in the cross section and “nnode” is the total number of nodes. Eq.(5) is a nonlinear equation for initial preform optimization with three degrees of freedom per a node. The Newton-Raphson method was used to solve Eq.(5).

**FIGURE 3.** Schematic view of the local coordinate system defined for a node set in the initial configuration

The direct design method was applied to obtain the optimum initial preform shape for the industrial part geometry shown in Fig.4, which is supposed to be the final target geometry after pre-bending and hydroforming.

**FIGURE 4.** Final target shape after mesh generation

In this work, the minimum plastic work assumption was applied for the whole processes including pre-bending and hydroforming. So, calculation was simply carried out as one-step for those two stages. The original thickness for the perform used is 2mm. Hardening and anisotropic data are given as follows:

Srp98 : $a=4/3$, $\alpha_k (k = 1 \sim 3) = 1$, $c_{int,2,3,6} = 1$

Hardening Curve :

$$\sigma = 359.84(0.001 + \varepsilon)^{0.223} \text{ (Mpa)}$$

Fig.5 shows the optimum preform shape with the optimum cross sectional shape obtained from the ideal forming design theory. Note here that various initial cross-sectional shapes were tried out as prescribed shapes until the most uniform strain distribution was obtained for the optimum cross-sectional shape. In this example, it is shown that the optimum cross section is not a circular shape, rather close to an elliptic shape. Fig.6 shows the thickness strain contour for the final target geometry.

**FIGURE 5.** Optimum preform shape
By carrying out the simple simulation based on the ideal forming theory only with the target geometry shape, the essential data necessary for initial preform and die design can be obtained within few minutes. Besides, the calculation also helps to evaluate feasibility of the target shape by investigating the optimum strain distributions for the target geometry. The preform shape obtained from the ideal forming theory would be valuable to carry out FE analysis simulations as a first trial initial shape, ultimately minimizing trial and errors to obtain the optimum preform shape with FE analysis.

Fig.7 shows the yield stress and r-value anisotropies of AA2090-T4 alloy sheet modeled by Srp98. It can be shown that two directionalsities are well described by Srp98. Fig.9 shows the initial blank shape as an input data, while Fig.10 shows the deformed shape obtained from the one-step forward calculation on the prescribed final surface envelope. Here, it is required to assume a final surface envelope where the solution is optimized. Fig.11 shows the thickness strain distribution. Because of the planar anisotropy, the non-symmetric strain distribution was obtained.

Original thickness: 1.6 mm

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**FIGURE 6.** Thickness strain contour for final geometry

**FIGURE 7.** Yield stress anisotropy of 2090-T3

**FIGURE 8.** R-value anisotropy of 2090-T3

In the automotive industry, it was reported that using the dynamic explicit analysis code in the flanging analysis is not so efficient compared to its stamping analysis in terms of accuracy and computational time.
Therefore, using the one-step forward and backward calculations based on the ideal forming theory might be an efficient approach to resolve the drawbacks of dynamic explicit codes for flanging analysis. Here, the one-step forward and backward calculations were performed to design the optimum trimming line before flanging. Fig.12 shows the final target geometry after flanging. Usually, in the automotive industry, the initial trial blank shape is obtained based on CAD predictions, neglecting material deformation. Fig.13 shows the blank shape obtained from CAD for the final target geometry shown in Fig.12.

Rather than performing expensive dynamic explicit calculation, the one-step forward calculation was employed in order to check the validity of the blank shape designed using CAD calculation. Fig. 14 shows the one-step forward solution on the prescribed flanging surface envelope and Fig. 15 shows the significant difference between the target geometry and the one-step forward solution obtained utilizing the blank obtained from CAD, indirectly confirming that the blank shape obtained from CAD would not be so useful as expected to form the target geometry.
FIGURE 14. One-step forward solution obtained utilizing the blank obtained from CAD

FIGURE 15. Comparison of the target geometry with the one-step forward solution obtained utilizing the blank obtained from CAD

FIGURE 16. One-step backward solution for the blank shape with the trimming line.

Now, the one-step backward calculation was employed to predict the optimum blank shape suitable for the target geometry as shown in Fig. 16. It is worthwhile to mention that the blank shape considering material deformation shown in Fig. 16 shows a significant different trimming line compared to that shown in Fig. 13, which is obtained from a geometrical CAD calculation. Therefore, utilizing the blank obtained from the ideal forming backward calculation would be more useful than that obtained from CAD in designing flanging operations.

CONCLUSIONS

The ideal forming theory, developed as a direct design method to guide iterative design practices based on analytic methods, was applied for the hydroforming process having non-flat preform shapes and also for the flanging process utilizing forward and backward calculations. It was shown that the direct design approach based on the ideal forming theory would be useful to obtain information on optimum preform shapes and also to evaluate the feasibility of the target shape in the design stage.

REFERENCES