Use of the Inverse Approach for the Manufacture and Decoration of Food Cans


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Abstract. Innovation is a key objective in the metal packaging industry in order to produce new concepts, designs, shapes and printing. Simulation technology now allows both the can design as well as the manufacturing process to be carefully analysed before any physical prototypes or dies have been manufactured. These simulations are traditionally carried out using incremental simulation methodologies. However, much information may also be attained by using the inverse approach: the initial blank format for the can body as well as its lid may be optimised much faster, the actual decoration of the can may be evaluated and even calculated when deformation printing techniques are utilised. This paper presents some of the technical details relating to the inverse approach employed in Stampack to carry out simulations important for the manufacture of food cans that are shown via industrial.

INTRODUCTION

The automotive industry has been quick to capitalize on the use of CAD/CAM/CAE technologies in order to improve the production of high quality formed panels in a short time and at a low cost. However, in the design and manufacture of food cans this trend has been somewhat slower.

A natural use of simulation in the food can industry is to evaluate the deformation paths and the forming defects such as fracture and wrinkling. This generally requires the use of the so-called incremental algorithms (explicit or implicit methods) where the initial design of the blank and the tools is known and when the forming conditions are defined. These analysis tools are generally very precise, but need trained engineers and are time consuming to use.

In many scenarios this level of detail is not required or known and a simpler simulation method may be used. Various methods have been developed that are based on the fact that the shape of the desired part is already known: this enables a comparison to be made with the initial flat blank in order to estimate the sheet deformation by taking into account simple constitutive equations and assumptions regarding the tool actions. These simplified procedures have been called variously as "Geometrical mapping method", "Single and multi-stage forming formulations", "One step solution"[13], "Ideal forming theory", "Inverse approach"[1-2] and "Simplified approach", amongst others.

The Inverse Approach used in Stampack[3] is based on a discretization of the final part by simple triangular flat facet shell elements. Originally membrane CST elements and conical membrane elements were considered since these effects dominate many industrial processes, but more recently bending effects have been taken into account[4-6]. The formulation includes assumptions regarding the action of the tools (punch and die) in the forming process. Logarithmic strains and total deformation theory of plasticity are considered and equilibrium considerations leads to a set of nonlinear equations with only two degrees-of-freedom per node, even if bending effects are taken into account. This procedure has proved to be very efficient and quite precise for use at the preliminary tool design stage.

In this paper, we review the formulation of the Inverse Approach including the bending effects. Then we present some industrial application of the Inverse Approach to the design and manufacture of food cans.
THE INVERSE APPROACH

The Inverse Approach (IA) for sheet metal forming analysis has been presented in details by the authors [7-11]. This method exploits the knowledge of the final workpiece shape: starting with a finite element mesh on the final part, we look for the nodal positions in the initial flat blank. The simple vertical projection of the nodes on the horizontal plane provide an initial estimation, and these node positions are then modified by a Newton-Raphson algorithm in order to satisfy the equilibrium in the final workpiece. Two main assumptions are adopted: the proportional loading assumption avoids the incremental integration of plasticity (Deformation Theory of Plasticity) and the second assumption allows the use of simplified pressure-friction forces instead of the contact conditions between the tools and the sheet. These assumptions lead to a total or direct method independent of the deformation history. The IA is very fast and does not require much memory (only two degrees of freedom per node).

Kinematic Relations

In the Inverse Approach, only the initial flat blank C0 and the final 3D workpiece are considered. Using a generalized Kirchhoff assumption, the initial and final position vectors of a material point q can be expressed with respect to point p on the mid-surface of C (Figure 1):

\[ \mathbf{x}_q = \mathbf{x}_p + z^{0} \mathbf{n}^{0} = \mathbf{x}_p - \mathbf{u}_p + z^{0} \mathbf{n}^{0} \]
\[ \mathbf{x}_{q} = \mathbf{x}_{p} + z \mathbf{n} \]  

(1)

where \( \mathbf{u}_p \) is the displacement vector of point \( p \), \( \mathbf{n}^{0} \) and \( \mathbf{n} \) are the normals to the mid-surface at \( p^{0} \) and \( p \), and \( z \) are the coordinates along the initial and final thickness directions.

Let \( \mathbf{x} = <x, y, z> \) be the local orthogonal curvilinear coordinates. The transformation tensors at points \( q^{0} \) and \( q \) with respect to point \( p \) are then given by:

\[ d \mathbf{x}_q = [F_0]^{-1} d\mathbf{x}_p \]
\[ [F_0]^{-1} = \begin{bmatrix} x_{p,x} & \mathbf{u}_{p,x} & \mathbf{u}_{p,y} & \mathbf{n}^{0} / \lambda_3 \end{bmatrix} \]

(2)

\[ d\mathbf{x}_q = [F_z] d\mathbf{x}_p \]
\[ [F_z] = \begin{bmatrix} x_{p,x} + z \mathbf{n}_x & x_{p,y} + z \mathbf{n}_y & \mathbf{n} \end{bmatrix} \]  

(3)

where \( \lambda_3 = z / z^{0} = h / h^{0} \) is the thickness stretch (assumed to be constant through the thickness). So the inverse deformation gradient tensor at \( q \) is obtained from equations (2) and (3):

\[ d\mathbf{x}_q = [F]^{-1} d\mathbf{x}_p \; \; \; [F]^{-1} = [F_0]^{-1} [F_z]^{-1} \]

(4)

FIGURE 1. Kinematics for thin sheet deep drawing.

The tensors \([F_0]^{-1}\) and \([F_z]^{-1}\) are the membrane and bending contributions respectively. Simple expressions of the tensors \([F_0]^{-1}\), \([F_z]^{-1}\) are obtained in the local coordinate system defined by:

\[ \mathbf{t}_1 = \mathbf{x}_{p,x} \; \; \; \mathbf{t}_2 = \mathbf{x}_{p,y} \; \; \; \mathbf{n} = \mathbf{t}_1 \times \mathbf{t}_2 \; \; ||\mathbf{t}_1 \times \mathbf{t}_2|| \]

(5)

In a membrane model, \([F_z]^{-1}\) reduces to an orthogonal matrix. The inverse of the Cauchy-Green left tensor between \( q \) and \( q^{0} \) can then be defined by:

\[ [B]^{-1} = [F]^T [F]^{-1} \]

(6)

The \([B]^{-1}\) tensor can be obtained under the assumptions of constant thickness stretch without coupling of the in-plane stretches and the thickness stretch. The \([B]^{-1}\) eigenvalues give the two principal plane stretches \( \lambda_1, \lambda_2 \) and their direction transformation matrix \([M]\). Then the thickness stretch \( \lambda_3 \) is calculated via the incompressibility assumption.

Finally, the logarithmic strains are obtained as:

\[ [\varepsilon] = [M] [\ln \lambda.] [M]^T \]

(7)
Constitutive Equations with Planar Anisotropy

In the present IA, the elasto-plastic deformation is assumed to be independent of the loading path and the so-called Hencky deformation theory of plasticity is adopted. If we consider a planar anisotropic sheet, then yielding can be described by the Hill criterion with the plane stress condition:

\[ \phi = \langle \sigma \rangle [P] \sigma - \overline{\sigma}^2 = 0, \]
\[ \langle \sigma \rangle = \left( \sigma_x \quad \sigma_y \quad \sigma_{xy} \right) \]  
(8)

where \( \overline{\sigma} \) is the equivalent yield stress and the matrix \([P]\) is expressed in terms of the mean planar anisotropic coefficient \(\overline{r}\) defined by the three Lankford coefficients.

The proportional (or radial) loading assumption enables the following relation between the total plastic strains and the total stresses:

\[ \{ \varepsilon_p \} = \frac{\overline{\varepsilon}_p}{\overline{\sigma}} [P] \{ \sigma \} \]  
(9)

with the equivalent plastic strain given by

\[ \overline{\varepsilon}_p = \left( \langle \varepsilon_p \rangle [P]^{-1} \{ \varepsilon_p \} \right)^{1/2}. \]

If we assume the above anisotropy condition to be valid for the (small) elastic strains, then the Poisson coefficient is related to the mean anisotropy coefficient via:

\[ \nu = \frac{\overline{r}}{1 + \overline{r}}. \]  
(10)

So the total constitutive equation takes the following simple form:

\[ \{ \sigma \} = E_S [P]^{-1} \{ \varepsilon \}, \quad E_S = \frac{\overline{\sigma}}{\overline{\varepsilon}}, \]  
(11)

where \( E_S \) denotes the secant modulus of the uniaxial stress-strain curve and \( \overline{\varepsilon} \) is the equivalent strain. Using an estimation of the total strains \( \{ \varepsilon \} \), we can calculate \( \overline{\varepsilon} \) and \( E_S \) and then estimate the stresses. This operation is performed at the centroid of each element.

We then integrate the expression for the element internal work vector and define the global components of the internal force vector:

\[ W_{int}^e = \left\{ U_n^e \right\} \left\{ F_{int}^e \right\} \]  
(12)

with:

\[ \left\{ U_n^e \right\} = \left\{ U_i^e \quad V_i^e \quad W_i^e \right\} = 0 \quad i = 1, 2, 3 \]
\[ \left\{ F_{int}^e \right\} = [T]^T [B_m] \left\{ N \right\} A \]  
(13)

where the vector \( \{ N \} \) represents the membrane forces. In the above equation, only \( \{ N \} \) is changing during the iteration process. The virtual vertical displacements are zero since the real vertical displacements are known from the given workpiece shape.

The direct IA cannot deal with contact problems that depend on the loading history, so the tool actions (punch and die) are simply represented by some external forces at the final configuration. Several assumptions are made regarding the actions of the punch, die and the blankholder \([1, 2]\). The consideration of the tool actions gives the external force vector, leading to the following non-linear equilibrium system to be solved:

\[ \{ R(U, V) \} = \sum_e \left( \left\{ F_{ext}^e \right\} - \left\{ F_{int}^e \right\} \right) = 0. \]  
(14)

INDUSTRIAL EXAMPLES

Some industrial examples based on the manufacture of standard rectangular and oval food cans are presented here using the IA as implemented within the Stampack-OneStep software; it is noted that the same procedures are directly applicable to circular and other shaped cans be they shallow or deep. Three main aspects are dealt with: the pressing of the can body, the computation of the lid initial blank and the decoration of the can.

**Optimization of the Can Body**

With billions of food cans being produced each year can manufacturers wish to minimize the blank format of the can body as much as possible since this reduces costs by enabling more cans to be nested on a single sheet. Printing costs are also reduced since all decoration is carried out on the flat sheet prior to pressing. This is true for single-draw cans as well as
the typical draw-redraw process. Using the IA enables the initial blank shape to be predicted and optimized while at the same time getting a feel for the straining of the material.

Blank shapes for square cans produced via a single draw have been optimized using the IA without much difficulty but more interesting is extending the use to cans manufactured using the draw-redraw (or DRD) process. For an oval can produced via DRD, final size approximately 106mm by 66 mm, the calculation of the initial format is shown in Figure 2 and the change in thickness is shown in Figure 3.

![Figure 2](image1.png)

**FIGURE 2.** The final shape of the oval can shown superposed on the calculated initial format.

![Figure 3](image2.png)

**FIGURE 3.** The thinning of the sheet is shown as a contour on the final can shape.

As a means of checking and showing the accuracy of the simulation results obtained via the IA these results were compared with a Stampa**

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Traditionally manufacturers use a trial-and-error approach coupled with some formulas based on experience to calculate the initial format. However, differences in materials, sizes and shapes make this task more and more demanding and so it is now possible to utilize the IA for this task. The initial format for the lid (approximately 120mm by 75mm) as calculated using the IA is shown in Figure 5.

The best way of comparing this result is to resort to the experience of the die-maker. This simulation result, produced in a matter of minutes, was compared with an industrial case and showed a difference of 0.5% - it is still being investigated which result provides the best initial blank.

**Decoration of an Oval Can using Distortion Printing**

A novel application of the IA is the calculation of the decoration applied to typical food cans of the type described above. During manufacture it is much easier to print the decoration on the flat sheet and then to press the cans. The process is often called deformation or distortion printing, since a distorted image must be printed on the sheet in order to produce the desired decoration on the final shape.

Once the final can shape together with the required decoration is supplied (via the Decoration module) as shown in Figure 6 Stampack uses the IA to compute the initial blank format, implying the knowledge of the can deformation. Hence it is able to compute the flat image that needs to be printed on the original blank, shown in Figure 7, where it can be clearly seen that the image is more distorted along the major oval axis. Similar results on industrial decorations compare favorably to results obtained by artistic and grid-marking methods. It is noted that results are improved as more process parameters are included thereby taking into account as many pressing effects as possible.

**FIGURE 6.** The final can shape together with the applied decoration.

**FIGURE 7.** The computed initial format shown together with the distorted printing required in order to obtain the correct decoration.

The same process can be used for rectangular and other general 3D shaped cans, even though sometimes the application of the design is more complex. On rectangular cans the effect can be quite dramatic as shown in Figures 8 and 9, where the base deformation is minimal but the sidewall distortion is substantial.

**FIGURE 8.** Side view of a rectangular food can showing a decoration required from this viewpoint.

**FIGURE 9.** Calculated initial sheet format showing the distorted image required to obtain the decoration.
It is also possible to reverse the process and see what a flat printed image may look like on the final can. The calculated image to be printed is obtained with much less effort and industrial prototyping thereby reducing the cost enormously especially when new manufacturing processes or new decorations are virtually prototyped.

CONCLUSIONS

The Inverse Approach has been shown to provide excellent results when optimizing blank formats for can bodies in order to reduce material usage and also for calculating an accurate initial blank for the pressing of can lids in preparation of the subsequent seaming operation. Not only are the blanks optimized but valuable information is obtained on the stretching of the material. Even for DRD cans the accuracy provided by Stampack-OneStep is within industrial tolerances.

The initial format and stretching information obtained via the IA can also be used to great effect in calculating the initial printed image (flat) that is required in distortion printing techniques for food can manufacture.

The Inverse Approach is thus a feasible simulation tool for the food can manufacturing industry.

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