Formability Predictions in Stamping and Process Parameter Optimization Based on the Inverse Approach Code Fast_Stamp

J.L. Batoz¹, H. Naceur², Y.Q. Guo³

¹ Institut Supérieur d’Ingénierie de la Conception, Equipe de Recherche en Mécanique et Plasturgie, 27 rue d’Héliéule, 88100 Saint-Dié-des-Vosges, France
² Université de Technologie de Compiègne, Laboratoire Roberval, FRE 2833, BP 20529 60205 Compiègne Cedex, France
³ Université de Reims, Laboratoire GMMS, BP 1039 51687 Reims, France

Abstract. A simplified (one step) method called “inverse approach” (IA) for the numerical analysis of the stamping process has been continuously developed by the authors since the end of the eighties. In the present paper we recall the main finite element formulation aspects, for an efficient estimation of the large elastoplastic strains encountered in deep drawing operations. The capabilities of the code Fast_Stamp include: fixed (imposed) initial blank, bending effects due to tool curvatures, blankholder restraining forces (including drawbeads). Considerations of bending and unbending during forming stages can improve the IA regarding stresses distribution. In this case satisfactory estimation of springback can result. Since 1996 we also developed “math based” optimization algorithms and strategies. The cost functions and constraints are mainly expressed to reduce or control the thickness changes, the localized necking, the wrinkling tendency, the springback after forming. The design variables are describing the shape of the blank, the additional (addendum) surfaces, the restraining forces due to drawbeads and the material properties such as anisotropy coefficient and hardening exponent. Optimization algorithms are mainly based on surface response techniques with moving least square approximation and SQP to find the optimum solution at each iteration. Selected results will be presented related to the design of additional surfaces.

INTRODUCTION

FEM stamping simulations are routinely performed in industry for the formability predictions of sheet metal blanks and for the design of the tools to produce the parts. Commercial codes have been continuously updated since the early 90’s after academic and pre-competitive development of codes in research centers and university laboratories (with details found in [1 to 6]).

Two major families of codes are available. The first allows simulating the behavior of a known initial flat blank subjected to forming rigid tools. The second family of codes estimates the strains in the final part, mainly assuming the knowledge of the final part. The codes belonging to the first family are based on “direct” (explicit or implicit) incremental approaches taking into account the evolution of the strain paths and contact conditions between the tools and the part, with possibility of several forming operations in sequential steps. The second family of codes are based on indirect or Inverse Approaches - I.A.- (more known today as “one step codes” or OSC in the following) since they predict the material points positions belonging to the initial flat blank knowing the final mid-surface shape and with simplifying assumptions regarding the action of the tools and the material behavior. Both families are mainly based on shell finite elements formulations.

The usefulness of “one step codes” has been fully recognized to evaluate the forming difficulties at the early design stages, to perform fast estimation of the blank shape in complicated 3D part, to make fast analysis of the sensitivity of some process parameters and also to help tool designers. This, despite the fact that the validity of the assumptions is questionable in some situations leading to poor precision in results (specially regarding the stresses although progress is made [7 to 10]). Several major reasons can be given for the interest in OSC: the small amount of computer resources, CPU time and memory storage needed, the reduced level of code user skills, the relatively low price of OSC licenses and more by the fact that the starting point is the geometry of the part we want to obtain after stamping (for the incremental codes all process parameters must be known in
advance, including geometry and material properties of the blank). Another important aspect is the fact that, although possible in principle, it is yet extremely difficult, to perform “mathematically based optimization” of the process parameters using incremental codes in order to obtain a defect free part, mainly due to time and computer resources constraints. However such optimizations can be performed in practice using OSC to generate the state variables.

In the following sections:
- the main characteristics and assumptions of our FEM I.A. research code Fast_stamp are recalled with applications to practical stamping simulations including springback estimation after forming,
- the optimization of various process parameters is discussed (methods and results).

GENERAL DESCRIPTION OF FAST_STAMP FOR STAMPING ANALYSIS

Assumptions, formulation aspects

The detailed aspects of the formulation and main characteristics of the FEM code Fast_stamp based on the Inverse Approach will not be given here. Those details can be found in the papers [10 to 18] published since 1990. Of course other authors did proposed similar methods, called “geometrical mapping”, “one step solution” approaches, “ideal forming theory”, and “simplified formulations”. References can also be found in our previous papers.

**FIGURE 1:** Principle of the I.A. - In red (green) unknown (known) variables.

The main characteristics of our “classical” I.A. formulation are the following:

- The 3D final mid-surface, (defined from a CAD system) is known a priori. If the initial flat blank relies in an horizontal plane, then all vertical components of the (material) displacement vectors between the initial surface (the blank) and the final surface (the workpiece) are known. The direction of the normals to the initial and final surface is also known. Those considerations lead to the conclusion that the 3D deformation process involves only two unknown quantities: the two horizontal components of the displacement vectors of the material points (Figure 1).
  - The 3D kinematics is based on the generalized Kirchhoff-Love assumptions (“normals keep normals” and plane stress conditions), but with possibility of thickness change, within isochoric deformation constraint (at least on the mid-surface).
  - Large (logarithmic) strains are defined and computed via the formulation of the left Cauchy-Green tensor.
  - Hill 1948 criterion of plasticity for metallic sheets is considered, with average Lankford anisotropy coefficient r. Hencky deformation theory of plasticity, (assumption of radial or proportional loading), is invoked to obtain a constitutive law expressing the total Cauchy stresses and the total logarithmic strains. Uniaxial stress strain curve (like Hollomon or Swift) are necessary, as well as, Young and Poisson modulus, and average normal anisotropy r.
  - The Principle of Virtual Work (PVW), expressed on the final workpiece, is “discretized” using the simple triangular shell elements DKT12, with constant membrane and bending moments per element.
  - The external virtual work is defined with different contributions. The most important one results from the relative action of the punch and die. If friction is not taken into account, then normal forces are acting at each node. Their intensities are obtained from the estimation of the vertical reaction force during the iteration process. Effect of restraining forces under the blankholder due to drawbeads and blankholder pressure with friction can also be considered.
  - The nonlinear system of equilibrium equations (with 2 unknowns per node) resulting from the PVW is solved considering a Newton-Raphson iteration scheme (implicit approach) with a non symmetric tangent stiffness matrix. Symmetry conditions if they exist and elimination of rigid body modes (maximum 3 since all vertical displacements are imposed) are taken into account.
  - Robustness (convergence) and efficiency of the approach depends heavily upon the initial solution (position of the nodes in the initial blank). Vertical projection is a first idea but not
the best or the good one. Several techniques can be used to unfold the 3D part.

**Present capabilities of Fast_stamp**

The Fast_stamp code is the result of the integration of continuous developments since 1987, undertaken by the authors and collaborators. Some standard capabilities are:

- 3D discretization of final parts with 3 nodes elements (up to 120000 dofs with only 512 Mb of RAM) using CAD surface definition, including membrane and bending effects (due to curvatures of the final part).
- Consideration of normal nodal forces due to relative tool actions, drawbeads and friction effects due to blankholder pressure.
- Average normal anisotropy, Hollomon or Swift law.
- Possibility of imposing the shape of the initial blank contour.
- Results include the initial shape of the contour (or the final one if not imposed), the principal strains (and FLD), the thickness changes, the nodal forces and total press force.

The Automotive Deeklid Inner Panel (Benchmark 1 of the present Numisheet’2005) has been considered as an example of the application of Fast_stamp. The first forming operation is simulated but without considering the drawbeads. However the holder force of 1334 kN is considered with friction effect. The calculations using Fast_stamp are performed using 54914 DKT12 shell elements (figure 2) and we did consider the trapezoidal shape of the initial flat blank as required in the test. Stampack-Incremental® [13] is also used with the same conditions.

The thickness distribution is shown on figure 3 using Fast-stamp and Stampack-Incremental®, and the maximum thickness changes are reported in Table 1, if the friction effects and imposed initial blank contour are considered or not.

![FIGURE 2. Mesh of the final workpiece used for the IA.](image)

![FIGURE 3. Thinning comparison after first forming operation](image)

**TABLE 1. Thinning comparison (in mm)**

<table>
<thead>
<tr>
<th>Method</th>
<th>$\Delta h_{\text{min}}$</th>
<th>$\Delta h_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverse Approach NF, NB</td>
<td>-5.43</td>
<td>+5.67</td>
</tr>
<tr>
<td>NF, B</td>
<td>-5.10</td>
<td>+7.41</td>
</tr>
<tr>
<td>F, B</td>
<td>-5.32</td>
<td>+7.26</td>
</tr>
<tr>
<td>Explicit Dynamics F, B</td>
<td>-11.60</td>
<td>+7.94</td>
</tr>
</tbody>
</table>

*NF : no friction, NB: no imposed blank, F: friction, B: imposed blank. Initial thickness of 0.8mm.

The CPU time (on the same computer) is about 1mn 50s with Fast_stamp and 1h 3mn 11s using Stampack-Incremental® for quite comparable results, although the mesh using Stampack-Incremental® was coarser.

**Advanced capabilities resulting from more recent research works include:**

- Improvement of the “basic” I.A., mainly to better estimate the stresses distribution. For that purpose one can define “geometrically admissible intermediate steps” and use simplified incremental “path dependant” constitutive equations. This was called Pseudo I.A. [9]. Precision is gained but CPU time significantly increased. Another recent improvement is described in [7, 8, 10]. It consists in taking into account the most important bending-unbending
effects due to the material flow over the tool radius. The effects modify the values of the resultant forces without increasing the CPU time. Therefore the global efficiency of the I.A. is kept, however the modifications require a good preliminary geometrical inspection of the part. The method is called Improved I.A. (I2A).

The forming analysis stage using the I2A can be followed by an Updated Lagrangian Formulation (ULF) using the same type of DKT12 shell elements with 12 dof per element, but with assumption of small elastoplastic strains (after forming) and taking into account the knowledge of the residual forces at the end of the forming stage as initial conditions. The above ULF leads to an incremental implicit approach which is very efficient and quite precise for the estimation of the equilibrium and warping displacements due to springback after forming or cutting operations.

The results of an interesting springback problem proposed and studied experimentally [12], consists in three operations: first a classical deep drawing operation is carried to get a cylindrical cup (Figure 4.a), then the cup is cut to get a circular ring specimen (Figure 4.b,c), and the third operation is a radial splitting (Figure 4.d) leading to ring opening due to residual stresses. The objective of this application is to evaluate the ring opening gap value after forming and springback.

Geometry and material data are given in [9]. The I2A ([10]) has been used to carry out the deep drawing simulation. Only a quarter of the cup is modeled by 3150 DKT12 shell elements [15 to 18], with 5 Lobatto points through the thickness for plasticity integration. The results have been compared to those obtained using two incremental methods. Figure 5 shows the comparison of the circumferential bending moment distribution between Fast_stamp (I2A) and Stampack-Incremental® (explicitit dynamic code with the BST rotation-free triangular shell elements) [13]. Figure 6 shows the results of the circumferential stress distribution on the outer surface using ABAQUS® standard (Implicit) and Fast_stamp.

The membrane forces and bending moments at the end of the deep drawing operations (obtained using I2A) are stored and are considered as initial residual stresses for the second simulation stage consisting in performing an incremental nonlinear analysis using the ULF with DTK12 shell elements, but considering the ring as in figure 4c and d. The same mesh (with 1200 DKT12 shell elements) is used to model half of the ring (assumed clamped opposite to the split). Convergence is achieved in 10 steps. The results (opening gap) is compared with results using Stampack-Incremental®, with results from the Pseudo I.A. [9] and finally with the experimental results extracted from [12], Table 2. The results obtained by the I2A followed by the ULF
are very good compared to experiment, for a CPU time of a few seconds.

<table>
<thead>
<tr>
<th>Method</th>
<th>nb. elem.</th>
<th>Gap [mm]</th>
<th>CPU time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stampack® [13]</td>
<td>7000</td>
<td>45.7</td>
<td>2h 33m 53s</td>
</tr>
<tr>
<td>Gati et al [9]</td>
<td>9984</td>
<td>45.0</td>
<td>2h 05m 20s</td>
</tr>
<tr>
<td>Fast_stamp</td>
<td>3150</td>
<td>47.8</td>
<td>0h 00m 13s</td>
</tr>
<tr>
<td>Experiments [12]</td>
<td>50</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 2.** Summary of principal springback results - comparison

OPTIMIZATION OF PROCESS PARAMETERS

Since the I.A. is a valuable analysis tool to estimate the forming difficulties at the preliminary design stage, it is natural to include the analysis capability in an optimization loop of stamping parameters. The I.A (and now the I2A) has been combined with different optimization algorithms to optimize:

- The initial blank contour (1996) [11,16],
- the restraining forces due to drawbeads [16,17],
followed by drawbeads design [17],
- the material parameters such as hardening exponent n and mean planar anisotropy r [18],
- the geometry of the addendum surfaces [19],
- the geometry of the forming tools to compensate springback [10].

Objective functions (OF) and constraints functions have been defined to characterize a defect free part: minimization of thickness changes [11,16,17,18], minimization of principal strains based on the use of Forming Limit Curve (with a safety margin) [18], limitation of wrinkling tendency in the final shape.

Several optimization strategies and algorithms have been proposed and evaluated. The first optimization problems (period 1996 to 1999) were based on the computation of the gradients of the OF and constraints functions with respect to the DV set. Those gradients were obtained analytically when possible, or numerically (by finite differentiation). BFGS and SQP algorithms are used to update the DV set at each iteration of the optimization loop. More recently response surface methods with diffuse approximation and adaptive strategy to update the research space have been considered [10].

As an application of the optimization procedure combining the I.A. with a Feasible Sequential Quadratic Programming we briefly present the results of an academic problem dealing with the optimization of addendum surfaces (details found in [19]). Let us assume that we wish to produce a square box of mild steel 12.5 mm depth after trimming. We optimize four geometrical parameters (figure 7) describing the addendum surfaces, in order to achieve a box with thickness variation between 20% to 15% (constraint function). The OF is related to surface quality preventing the sheet from scratch when passing over the die entrance radius (zone F to E on figure 7). This OF is defined such that any material point belonging to the useful part (zone ABCD on figure 7) never passes through point F. Figure 7 shows a typical cross section of the square box from the center A to the outer contour of the initial blank G. The geometry of the useful (fixed) part are: \( B_u = 25\,\text{mm}; \alpha_u = 5.4^\circ; H_u = 12.5\,\text{mm}; \ R_u = 8\,\text{mm}. \) The 4 DVs are subjected to the empirical constraints: \( 10 \leq H \leq 20\,\text{mm}; \ 2 \leq B \leq 40\,\text{mm}; \ 5^\circ \leq \alpha \leq 30^\circ; \ 5 \leq R \leq 10\,\text{mm}. \)

**FIGURE 7.** Design variables: 4 geometric parameters

The square box is discretized with 3628 elements. The calculations are performed in 36 m of CPU on a PC-IV. The optimization procedure needs 25 I.A. calls (8 for feasibility and 15 for optimization searching) and gives the following results: \( H = 12.34\,\text{mm}; \ \alpha = 10.7^\circ; \ R = 7.5\,\text{mm} \) and \( B = 29.\,\text{mm}. \) The thickness distribution remains within the thinning and thickening limits (figure 8).

**FIGURE 8.** Thickness distribution
CONCLUSIONS

The standard and advanced characteristics of the research code Fast_stamp for sheet stamping difficulties analysis, for estimation of springback effects and also for process optimization parameters have been presented in general terms, with selected numerical results. Theoretical improvements, validations, robustness and integration of developments to satisfy industrial requirements are continuously performed in our research groups.

The standard I.A. capabilities included in Fast_stamp are presently integrated in the commercial code Stampack® (module Stampack-OneStep®), within a collaboration agreement between Quantech ATZ and the authors.

ACKNOWLEDGMENTS

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