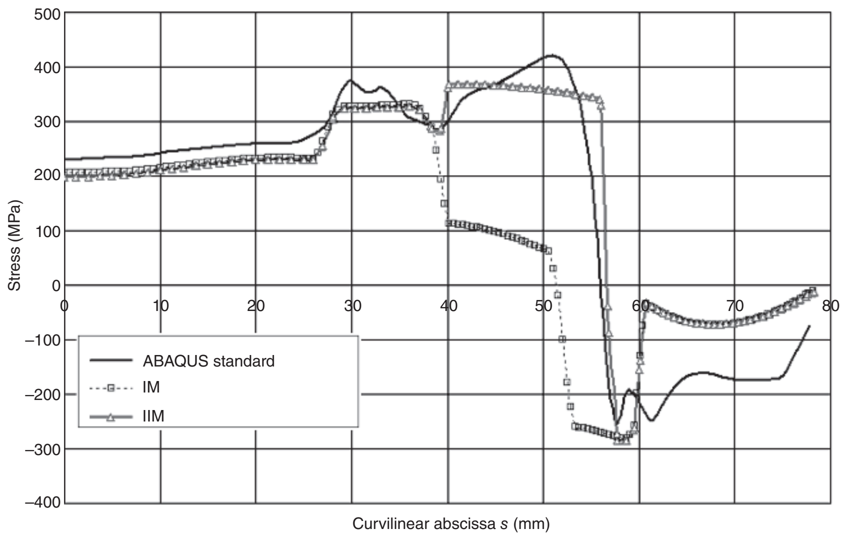


Figure 1.20 Distribution of the maximum stress on the upper layer.

To analyze the obtained results, the evolution of the maximum stress on the upper layer of the box along the *XZ* plane of symmetry is plotted as shown in Figure 1.20. One can remark that unlike the standard Inverse Method, the Improved Inverse Method allows a good prediction of stresses especially in the potential zone between the die entrance line and the punch, i.e. $40\,\text{mm} \leq s \leq 60\,\text{mm}$.

Figure 1.21 shows the distribution of the maximum stress on the upper layer of the square box obtained by the Inverse Method before and after improvement as well as the reference solution of ABAQUS standard. One can notice that the Improved Inverse Method allows the detection of the potential area of elements which have undergone bending and unbending effects and improve the stresses in the part of the free strand (free area between the punch and the die radius). Hence, the Improved Inverse Method becomes of a great interest in simulating the springback effects at the end of the stamping.

1.3 Optimization of Stamping and Hydroforming Parameters

Perhaps one of the most important added values of the numerical simulation of sheet metal forming processes such as stamping and hydroforming is to help the user understand the material deformation process involved during the forming of the workpiece for given operating conditions. The main objective is to produce parts which meet the customer's specifications. Understanding the material deformation process allows a user with a significant metal forming knowledge to control and modify the process conditions avoiding fracture and wrinkling risks.

As soon as the finite element simulation codes based either on explicit dynamics or implicit statics were shown to predict accurately the quality of the final

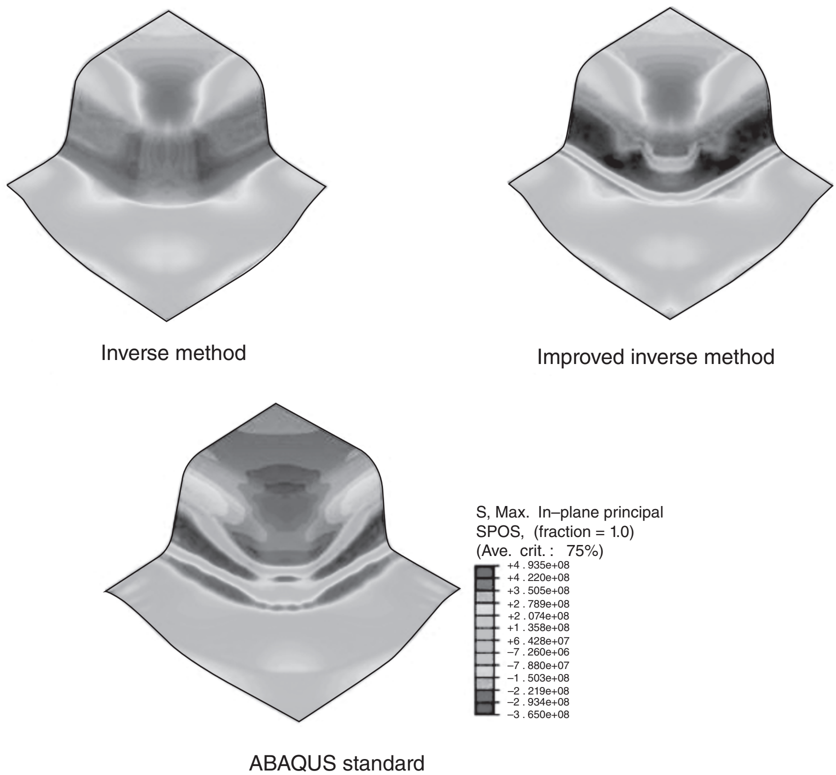


Figure 1.21 Distribution of the maximum stress on the upper layer.

workpiece, different research groups proposed to introduce the mathematical optimization problem to automatically predict "ideal" values of some key forming process parameters in order to obtain a defect-free workpiece. The goal here was the prediction of the best sheet metal forming conditions for a given CAD geometry.

This section does not intend to be exhaustive and cover all recent research works on the optimization of stamping and hydroforming processes parameters, since the number of research investigations on this topic is extensive. In this section, a brief overview of recent research related to the optimization of sheet metal forming is presented.

One can group the investigations from the simplest to the most difficult from the numerical implementation point of view:

- the geometry and position of the initial blank,
- the holding pressure exerted by the blankholder, the position and geometry of the drawbeads,
- the tool geometry (to control the springback),
- the nature and quantity of the lubricant,
- the blank material,
- the nature of tools.

1.3.1 Mathematical Optimization Problem

Most of the applications presented in this chapter were solved using mathematical programming methods where the objective was the numerical resolution of the optimization problem. The optimization problem can be stated as follows:

$$
\begin{aligned}
& Min\ f(v_i) & & \\
\text{with}\quad & g_j(v_i) \leq 0 & & j = 1, m \\
& h_l(v_i) = 0 & & l = 1, m_e \\
& v_{i\,\min} \leq v_i \leq v_{i\,\max} & & i = 1, n
\end{aligned}
\tag{1.10}
$$

where f is the objective or cost function to be minimized according to the design variables v_i, and g_j and h_l are the inequality and equality constraints respectively.

Design variables are the sheet metal forming process parameters chosen to be modified. The objective and constraint functions aim to describe in mathematical form the objective of producing a defect-free workpiece. The constraints functions also make it possible to introduce geometrical bounds on the design variables. From the mathematical point of view, the chosen functions must reproduce the user desire in producing a final workpiece by avoiding fracture and wrinkling [30, 31, 34]. Therefore, it becomes necessary to be able to translate into a mathematical form the concept of a "defect-free" part from the mechanical state estimated using numerical simulation. The determination of "good" objective and constraint functions will not be detailed in this section. Interested readers are invited to refer to the references.

1.3.2 Shape Optimization of the Initial Blank

In early 1996, we proposed to optimize the shape of the initial blank [35]. The design variables are the control knots distributed on the contour of the initial blank and used to build a cubic B-spline parametrization. Different objective functions were tested. They used variations in thickness to control the risks of excessive thinning, which precedes the metallic sheet fracture and the risks of thickening, which reflects a tendency for wrinkling. Numerical simulations were performed using an Inverse Method to solve the stamping problem in a single step, coupled with an optimization algorithm based on Sequential Quadratic Programming method. The gradients of the objective function and constraints were calculated using the adjoint state variable method, i.e. analytically in our in-house stamping software FASTSTAMP© [31]. The procedure was applied to the optimization of a Twingo car dashpot cup (Figure 1.22). The initial blank contour was described using eight control knots. Therefore, 16 design variables were generated. Convergence was achieved after 20 iterations. The thinning evolved from an initial value of −20.27% to −12.92% and the thickening evolved from 17.44% to a final optimal value of 13.41%.

During the first presentations of these results, criticisms were raised on the complexity shape of the contour which is difficult to cut in an industrial context of high production rate. It seems that the introduction of a laser cutting portal and the increase in the price of steel make nowadays this type of optimization more interesting.

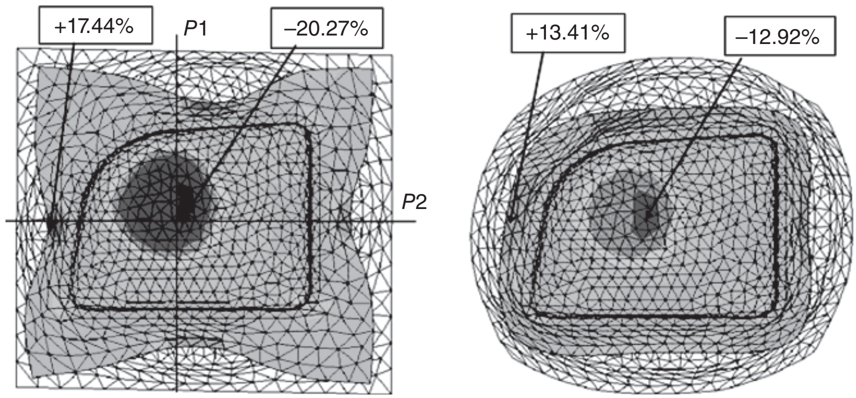


Figure 1.22 Optimization of a Twingo car dashpot cup: initial and optimal contour.

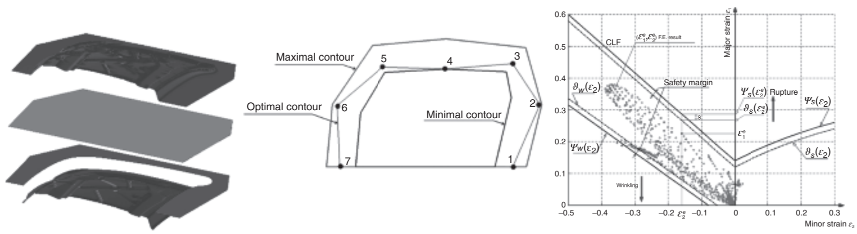


Figure 1.23 Blank shape optimization procedure in the stamping process.

However, an alternative method has been proposed for working on blank contours by using line segments. The design variables are the coordinates of segments intersections. The optimization problem is solved by carrying out an approximation of the objective function and constraints using diffuse approximation (or weighted least squares method). An optimization algorithm solves the approximated problem. It is possible to improve the solution obtained by carrying out a second design of experiments located around the first identified optimum. This technique has been successfully applied in the optimization of several industrial applications (Figure 1.23).

1.3.3 Optimization of Addendum Surfaces of Stamped Parts

A variant of topology family method called “Evolutionary Structural Optimization” or ESO for the topological optimization of structures and mechanical parts has been proposed by Xie and Steven. This method is based on the concept of progressive removal of ineffective material from the structure. Thus, the structure will evolve from a large very simple shape (usually rectangular) to the desired optimal shape (usually complex).

Compared to other structural optimization techniques, such as the homogenization method and the density function method, the ESO method is very attractive because of its simplicity and efficiency. Recently, it has been demonstrated that the ESO method can solve a variety of problems of shape and topology optimization, in statics, dynamics, and buckling.

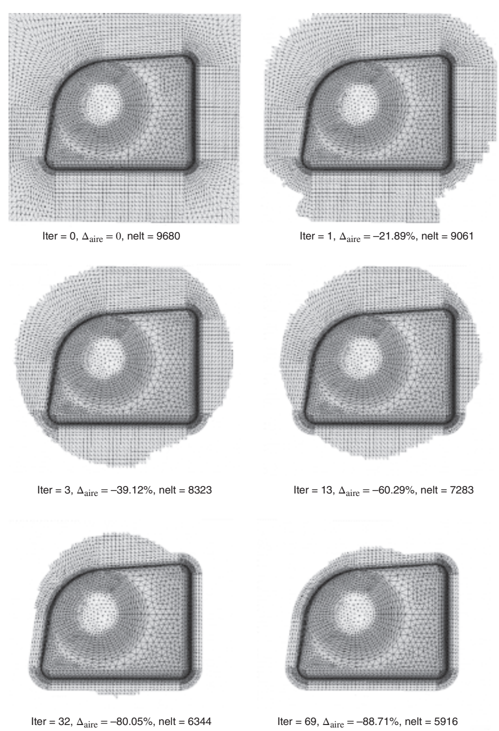
The ESO technique has been implemented and evaluated for the shape optimization of addendum surfaces for the stamping of three-dimensional workpieces by exploiting the main advantages of the inverse method which are speed and functionality.

After evaluating the ESO technique, one can conclude that the shape optimization of addendum surfaces in sheet metal stamping can be solved in a simple and effective way using the evolutionary optimization procedure. Indeed, the obtained shape of the blank contour at each ESO state can be chosen as an effective design. Thus, the ESO method can offer to designers several optimal configurations during the preliminary design stage of a prototype. For our applications, only constraints on the volume of material have been imposed, and the evolutionary design which satisfies the constraints is considered to be optimal.

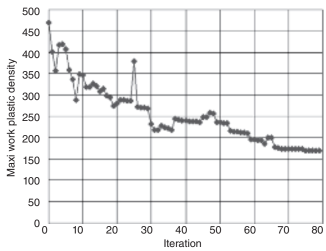
From a theoretical point of view, there are a few points to study. In particular, the reduction in the total number of iterations of the optimization process, especially when approaching the optimum where 40% of iterations are done without a substantial improve of the objective function.

Another point of reflection concerns the optimization criteria, since a good choice of the criterion is decisive in obtaining a good final optimal solution. This point remains crucial because it can only be done in concert with manufacturers.

Figure 1.24 Topology optimization of addendum surfaces: (a) addendum surface of Twingo dashpot, (b) convergence process. Source: (b) Hakim Naceur.



(a)



(b)

Figure 1.24 (*Continued*)

This method has been successfully applied for the determination of optimal addendum surfaces for industrial parts (Figure 1.24). The technical details relating to this method can be found in the references [25, 26].

1.3.4 Optimization of Drawbead Restraining Forces

A drawbead is a baffle located in the die under the blankholder zone on the trajectory of the metallic sheet flow and whose role is to slow down the sliding of the metallic sheet according to its geometry (Figure 1.25). The geometry of the drawbead is

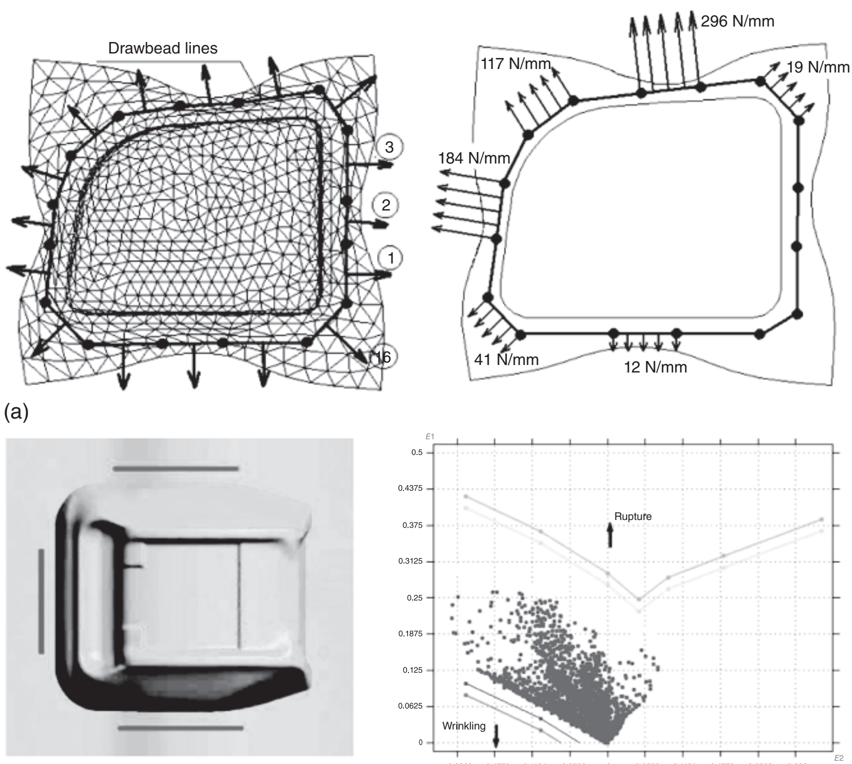


Figure 1.25 Optimization of drawbead restraining forces in the stamping of industrial parts (dashpot cup and oil pan).

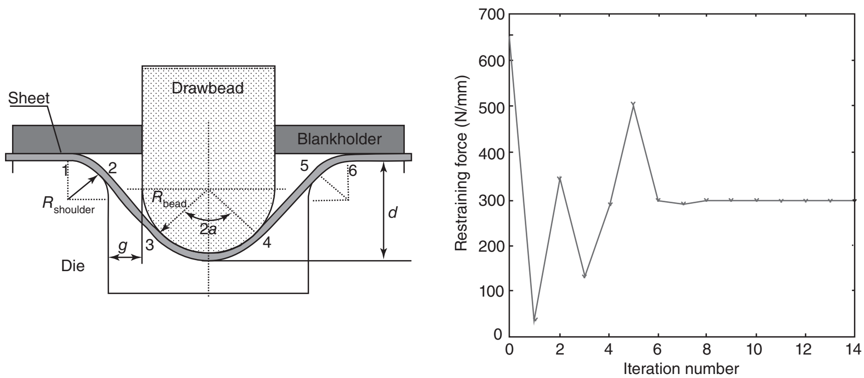


Figure 1.26 Geometrical description of a drawbead used in stamping.

not of the same order of magnitude as the dimensions of the piece to be formed. A numerical simulation which integrates the contact-friction between the sheet and the drawbead will be costly in terms of CPU computing time. In particular, it will be necessary to locally use a fine mesh in the area of the drawbead, while the part under blankholder is generally not in the useful part of the workpiece and disappears in the post-stamping operations (e.g. cutting).

In professional stamping software, the modeling of the drawbeads is carried out by the introduction of retaining forces. These forces are either calculated using analytical models or using finite element simulation in 2D with the assumption plane strains.

An approach is proposed here to optimize the drawbead restraining forces. Figure 1.26 shows an example of design of drawbead restraining forces. Sixteen drawbead lines were used for the benchmark of the Twingo dashpot cup. The Inverse Method was used to simulate the stamping process. The aim of optimization was to minimize thickness variations in order to minimize risks of rupture and wrinkling.

Convergence was obtained after 35 iterations. The thinning evolved from −18.04% to −17.39% and the thickening from 25.74% to 22.26%. Numerically the values of the drawbead restraining forces are optimized and then need to build up the corresponding drawbead geometries. An optimization procedure has been developed for this task; it is based on an analytical response of a 2D drawbead restraining force to perform its design [32–34]. This involves determining the geometry of the drawbead which allows obtaining the optimal drawbead restraining force to be produced to generate a defect-free workpiece.

Knowing the drawbead geometry and the physical properties of the metallic sheet, one can estimate the drawbead restraining force using the analytical model of Stoughton. At this stage, it is a question of solving an inverse problem: identify the geometry of the drawbead which is capable of producing the imposed optimal drawbead restraining force found previously. Now the design variables are the geometric characteristics of the drawbead, namely, the radius $R_{shoulder}$, the radius $R_{drawbead}$, etc. Our goal is to obtain at the end of the optimization process a retaining force equal to the imposed optimal one. Moreover, the drawbead restraining force has to be distributed as uniformly as possible along the drawbead line. The objective function in this case was chosen as the mean difference between the bending/unbending forces. This 2D simulation is very fast since it is based on the analytical drawbead model. It must be carried out for each of the forces found in the first stage, i.e. the design procedure will be repeated for each drawbead line.

1.3.5 Optimization of Tool Geometry

The prediction of springback is directly influenced by numerical parameters involved in the forming process, such as element size and type, punch velocity, pressure control, contact treatment, tools discretization, etc. But also it depends on physical parameters of the forming process, such as material hardening, geometry of workpiece, holding forces, temperature, etc.

From the numerical simulation point of view, the most important point is to obtain a precise stress state at the end of the sheet metal forming process. The springback simulation can be carried out numerically in different ways.

- A full simulation with tool contact treatment.
- A simplified simulation using external forces to replace the tool actions.
- A simplified simulation considering only the residual stresses at the end of the forming process.

As part of our research investigation in this topic, a co-simulation has been carried out by coupling of two codes: one FE software for the forming simulation and the other FE software for structural analysis. Special numerical procedures for field exchange interface were developed for communication between the two codes. A numerical procedure was also developed for tool (punch and die) radii optimization based on the minimization of residual stresses in the workpiece after tool removal (Figure 1.27). The objective was to determine optimal tool radii which minimize the opening distance d_i as shown in Figure 1.28 [29].

Punch radius R_p and matrix radius R_d were considered as design variables, while the objective function represented the opening distance d_i (Figure 1.28).

$$J = \sum_{i=1}^{nnt} \{d_i\}^T \{d_i\} = \sum_{i=1}^{nnt} (u_{X_i}^2 + u_{Y_i}^2 + u_{Z_i}^2) \tag{1.11}$$

The optimization problem was solved with an optimization procedure based on moving least square response surface method. An initial grid of 6×6 equidistant knots was used to evaluate the objective function with the following constraints:

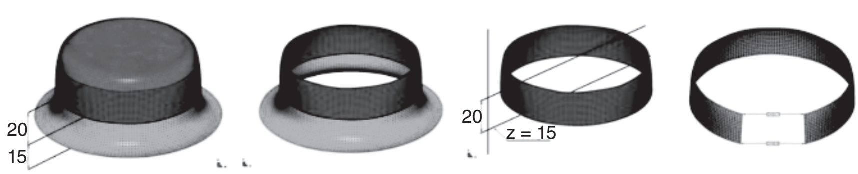


Figure 1.27 Demeri spring back benchmark.

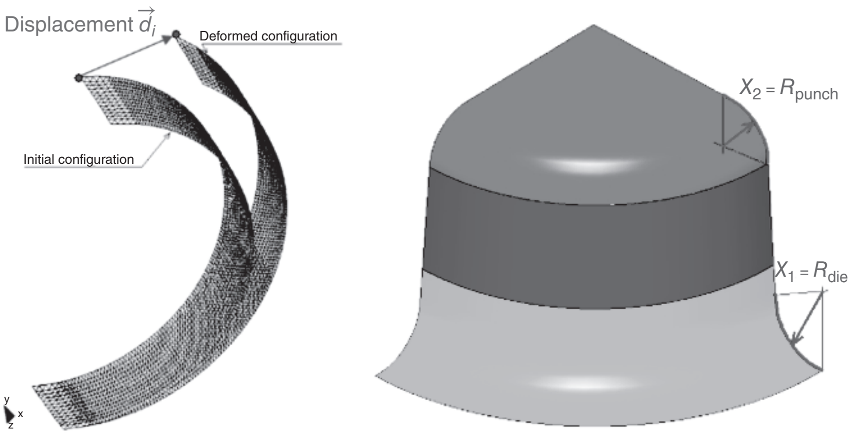


Figure 1.28 Spring back optimization problem based on tools design.

$R_{min} = 2$ mm and $R_{max} = 23$ mm. Convergence was achieved in 15 iterations leading to an optimal solution corresponding to a punch radius of $R_p = 4.13$ mm and a die radius of $R_d = 21.4$ mm.

1.3.6 Optimization of Material Parameters

Regarding the material properties, the aim of the research investigation was to identify optimal material characteristics which allow the successful forming of a given CAD geometry.

Forming limit curves were used to detect the risks of fracture and wrinkling in the final workpiece. The forming process simulation was carried out using an Inverse Method. The wrinkling was estimated according to the compressive stress state on each finite element located on the addendum surfaces. As shown in Figure 1.29, the forming limit diagram depends on the material and the deformation path. For each new material used during optimization a curve is determined using the model of Marciniak and Kuczynski.

Here the design variables are the hardening exponent n of the Swift–Voce law $\overline{\sigma}_{Swift} = A(\varepsilon_0 + \overline{\varepsilon}_p)^n$ and the Lankford anisotropy coefficient r.

The method was applied to solve several benchmarks. In particular, for the square box benchmark of Numisheet93, two materials, a steel and an aluminum alloy, were proposed to carry out experimental tests and numerical simulations. It was found that the proposed aluminum did not allow to exceed a forming depth more than 20 mm without fracture. A stamped box of 23 mm depth was then chosen. For this case, two optimization methods were used. The first was based on a metamodeling approach by using a diffuse response surface approximation coupled to Box–Behnken design of experiment and the second used a Sequential Quadratic Programming algorithm.

Table 1.2 summarizes the principal results obtained using both optimization procedures. The initial values were the properties of the aluminum alloy which has

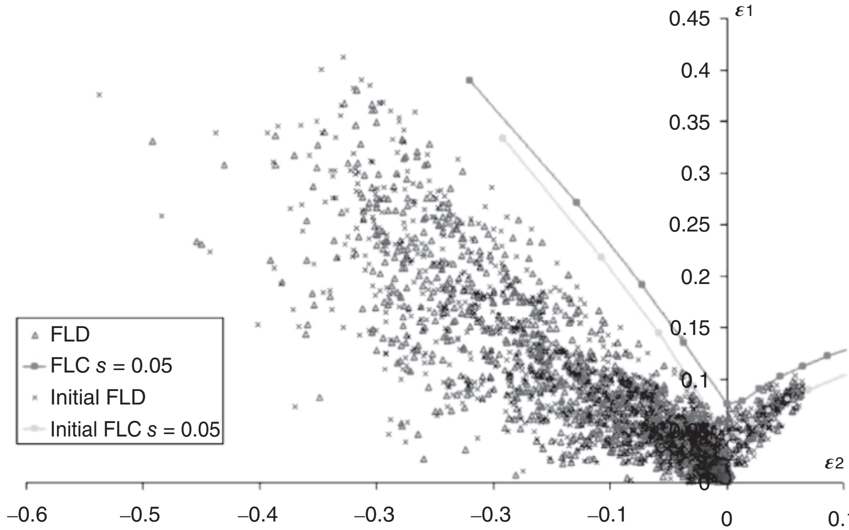


Figure 1.29 Forming limit diagram before and after optimization.

Table 1.2 Optimization of material parameters.

Material	n	r	R_w	Δt_{min} (%)	Δt_{max} (%)	Objective function evaluations	Iterates
Aluminum	0.36	0.64	10.4	−35.6	16.2		
Steel	0.26	1.77	5.85	−10.1	9.5		
Metamodel	0.19	1.93	3.81	−9.7	11.1	26	7
SQP	0.24	1.95	5	−9.9	10.8	48	12

knots above the forming limit curve (not shown). The wrinkling factor was $R_w = 10.4$. The objective was to avoid knots going above the forming limit curve using a wrinkling factor $R_w = 5$. This is achieved by the two optimization procedures. The properties obtained at the end of the optimization procedures tend toward the values of steel, which was proposed at Numisheet93. We also noticed a decrease in the minimum and maximum values of the thickness variation Δt_{min} and Δt_{max}.

The two optimization procedures are deterministic and the obtained results are different for the hardening exponent n but gave slightly the same Lankford anisotropy coefficient r as shown in Table 1.2. In terms of thickness variation, both optimization procedures gave approximately the same results with −10% of thinning and +11% of thickening (Figure 1.30).

The main assumptions of this work were to consider that material properties are continuous, and assume that any values of the couple (n, r) exists. This is not completely false since the anisotropy comes essentially from the rolling operation. If we optimize the preliminary rolling stage of the metallic sheet and also optimize the

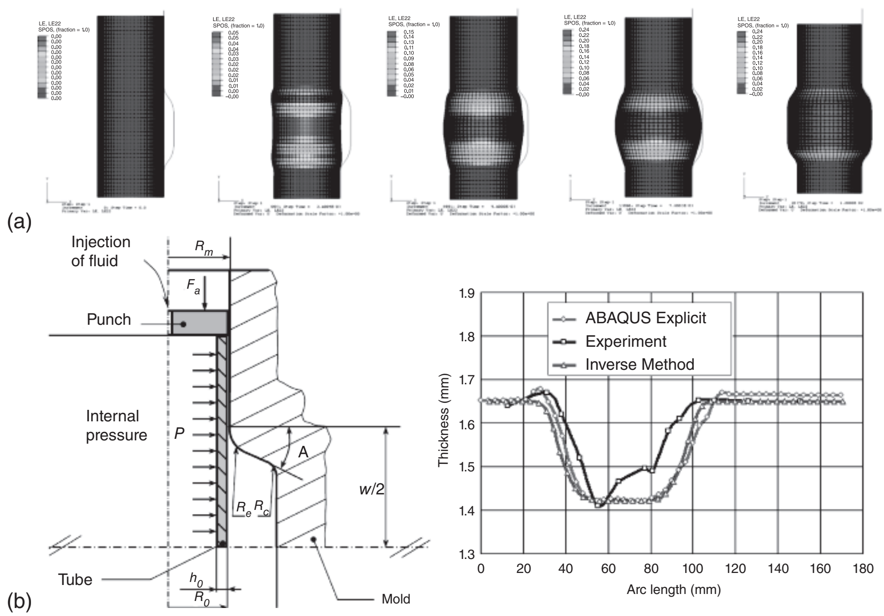


Figure 1.30 Tube hydroforming results comparison: simulation versus experiment.

heat treatments conditions, it is possible to obtain the desired material, but the price of this procedure may be prohibitive.

1.3.7 Optimization of Hydroforming Process Parameters

This section deals with the formulation, development, and simulation of a three-dimensional hydroforming process based on an inverse method for the rapid analysis in order to optimize the parameters of this forming process.

Knowing some limitations to generate tube CAD geometry, tube thickness distribution has to be as uniform as possible at the end of hydroforming process. During the hydroforming process, compressed and expanded zones may appear simultaneously in the workpiece. As a result, the calibration of process becomes a challenge since tedious optimization of successive hydroforming stages are mandatory. Although experimentation on surrogate models seems necessary, it will nevertheless be difficult to extrapolate calibration tasks to a real industrial part, especially for hydroforming of tubes which makes the situation more complex, since in the forming process usually some preliminary stages of bending and calibration are necessary.

The optimization concerns the process operating parameters such as the friction conditions, the pressure and backpressure control, the drawbead forces, the rheology of material or initial thicknesses, and the tool geometry to take account for springback estimation. The results obtained with different types of material data, geometries, and operating conditions are compared with the objectives or targets defined in conjunction with industrial needs (see references [27, 28]).

The use of a rapid simulation method makes it possible to consider a large number of evaluations of quality functions.

A typical example consists in determining the optimal length L_0 of the initial tube as well as the “ideal” properties of the material, which can be described simply by the coefficients of the Swift–Voce hardening law (K, n) so as to obtain a final “feasible” tube (without necking nor wrinkling) as well as a minimal plastic work. The objective function chosen for this purpose can be expressed as

$$f = \sum_{e=1}^{\text{nelt}} f^e; \quad \text{with} \quad f^e = \int_V \left(\int_0^{\overline{\varepsilon}_p} \overline{\sigma} d\overline{\varepsilon}_p \right) dV \tag{1.12}$$

where $\overline{\varepsilon}_p$ is the total equivalent plastic strain, V is the total volume of the workpiece and $\overline{\sigma}$ is the equivalent stress depending on the hardening type, for instance if the combined Swift–Voce law is used, then the equivalent stress is

$$\begin{aligned} & \overline{\sigma} = \alpha \ \overline{\sigma}_{\text{Swift}} + (1 - \alpha) \ \overline{\sigma}_{\text{Voce}} \\ \text{with} \quad & \overline{\sigma}_{\text{Swift}} = A(\varepsilon_0 + \overline{\varepsilon}_p)^n \\ & \overline{\sigma}_{\text{Voce}} = k_0 + Q(1 - \exp(-\beta \overline{\varepsilon}_p) \end{aligned} \tag{1.13}$$

In practice, nonlinear constraints are imposed on the design variables, so as to avoid obtaining non-feasible solutions. For this purpose, the thickness variation of the tube will generally be limited between −20% as a lower value and +15% as a higher limit. It is also important to impose geometric constraints on the design variables (tube length L_0 and material hardening exponent n). The optimization problem can be stated as

$$\begin{aligned} Min \quad & f(L_0, n) = \sum_{e=1}^{nelt} \int_V \left(\int_0^{\overline{\varepsilon}_p} \overline{\sigma} d\overline{\varepsilon}_p \right) dV \\ \text{with} \quad & \lambda_z^{\max} \leq 1.15 \\ & \lambda_z^{\min} \geq 0.8 \\ & 150 \ \text{mm} \leq L_0 \leq 200 \ \text{mm} \\ & 0.1 \leq n \leq 0.6 \end{aligned} \tag{1.14}$$

where $\lambda_z = t/t_0$ is the stretch, t and t_0 are the thickness and initial thickness respectively. At the beginning, a design of experiment based on the central composite algorithm was used for the construction of response surface in order to estimate the cost function. Then a normalization of the variables (between −1 and +1) is used in order to guarantee a stability of the optimization algorithm and to facilitate the data processing. A global response surface based on the diffuse approximation was built using the design of experiment already prepared, and the final result is shown in Figure 1.31.

The minimization of the objective function, under constraints, was done by using a Sequential Quadratic Programming algorithm based on the work of Powell M.J.D. using multiple starting initial solutions. The optimal solution was obtained in only four iterations, allowing an optimal solution corresponding to $L_0 = 178.82$ mm, $n = 0.59$.

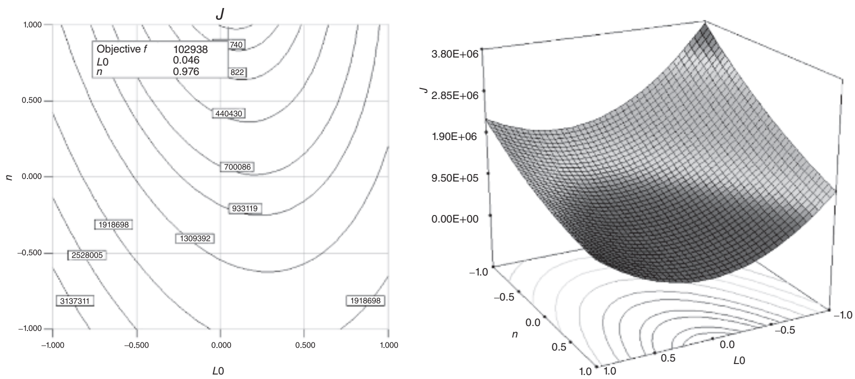


Figure 1.31 Global diffuse response surface approximation for the optimization of tube hydroforming process parameters.

1.4 Future Outlooks

Nowadays, the most economical technique for obtaining a car body part is still stamping. However, each stamped part has defects, which can be classified as: "aspects defects" and "geometrical defects." For the calculation of geometrical defects, quality requirements mean that one can no longer reason on a single stamped part but rather on a group of parts because after assembly, the stamped workpiece will be part of a complex assembly (e.g. car body in white) forming the overall vehicle body.

In order to fulfill the requirements of obtaining a "good quality" vehicle body, it is crucial to analyze the interactions between all the involved parts. Thus, the final result of the assembly deformation (Figure 1.32) is dependent on many local parameters such as part stiffnesses, sheet metal thicknesses, material parameters, and so on or global parameters such as positions and number of weld joints, modeling of boundary conditions, types of finite element models, and so on.

The scope of future developments is as follows:

- The development of numerical procedures to take into account uncertainty of the forming process parameters (local and global) on the overall quality of the final assembly (springback, residual stresses in the full assembly). This will allow the definition of tolerance margins on elementary parts when they are initially processed using stamping or hydroforming followed by springback operations, during the early design or pre-project phases.
- A second step would be to carry out optimization procedures based on meta models and artificial intelligence for the robust optimization of assembly defects (due to springback, residual stresses, etc.) by using local and/or global forming process parameters and their variability.

1.5 Conclusions

Deep drawing and hydroforming processes are very important for several industrial sectors and the simulation of these processes needs to be continuously enhanced. In the future, several investigations may be followed to achieve this target. The numerical applications presented previously, have shown the importance of mastering the process parameters in order to control the mechanical behavior of the final workpiece obtained using either stamping or hydroforming. Nowadays, the use of various numerical optimization algorithms coupled to explicit/implicit nonlinear forming solvers has gained maturity and has allowed a quasi-automatic design of numerous process parameters to achieve a final workpiece without defects such as wrinkling or fracture. However, in the last few years, new challenging expectations have arisen regarding a higher level of quality commitment of sheet metal forming parts obtained by deep drawing and hydroforming. In particular, for the automotive and the aeronautical industries, it is becoming important to ensure at the end of forming simulations (stamping or hydroforming) that the final “defect-free” workpiece satisfy specific requirements regarding a higher level of crash safety while maintaining a reduction of overall weight. The new level of parameter design will be the coupling of optimization algorithms with a set of nonlinear solvers successively (such as buckling, crash/impact, durability, and so on) to assess the workpiece quality. Therefore, it will be possible, at the early design stage, to design some key process parameters using specific objective functions and constraints to improve the part in service life expectancy. Therefore, the final workpiece will be not only a “defect-free” part but also a part with an “optimal” strength to weight ratio.

Mathematical optimization is currently used to calculate the best process parameters. Expert systems allow an initial adjustment which may or not be refined by optimization to avoid process instability problems. It is therefore a matter of robustness. A change in the process parameters should not have much influence on the quality of parts obtained using deep drawing or hydroforming.

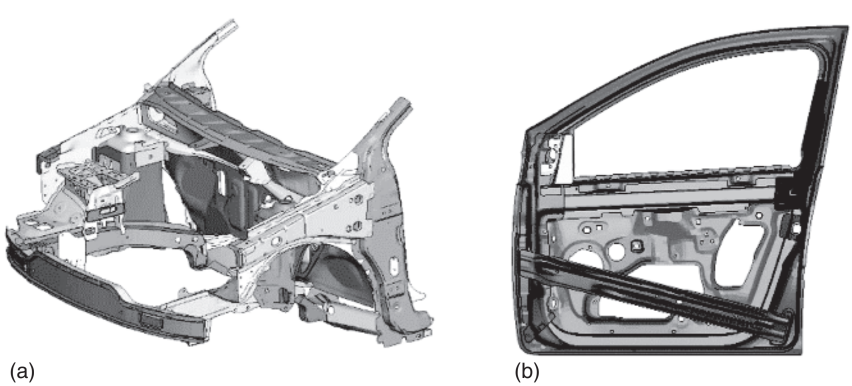


Figure 1.32 Uncertainty simulation in assemblies of stamped parts constituting an automobile body in white. Source: (b) Hakim Naceur.

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