INTRODUCTION TO SHEET METAL FORMING PROCESSES

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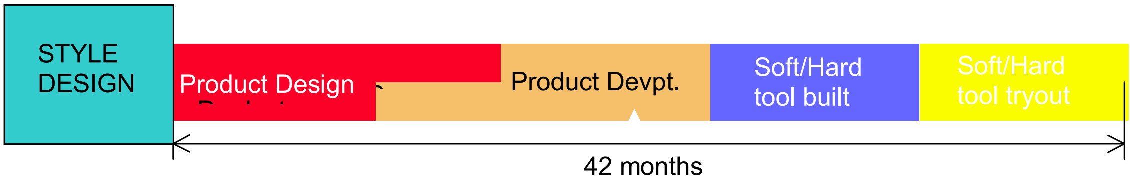
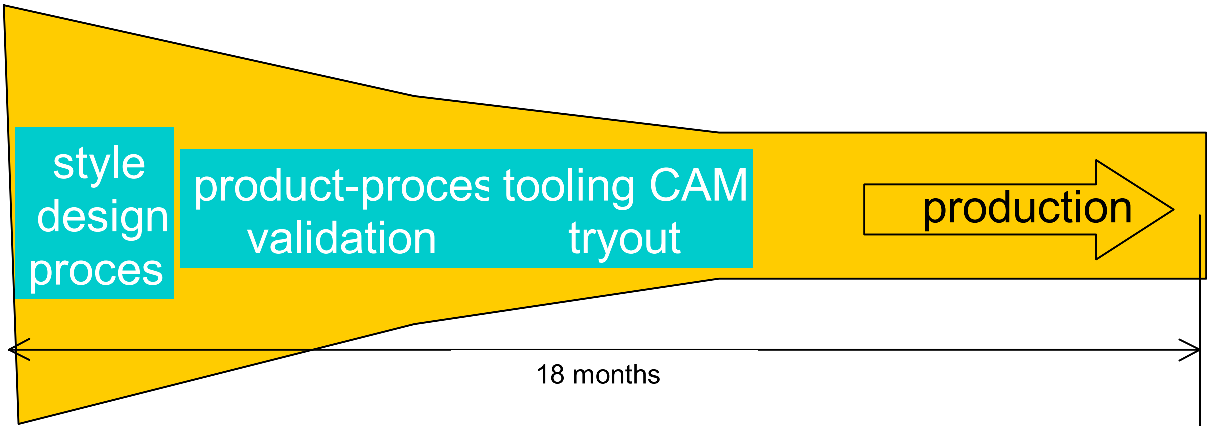
INTRODUCTION: EVOLUTION OF INDUSTRIAL STAMPING

Back in 1985, the development cycle of a stamped part looked more or less like this (a sequential series of operations stemming from a single style design):



Today, people look at it rather as a sort of funnel, where key decisions are taken on the basis of different factors and alternative choices.



OVERVIEW: THE STAMPING SYSTEM AND STAMPING DESIGN

Like all complex system, stamping can be decomposed in hardware and software. By hardware we mean factors that cannot be changed from one operation to another. Conversely, by software we mean factors that the operator can change in order to obtained the desired result : a part with a given quality.

HARDWARE	SOFTWARE
Press	Press set-up
Tools	Material
	Lubrication

The highlighted areas represent the components of the stamping design.

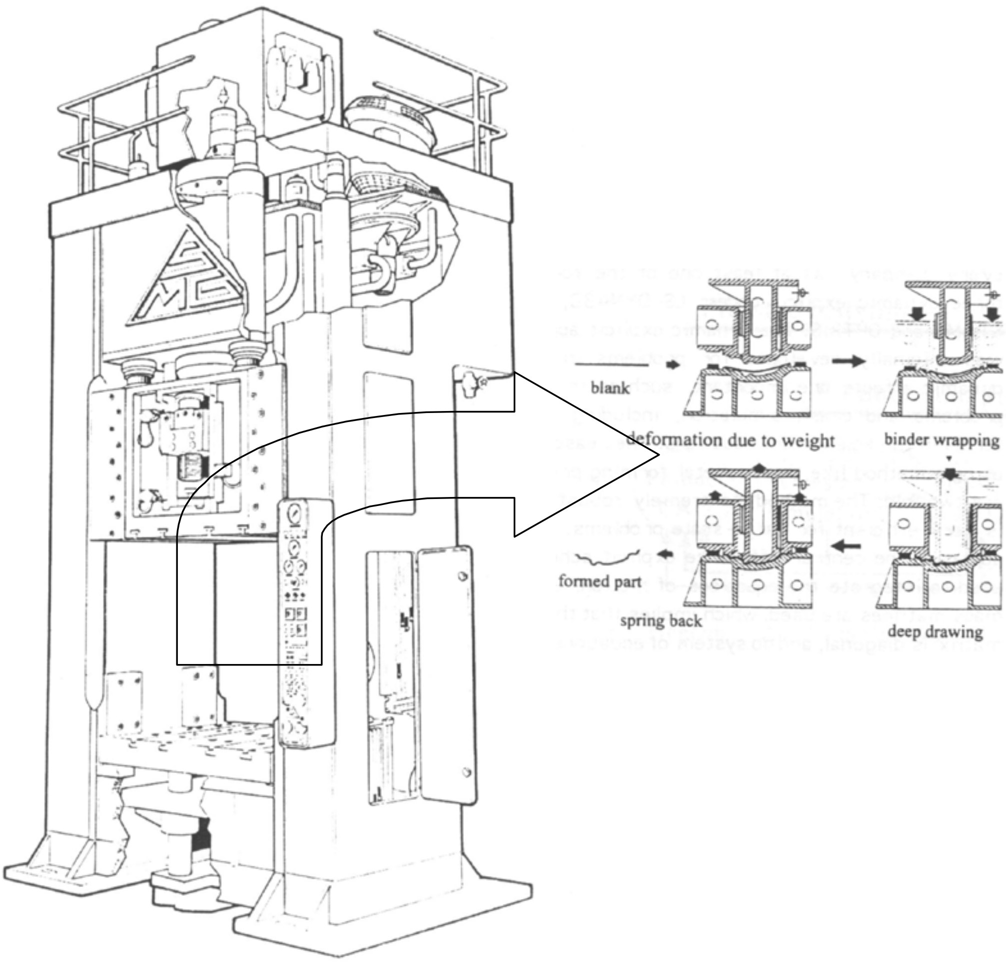
What is a stamping press ?

A stamping press is a machine that houses the stamping tools (tooling) and carries them around according to the kinematics indicated by the user (process set-up).

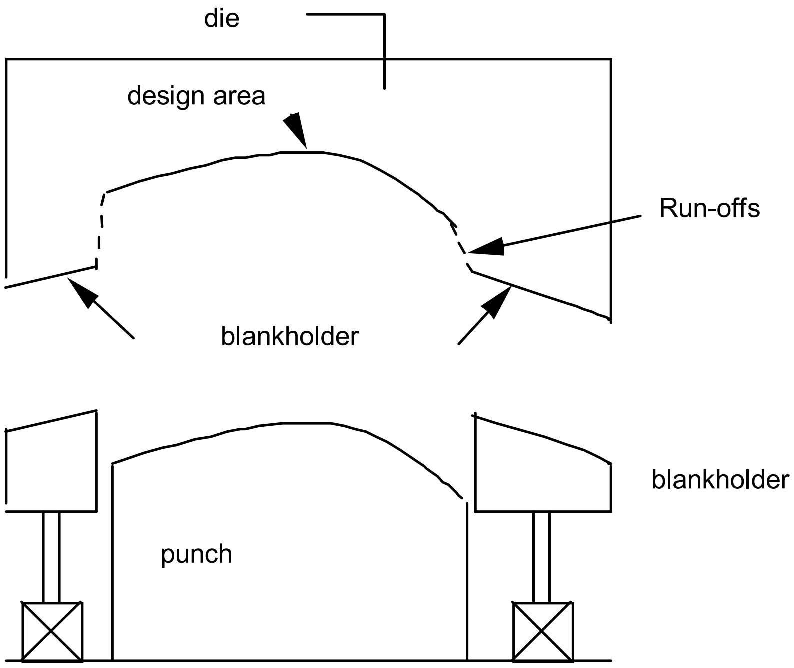
The knowledge of the press used for a stamping operation provides us with useful clues regarding:

- Value and distribution of restraining forces
- Tool deformation caused by stamping forces
- Contact and/or gap between tools and blank

However, we should recall that, at the moment when the die design is carried out, the press is usually not yet known, so that its characteristics are rather a factor of noise than a useful information. Therefore, it will be important to have a design that is robust with respect to the press type.



What is a stamping tool? What is process design?



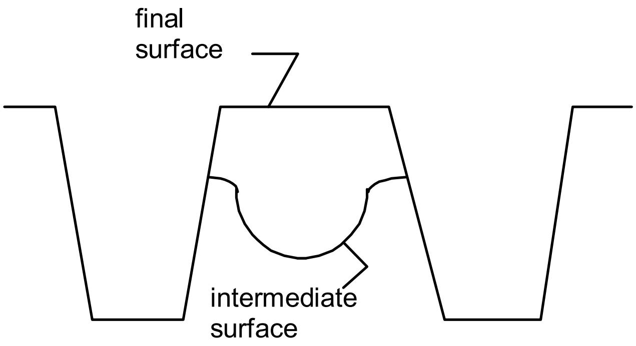
GLOSSARY:

Design surface	Part as designed to fit in the car (after trimming)
Blankholder surface	Surfaces that hold the blank before the forming operation, including the restraining
Production surface/run-offs	Junction between the two former surfaces, protecting the design surface and controlling material flow
Dieface	Run-offs + blankholder

Process design is the ensemble of operations leading from the design geometry to the dieface.

What is a stamping operation?

A sheet formed part is usually obtained through a number of operation (phases)



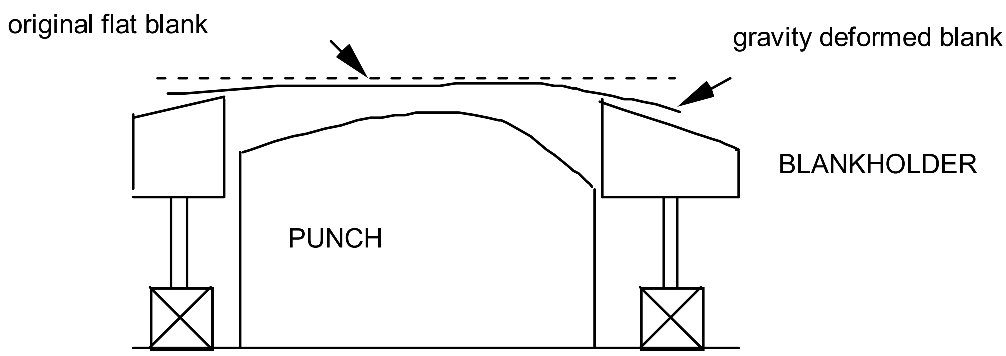
Each operation can be decomposed in several phases. It may be necessary to model each of them

- Gravity fall
- Holding
- Forming
- Trimming, flanging
- Springback

Most problems in sheet metal forming come from a bad control of holding, restraining and springback.

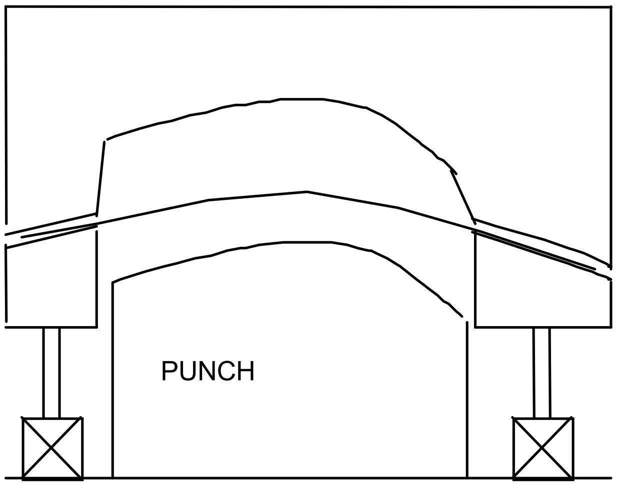
Gravity fall

The blank adapts to the blankholder shape



Holding

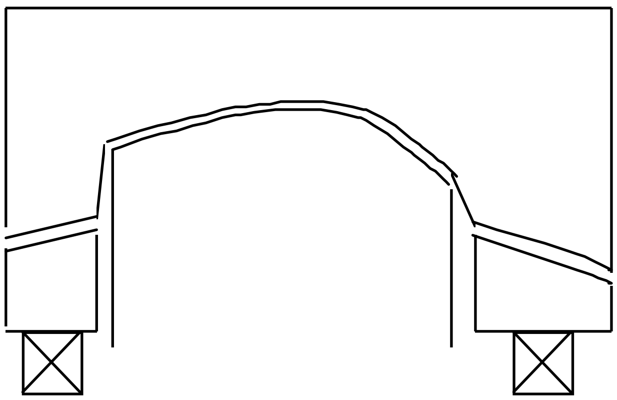
The die pushes on the blankholder and squeezes the blank



Holding controls the shape of the blank and the contact between the blank and the punch.

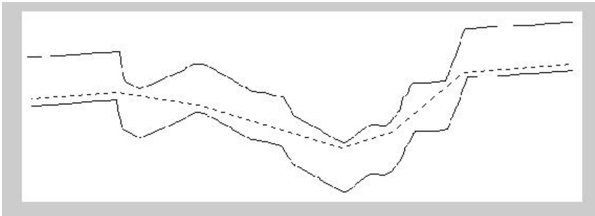
Forming

The die goes down until it squeezes the blank onto the punch



The forming operation can in turn be divided in two parts:

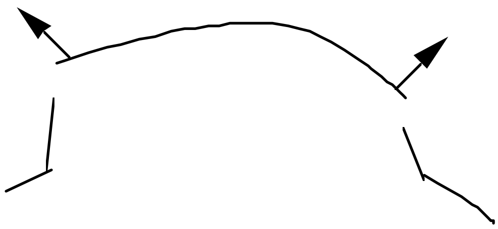
First the volume of the part is created: this is mostly controlled by the production surface and by the restraining system



Last the geometry details are formed: this is controlled by the geometry of the part

Trimming and springback

Plastic deformation leaves some stresses locked through metal thickness. After the extraction from the tools these stresses are released originating a different shape than that of the tools.



Springback before trimming is sometimes important for the design of the tools and robots of the press.

Springback after trimming may change the shape of the part to the point that it is impossible to assemble.

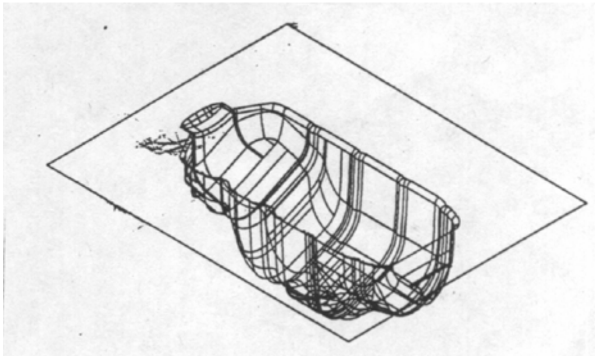
STAMPING PROCESS DESIGN

Deliverables of process design

Dieface design

Delivered in drawing or, most often nowadays, CAD format.

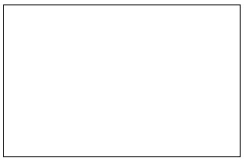
Dieface design specifies the geometry of the dieface for each of the stations considered.



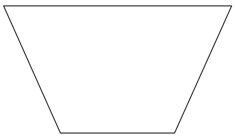
Cutting pattern

Cutting pattern profile is also delivered in drawing or CAD format. It specifies the geometry of the punching tool prior to the actual stamping operation.

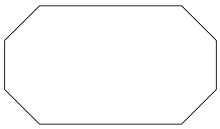
Production constraints usually force the use of simple cutting patters. In practice, some basic shapes are used:



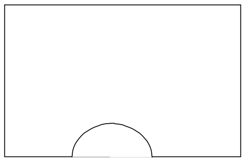
rectangle



trapeze



rectangle w/ cuts

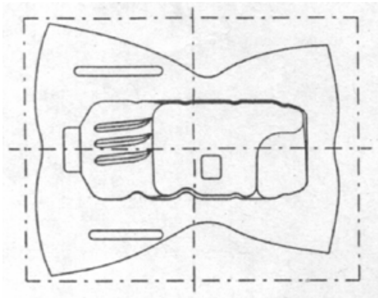


rectangle w/ slot

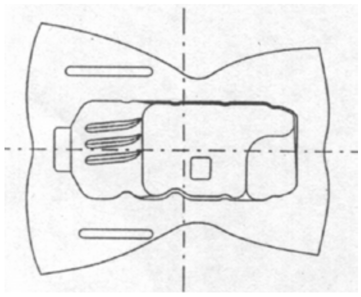
Stamping cycle

Stamping cycle is the description of all the operations leading to the production of the finished stamped part. A typical stamping cycle includes:

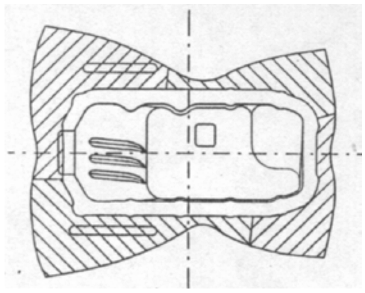
- One or more stamping stations



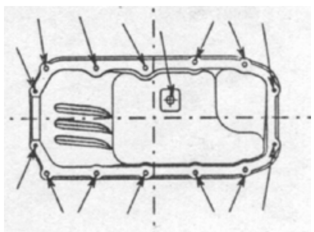
- One coining station



- One trimming station



- One punching and flanging station

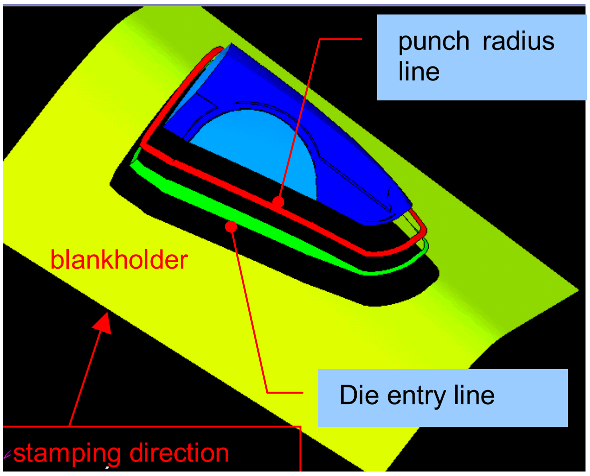


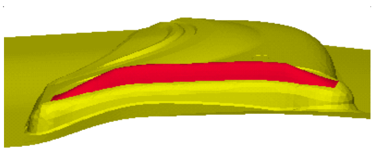
Dieface design

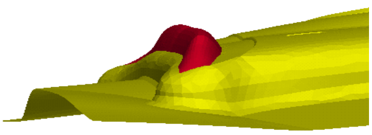
The simplified die addendum: basic geometry feature of the dieface

Although an actual dieface is a rather complicated system of surfaces, some basic geometry features can be identified. Such basic features can be summarized as follows :

- Stamping direction : identified on the basis of minimum undercut, inertia moment or straightness of projected characteristic lines.
- Punch radius line : identified after flange development and protection
- Die entry line : joins the punch line to the blankholder, with an opening angle to avoid undercuts
- Blankholder : can be developable (conical or ruled) or quasi-developable. Non-developable blankholders may give rise to wrinkling problems during the holding phase.
- Other run-offs components. Typically, a dieface contains local elements (sausages) designed to control punch/blank impact and/or to stretch locally the material.







How many steps ?

Coining

Flanging

Trimming and springback reduction

MATERIAL DEFORMATION DURING SHEET METAL FORMING

Deformation analysis

Principal strain plane

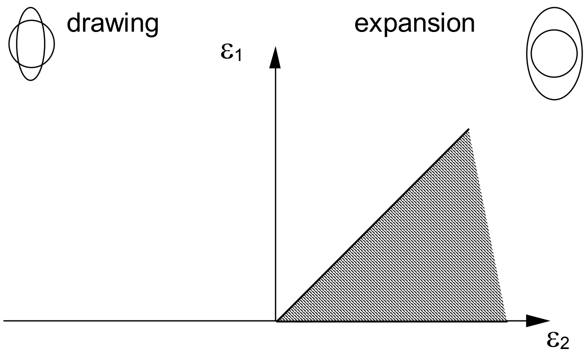
The analysis of deformation in sheet metal forming is often based on the two principal membrane strains ε_1 and ε_2.

Most often, the maximum principal strain ε_1 is positive in a forming operation. Hence, only half of the strain plane is considered (actually, three quarters).

Deformation pairs relative to different points of a stamped part are often plotted on such a half-plane.

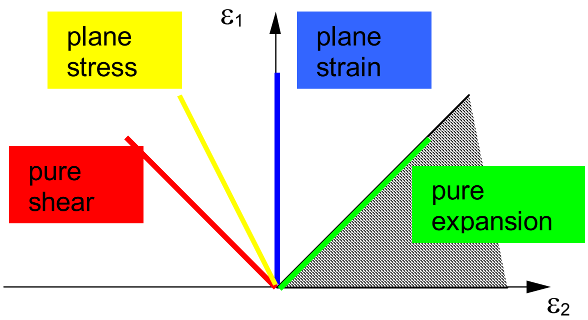
This information can be drawn either from FE simulation or from experimental analysis (grids).

The analysis of such deformation plots gives useful insights into the mechanics of a forming operation.



The deformation plot lends itself to several interesting considerations.

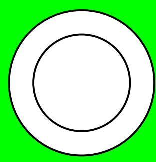
Lines departing from the origin are equivalent to constant strain mode $\frac{\varepsilon_2}{\varepsilon_1}$.



We can identify:

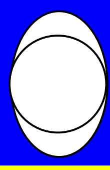
A line of pure expansion, where

$\varepsilon_1 = \varepsilon_2$



A line of plane strain, where

$\varepsilon_1 = 0$

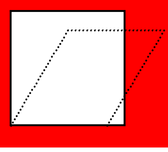


A line of plane stress, where

$\sigma_2 = 0$

A line of pure shear, where

$\varepsilon_1 = -\varepsilon_2$

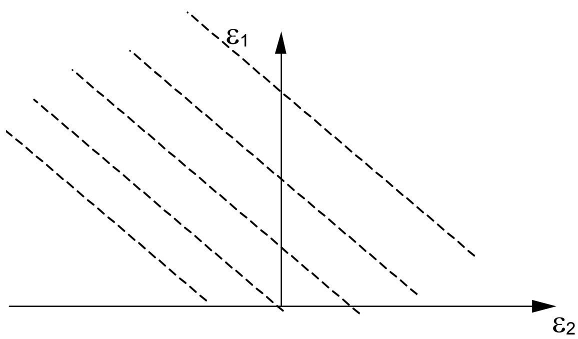


Further, based on the principle of conservation of volume, lines at 45°

$\varepsilon_1 + \varepsilon_2 = -\varepsilon_3 (cst.)$

represent the loci of constant thickness.

For each of these lines, the thinning Δt,



relative to the initial thickness t_0 can be computed from basic rules of mechanics :

$$\frac{\Delta t}{t_0} = 1 - e^{-(\varepsilon_1 + \varepsilon_2)}$$

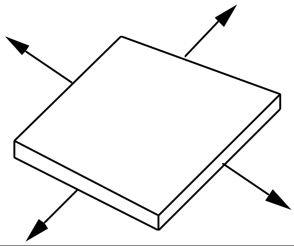
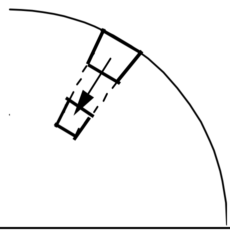
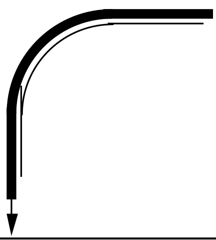
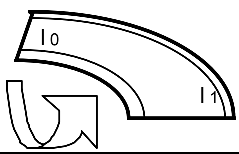
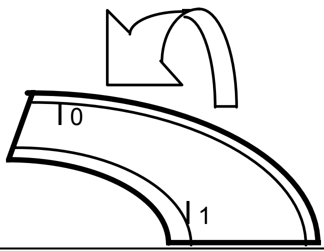
Grid analysis

Modes of deformation

In this chapter, we address the topic of material deformation, following the jargon of die engineers rather than of the mechanical engineers. The reader is encouraged to compare the deformation modes described here and in the preceding chapter.

Definition

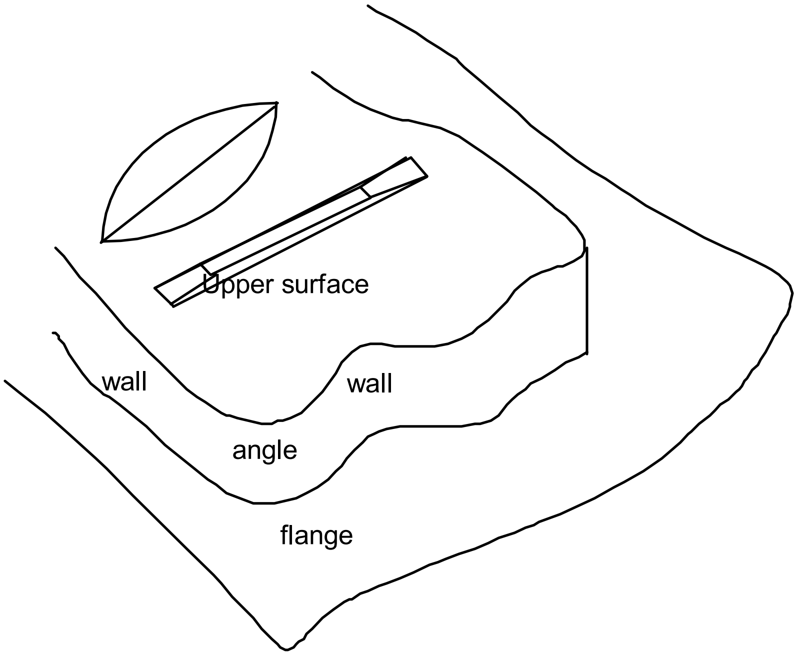
In sheet metal forming practice, we distinguish five basic modes of deformation:

• STRETCHING: The material is expanded in both directions. This mode of deformation is found mostly on smooth bottoms of shallow parts and in hydroforming processes.	
• DRAWING: This mode is typical the material flow from the flange towards the inner part of the die.	
• BENDING/UNBENDING: This is a cyclic deformation (most often associated with plane strain). It is found on the die entry line as well as in drawbeads.	
• STRETCH-AND-BEND: This mode is associated to flanging operations for which the bending line is concave.	
• COMPRESSION-AND-BEND: This mode is associated to flanging operations for which the bending line is convex.	

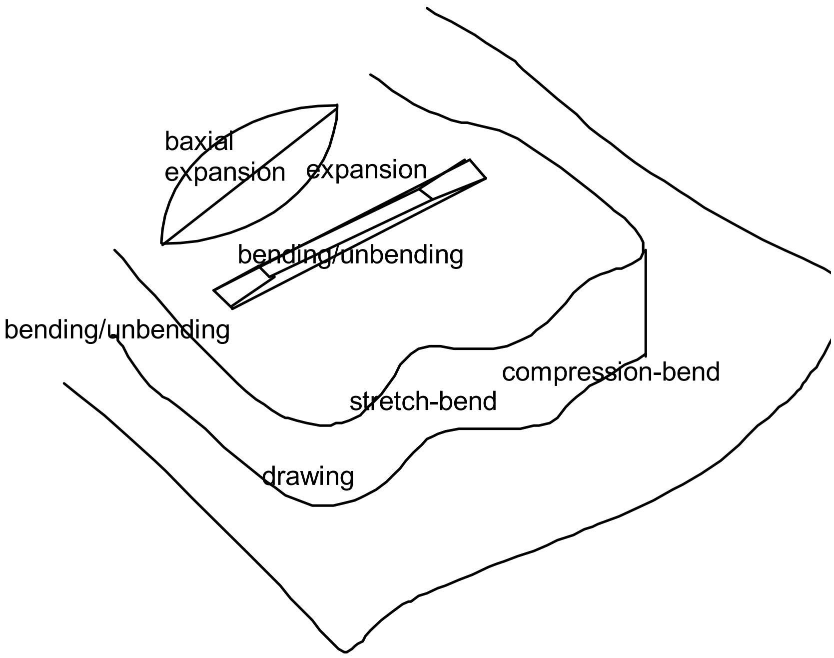
Correlation between deformation modes and geometry

Remember:

The designer thinks in term of geometrical features: wall, angel, flanges, etc...



... but the die engineer sees the part as a collection of areas, often quite well separated, where different deformation modes occur.



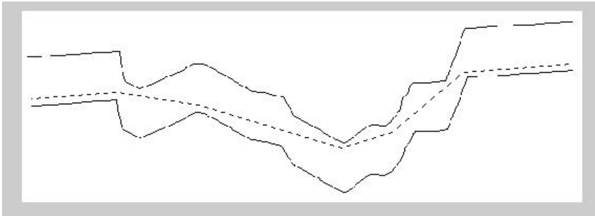
FACTORS CONTROLLING DEFORMATION

In the following, several factors controlling the stamping operation are analyzed. However, it should be pointed out that a hierarchy exists among the different factors, which is partially echoed by the traditional product development workflow. In order of importance, we can thus identify:

1. Part geometry
2. Dieface (active tooling surface) geometry
3. Material rheological properties
4. Lubrication and restraining systems

Part geometry

In order to appreciate the foremost importance of the part geometry with respect to all other factors influencing sheet metal forming, we should recall that a sheet metal forming operation can always be, from the conceptual point of view, divided in two stages:

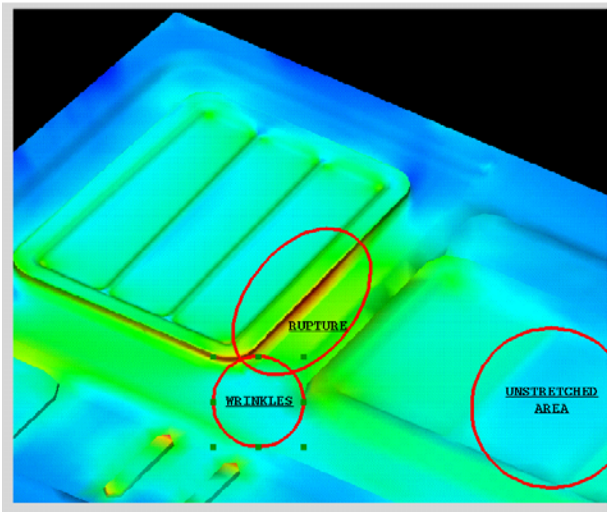


- A first stage where the volume of the part is generated
- A second stage where the geometrical details are formed (reverse drawing)

In the first stage, deformation and material flow are mostly controlled by run-offs (die addendum or dieface).

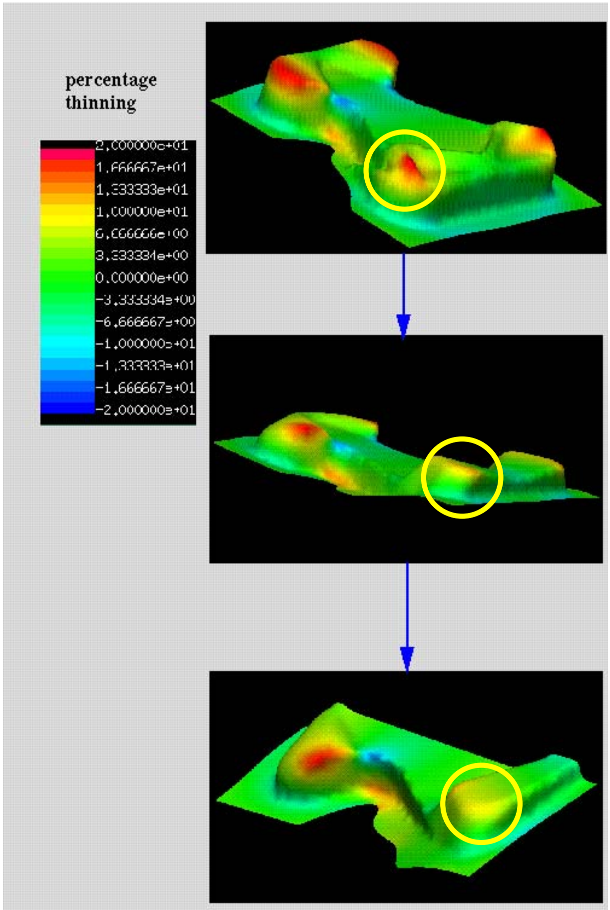
In the second stage, however, most of the deformation is due to local reverse drawing or stretching, on which die addendum has little or no impact. Most "unfeasible" parts present defects produced in this stage. The identification and the correction of these problems, which can be achieved through the early use of numerical simulation, lead to anticipate the modifications, which can be made at a much lower cost.

The rear wall of the IVECO cabin represents a very interesting example. Here, all the problems encountered at the die try-out stage have been identified on the base only of the part as designed analysis. On the other hand, defects appear with the same calculation (folds on the edge of the part) which would have disappeared as soon as a run-off and a blankholder surface were added.



Tool geometry

If part geometry controls mainly deformation in reverse-drawing areas, relatively far from the die edge, it can be expected that tool geometry be mostly important in deep-drawn areas around the part boundary. As it always happens with complicated problems, this statement is dangerous to generalize but can be found true in many occasion.



For the RENAULT LAGUNA's engine support, the first proposition of blankholder (flat surface) yields very large strains in an area where subsequent flanging produces rupture.

The modification of the dieface (curved blankholder surface) allows for a more even drawing depth along the part contour. Part thinning is halved (from 20% to 10%), though using less metal sheet, thanks to a removal of an excessive run-off.

At last, run-offs around the problem area can also be improved, via the use of evolutionary radii instead of constant radii. This leads to a further decrease in thinning (down to 8% for the case studied).

Other examples of run-offs geometry are die entry radius

INSERER DISCUSSION SUR COPPA DIEX

Cutting pattern

The profile of the initial blank has a great influence on the material flow, especially for deep drawn parts.

Typically, cutting corner eases the material flow in corner areas, with a significant reduction of thinning and a corresponding increase of wrinkles or wrinkle risk.

The identification of the optimal cutting pattern may be useful in process design.

It is often assumed that the optimal cutting pattern is an offset of the die entry line. Actually, it also depends on the different section lengths of the stamped part. Inverse simulation codes enable the user to identify optimal cutting pattern accurately.

Material mechanical properties

Ductility (strain hardening)

A basic engineering notion is that material behavior in the first stages of deformation is approximately elastic, i.e. the material returns to its initial state after the external cause (force) is removed.

Further deformation will be at least partially permanent. For metals, this pattern of permanent deformation is called plasticity.

After the onset of plastic deformation (yield point) the stress generated in the material continues to grow (even though at a slower pace) as deformation increases. This phenomenon is called **strain hardening.** The ability of the material to deform plastically before failure is called **ductility**. The two properties are tied to each other, as it will be shown later.

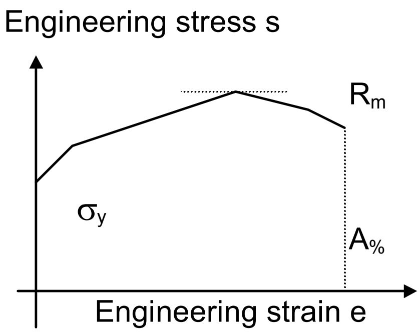
The standard description of ductile behavior is the tensile test:

Experimental data:
(tensile test, engineering stress and strain)

σ_y = yield stress

R_m = ultimate strength

$A_{\%}$ = elongation to failure



The tensile test identifies three thresholds:

- Passage from the elastic phase to the plastic phase: σ_y. This is not interesting for sheet metal forming simulation.
- Necking: R_m. This phase of the deformation is well known and reasonably well modeled.
- Rupture: . Little is known of material behavior between necking and rupture. In particular, SMF simulation codes simply extrapolate pre-necking behavior.

Good stamping practice suggest remaining below necking level, so that surface defects (for outer panels) or excessive thinning (for structural parts) are avoided. However, in many cases the actual stamped part is formed way beyond necking point (e.g. tanks, sinks and other deep drawn parts).

Material strain hardening is usually modeled into account via the Krupkovsky-Swift law, linking the equivalent stress in the Hill-Von Mises sense to the equivalent plastic deformation.

$$\sigma = k\left(\varepsilon_0 + \varepsilon_p\right)^n$$

where k, ε_p and n are material constants defined below.

Remark :

It is important to stress again that the Krupkovsky-Swift law is valid only below necking point.

The above defined Krupkovsky-Swift law is obtained in practice by modifying the better-known Hollomon law (valid for $\varepsilon_p >> 0$) :

$$\sigma = k\,\varepsilon_p^n$$

so that the value of stress at or around zero coincides with the yield stress.

Remark :

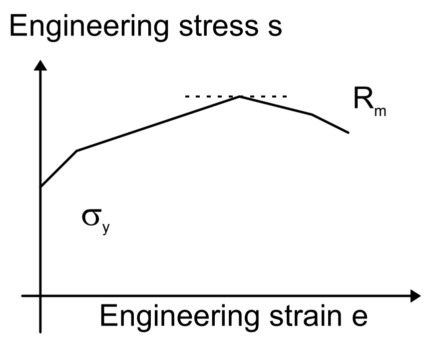
- *High strain hardening coefficients are beneficial for the forming of stretched parts*

Material characteristics required for the definition of the Krupkovsky-Swift law can be deduced from the results of a standard tensile test using the following procedure:

Experimental data:
(tensile test, engineering stress and strain)

σ_y = yield stress

R_m = ultimate strength



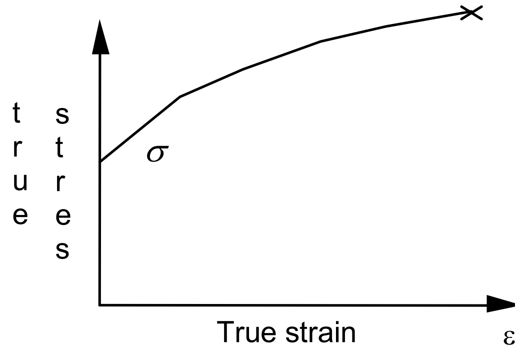
Krupkovsky law :

$$\sigma = k(\varepsilon_0 + \varepsilon)^n$$

Useful formulas:

$$s = \frac{\sigma}{1+e} \Leftrightarrow \sigma = (1+e)s$$

$$\varepsilon = \ln(1+e) \Leftrightarrow e = \exp(\varepsilon) - 1$$

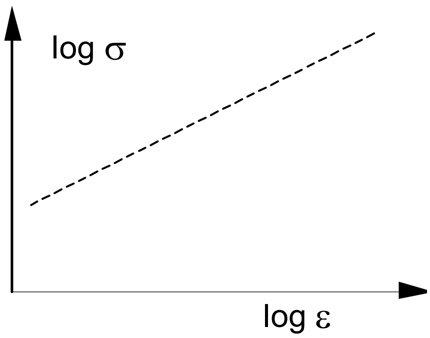


n = strain hardening coefficient

is easily computed by linear regression on a log/log plot.

Remark:

Estimation of n is highly dependent on the deformation window considered.



1) Computation of $\boxed{k}$:

for $\varepsilon >> \varepsilon_0$ $\sigma = k(\varepsilon_0 + \varepsilon)^n \approx k\varepsilon^n$

With some algebra, we can show that the engineering stress la R_m is reached for an elongation $e = \exp(n) - 1$, i.e. that the true strain corresponding to necking is equal to the hardening coefficient n. The true stress corresponding to ultimate strength R_m is therefore:

$$\sigma_{s=R_m} = (1+e)R_m = \exp(n)R_m \Rightarrow \exp(n)R_m = kn^n \Rightarrow k = R_m\left(\frac{e}{n}\right)^n$$

2) Computation of ε_0

We can impose that the strain hardening curve passes through the yielding point when plastic deformation is equal to zero:

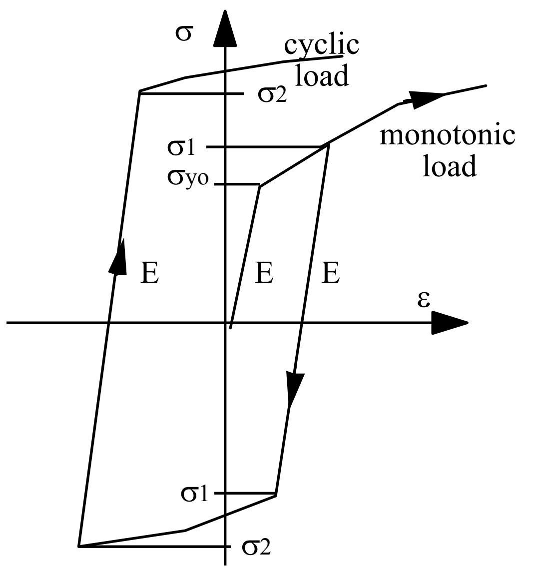
$$\sigma_{e=0} = \sigma_y \Rightarrow k\varepsilon_0 = \sigma_y \Rightarrow \varepsilon_0 = \sqrt[n]{\frac{\sigma_y}{k}}$$

Behavior under load cycles (isotropic vs. cinematic hardening)

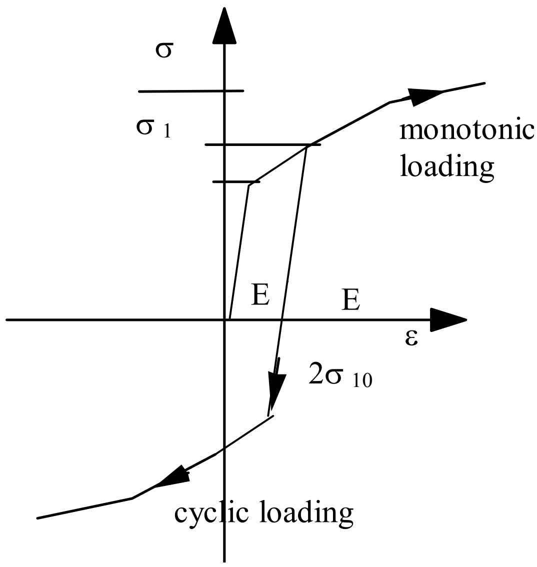
Material resistance (yield and ultimate strength) may be significantly different after a prior deformation.

Two idealized models are used:

- Isotropic hardening. If loading is reversed after a first monotonic loading (up to σ_1), the second yielding point is symmetrical with respect to the maximum stress in monotonic loading ($-\sigma_1$).
- Kinematic hardening. If loading is reversed after a first monotonic loading (up to σ_1), the material shows always the same apparent resistance to yielding, so that the yielding point for the reverse load is $\sigma = \sigma_1 - 2\sigma_{y0}$



isotropic hardening



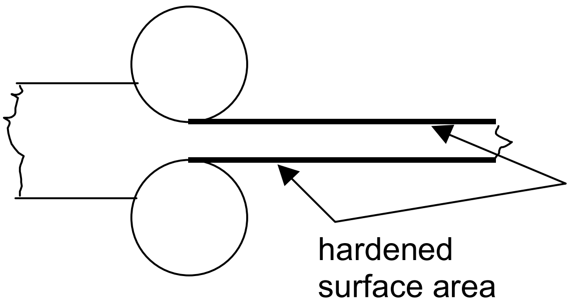
cinematic hardening

Anisotropy

While strain hardening and ductility are general characteristic of metallic materials, anisotropy (at least, the kind that we consider here) is a typical feature of cold rolled steel sheets.

During rolling operation, two phenomena happen in the material:

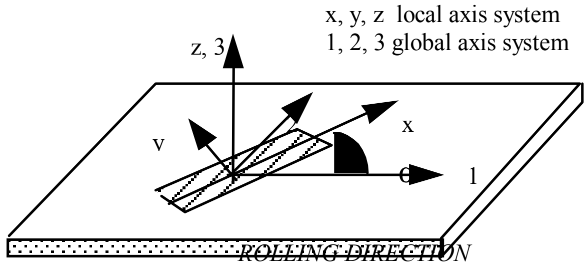
- The surface is hardened, leading to a greater stiffness and resistance in the thickness direction.
- The fibers are oriented in the rolling direction, changing directional response in the sheet plane.



Material anisotropy for metal blanks is quantified using the Lankford, ratio, measured during the tensile test.

Lankford ratio r_α

$$r_\alpha = \frac{d\varepsilon_{\alpha+\pi/2}}{d\varepsilon_t} = \frac{d\varepsilon_{yy}}{d\varepsilon_{zz}} \cong \frac{\varepsilon_{yy}}{\varepsilon_{zz}}$$



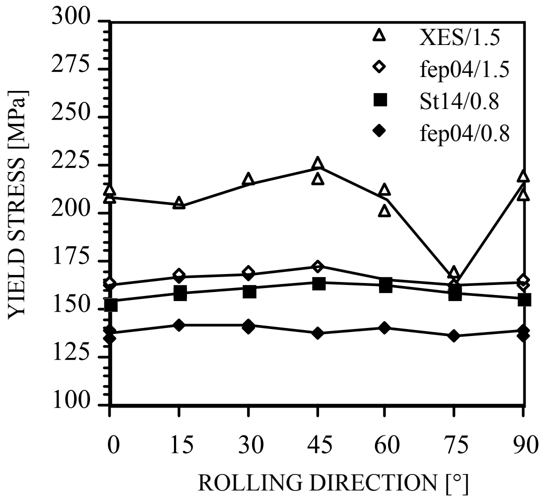
Reference frame definition

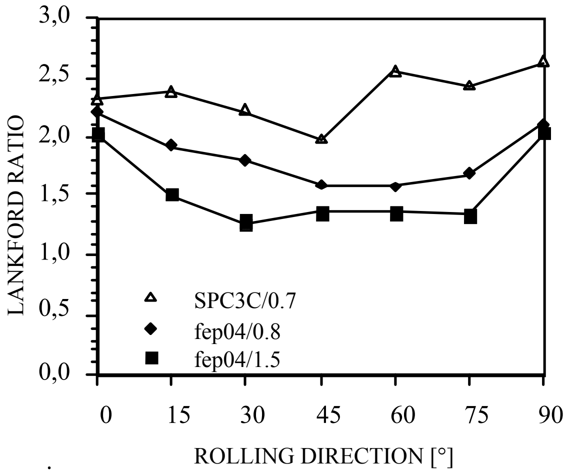
Remark:

- *High Lankford ratios reduce the thinning of the sheet during stamping processes.*

During a uniaxial tension test, specimens cut at different angles α to the rolling direction show different yield stresses and Lankford ratios.

Such differences are also found in the yield stresses measured at different orientations.

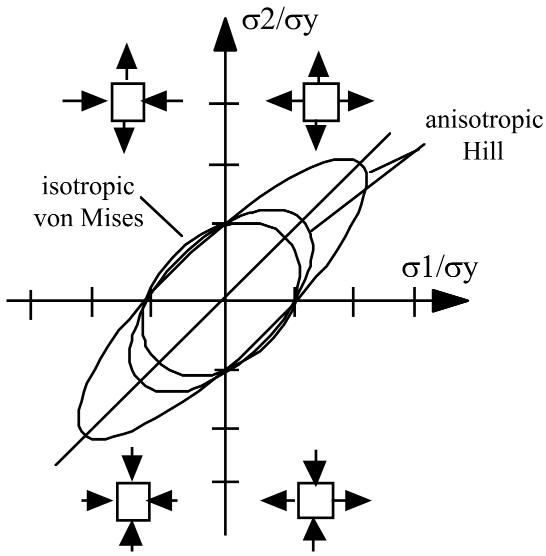




Material anisotropy also affects the shape of the yielding surface, as shown in the figure.

The most common model used for sheet anisotropy is the **orthotropic model** (Hill, 1948), which assumes that the direction 1,2,3 of the global axis system (1 coincides with rolling direction) define symmetry planes for material behavior.

In terms of the Lankford coefficients measured in different directions, the yield criterion becomes:

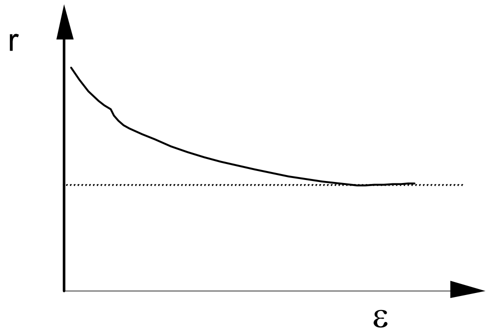


$$\bar{\sigma} = \frac{1}{\sqrt{P(R+1)}} \left[R(P+1)\,\sigma_{22}^2 + P(R+1)\sigma_{11}^2 - 2RP\sigma_{11}\sigma_{22} + (2Q+1)(R+P)\,\sigma_{12}^{2}\right]^{1/2}$$

where R, Q, P are the Lankford ratio values at 0°, 45°, 90°

As it usually happens, the assumption

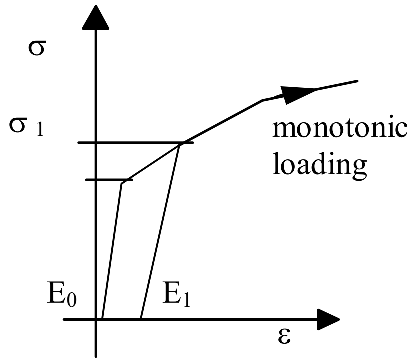
$\frac{d\varepsilon_{yy}}{d\varepsilon_{yy}} \cong \frac{\varepsilon_{yy}}{\varepsilon_{yy}}$ (which would lead to a constant Lankford ratio independently of the strain level) is far from being correct at all times. In practice, for steel and some aluminum, Lankford coefficient tends to decrease as plastic strain increases.



Young modulus

The Young modulus $E = \frac{\bar{\sigma}}{\bar{\varepsilon}}$ is defined as the ratio between equivalent stress and equivalent strain for the material in the elastic phase.

There is little or no influence of the Young modulus on the material behavior during the forming phase. However, this parameter is a controlling factor of the springback behavior.



The residual strain after unloading is given by :

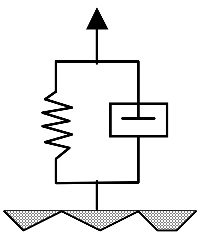
$$\varepsilon_1 = \frac{\sigma_1}{E_1}$$

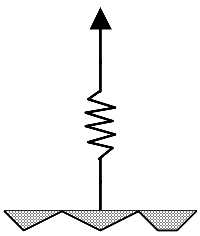
Strain rate sensitivity

There is experimental evidence that the hardening curve of a material depends on the rate at which the strain is imposed on the specimen.

The visco-elastic model (classic spring-damper system) represents the simplest rate-dependent behavior.

In a metallic material and for large deformation, the behavior of the material is visco-plastic (large





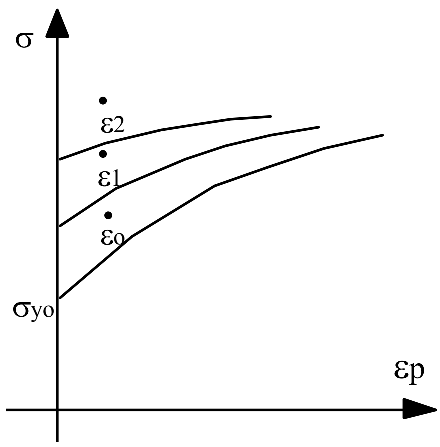
deformations take place).

Visco-elastic Purely elastic

In practice, the stress-strain curve of a material is modified for different strain rates.

For strain rates currently encountered in sheet metal forming (around 10^{-3} to 10^{-2} sec^{-1}), variation in material behavior is not significant.

Strain rate effect is important for special operations (blow forming, super plastic forming).



Strain rate effect is also encountered in the passage through drawbeads and stepbeads during conventional forming operations.

Material friction properties

Coulomb friction standard law

The simplest and most used friction law is named after Coulomb. It establish a linear relation between the tangential friction force τ and the normal force N :

$$\tau = \mu N$$

In practice, the friction coefficient μ is a function of a number of variables, as described below.

Macroscopic properties

Macroscopic properties can be measured over an area that is large with respect to surface rugosity (in practice, a few squared mm, i.e. enough room for a sensor).

Surface pressure : $p = \frac{N}{A}$

Sliding velocity v

Temperature θ

Hydrodynamic lubrication

$$\mu_{static} \neq \mu_{dynamic}$$

Microscopic properties

Microscopic properties are related to single surface rugosity peaks or groups thereof. Hence, they are very difficult to quantify and they are usually described using statistical methods.

Surface interaction (adhesion vs. abrasion) FIGURE ????????????????????

Mixed lubrication

Restraining systems

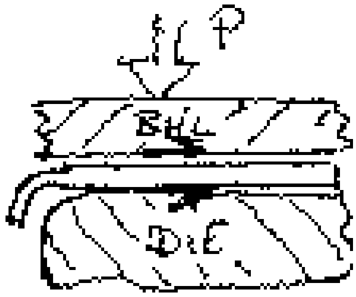
The contact between blankholder, die and blank can control the material flow into the die cavity. This is very useful during the first phase of a forming operation, where the volume of the part is created.

Contact/friction under blankholder

The mechanism of this restraining system is the bilateral contact between the blank and the two tool surfaces.

This contact takes place only in hydraulic presses, or in mechanical presses with hydraulic cushion.

The actual contact conditions are quite unpredictable, so that this mechanism is very rarely used to control the material flow.



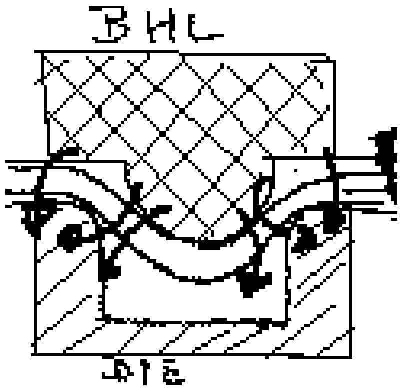
Drawbeads

A drawbead consists in a pair of inserts (male/female) mounted on opposite faces of blankholder and die.

The blank is forced to pass through these surfaces, taking as it goes through the curvature of the tool inserts.

The deformation energy dissipated in these bending/unbending cycles is transformed in restraining force.

As the radius of curvature of the tools can be changed at will during try-out, drawbeads can control material flow very finely in any press conditions.



Hard points

Hard points are limited areas where high friction conditions are imposed, very often by spot-welding some material on the die surface.

Material flow is all but blocked on the hard points, enabling a stretching condition on some lines chosen during try-out.

SIMEX® INVERSE SIMULATION OF SHEET METAL FORMING

The inverse numerical simulation is based on the knowledge of the final shape of the part to stamp. The method is to set up a non-linear system, which will enable to establish the nodes' position on the initial shape.

The principles of the inverse approach in sheet metal forming simulation

The starting point of the inverse approach is the discretised model of the stamped part. The algorithms of the inverse simulation enable the user to establish the position of the mesh's nodes on the initial blank, which is considered to be plane or of known shape.

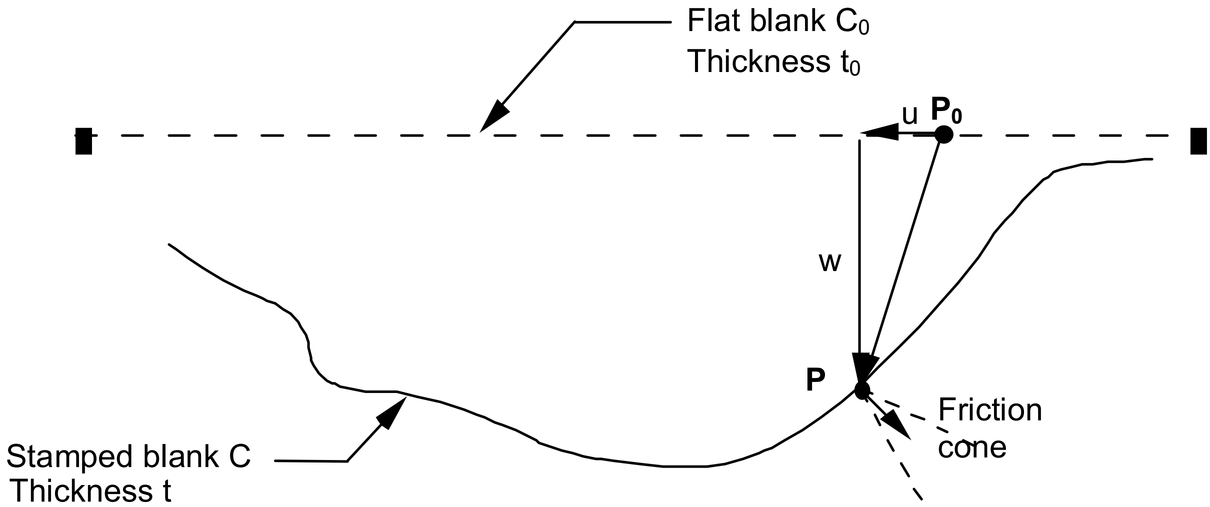
During the sheet metal forming process, a displacement field is associated to the nodes. This field is the basis of the calculation of the deformations, stresses, and internal forces, necessary for the search of the stamped blank's equilibrium.

The results of a Simex calculation are the shape of the initial blank (enabling to obtain the stamped part), as well as a certain number of quantities such as the displacement field associated to the nodes of the stamped part, the thinning, the deformations and equivalent stresses,…

It is important to notice that no model of sheet metal forming tools (matrix, punch and blankholder) is taken into account for the inverse simulation. However, their influence on the stamped blank is taken into account through external forces (contact forces, friction forces, restraining forces,…). This influence is taken into account through the definition of different types of "materials", according to the type of friction coming into play between the stamped blank and the sheet metal forming tools.

Problem formulation

In an inverse simulation, **we model the blank in the latest stage of the forming operation.**



Unknowns of the problem

	Known	Unknown
Initial blank	Thickness e_0.	Displacement u and v of a node P
Stamped part	Geometry, Displacement w of a node P, Restraining force, friction.	Thickness e.

Position of the problem :

find the displacements u and v so that, given a field of vertical displacement w, the stamped part is in equilibrium under the action of

⇒ *internal stresses*

⇒ *reaction forces*

⇒ *friction forces*

⇒ *restraining forces*

In order to find the solution, we must find the minimum of the total energy functional :

$$\min!_{u,v}\left(\Phi\left(\varepsilon_{ij}\right)+W\left(u_i\right)\right)$$

where

- $\Phi =$ internal strain energy
- $W =$ work of external forces

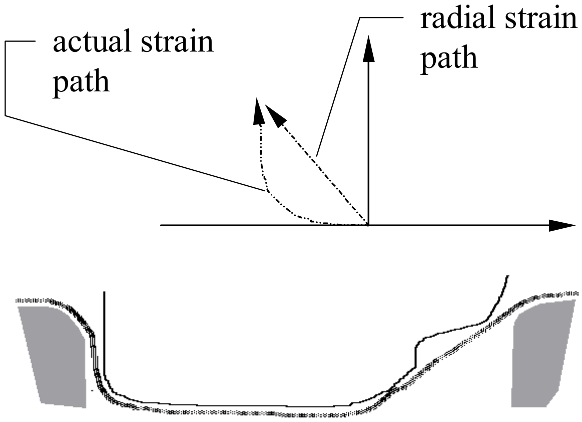
N.B. : we solve a static, non-linear problem

Simplifying assumptions of the inverse method

radial strains:

- the history of deformation is neglected
- we can use the Henky-Mises integrated plasticity theory :

$$\bar{\sigma} = \frac{1}{\bar{\bar{E}}} P^{-1} \bar{\varepsilon}$$



static analysis:

- the history of contact between tools and blank is taken into account approximately

Of course, this simplifying assumptions introduce an error which can be estimated at 15 to 20% of the deformation for most parts.

SIMEX® V2.0 Technical Specifications

Finite elements models	Membrane elements, 3-4 nodes Bar elements (drawbeads)
Kinematics	- Large deformation - Large displacements
Type of analysis	- Plastic, - Elastic
Tribology	Coulomb's friction : - Punch/blank - Blankholder/ blank/ die
Boundary conditions	- Nodal displacements in all directions - Initial cutting pattern (possible)
Loads	- Restraining force of the blankholder - Restraining force of drawbeads
Options	- Definition of a stick component - Check - Stamping direction
Results	- Initial blank shape - Chart of engineering quantities - Risks of defects
I/O interfaces	- DIE EXPLORER - PAM/QUICKSTAMP

The inverse approach using the SIMEX® software

Material behavior

Simex takes into account the following characteristics of the materials' behavior:

- *Hardening*

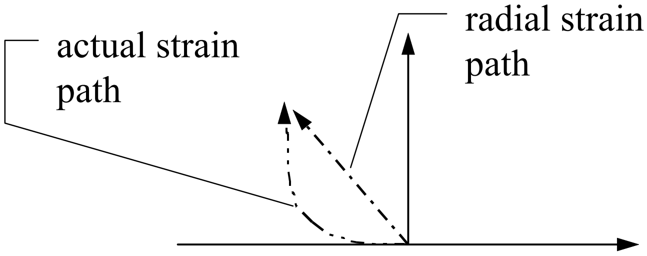
Modeled through Krupkovski-Swift's law:

$$\sigma = K.(\varepsilon_0 + \varepsilon_{eq})^n$$

The material model implemented in SIMEX follows the plasticity laws of Henki-Mises, which are based on the following hypotheses:

1. The deformation's elastic component can be ignored with respect to the plastic component.
2. The deformation paths are radials: At each time t>0,

$$\frac{\varepsilon_1(t)}{\varepsilon_2(t)} = \alpha(constant)$$



On the base of these hypotheses, the equations of the material flow (associative plasticity of Von Mises and Hill) can be integrated to give rise to and explicit relation between constraints values and deformation:

$$\begin{matrix}\sigma_1\\ \sigma_2\end{matrix} = E_s P^{-1} \begin{matrix}\varepsilon_1\\ \varepsilon_2\end{matrix}$$

where

E_s is the secant modulus,

and

P is a matrix, function of the chosen plastic flow criterion.

- *Normal anisotropy*

Expressed through Lankford's mean coefficient R:

$$R = \frac{R_0 + 2R_{45} + R_{90}}{4}$$

With R_0, R_{45} and R_{90}, Lankford's coefficient R= $\varepsilon_2/\varepsilon_3$ expressed in three directions α=0°, α=45° and α=90° with respect to the lamination's direction.

The following data define the material properties and are included in SIMEX® material database

- - Type of material,
- -Material's thickness,
- -E Elastic modulus of the material,
- - R Modulus of the mean (normal) anisotropy of the material,
- - K First coefficient of Krupkovski-Swift's law,
- - ε_0 Second coefficient of Krupkovski-Swift's law,
- - n Hardening coefficient, third coefficient of Krupkovski-Swift's law.

Components definition within the blank.

It is important to point our that, in an inverse simulation, we model the blank in the latest stage of the forming operation. Therefore, when we talk about "punch" or "blankholder", it should be understood "the portion of material under the punch" or "the portion of material under the blankholder".

Two areas are to be taken into account with respect to the friction between blanks and tools:

- The blank's part held between the blankholder and the matrix. The contact at that level is bilateral **bilateral.**
- The part corresponding to the rest of the blank, where the friction is only carried out between this one and the punch.

Thus, for a coefficient μgiven, intervenes μ for the friction blank/punch part (**Punch component**), and 2μ for the blank/matrix/blankholder (**blankholder component**).

Friction model used by Simex

Friction between the blank and the blankholder

The friction between the blank and the blankholder is taken into account through a restraining force. This one is applied to the blank's nodes defined as belonging to the component of blankholder type. It is opposite to the elements' displacements.

The restraining force per unit of surface is defined to be **2μp**, where:

- P is the contact pressure per unit of surface, as **p=F/A,**
- A is the surface and F, the blankholder force, defined by the user.

The restraining force goes on the same direction as the blank displacement.

Friction between the blank and the punch

For each node belonging to a material, μ different from zero, Simex estimates the friction force between the blank and the punch to be μf_n.

With f_n the punch reaction on the blank, of which direction is equal to the blank's displacement one.

Restraining conditions

Blankholder force

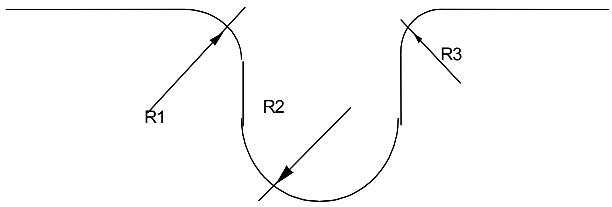
As we have seen previously, the friction between the blank and the blankholder is taken into account through a restraining force which is equal to **2μP.**

Drawbead restraining action

Simex enables the introduction of **restraining drawbeads**.

Depending on the user configuration (file simex.env in directory SIMEXDIR) the restraining force can be input by the user in consistent units (for example, N/mm), or computed by SIMEX. In this case, the user inputs a percentage of the restraining force of a standard drawbead.

This drawbead is characterized by a certain number of radii, which the blank is supposed to match:



From the standard drawbeads, Simex calculates automatically the restraining and holding force for this geometry, according to the material chosen by the user, to its thickness and to the friction coefficient between the blank and the punch.

The standard drawbead used by Simex is the DIN drawbead, characterized by the following radii:

- - R1=3 mm
- - R2=6 mm
- - R3=R1=3 mm

These features are contained in a file called simex.jonc, placed in the SIMEXDIR directory. The user can modify this file as follows:

Line	Contents	Data type
1	Number of nr radii	Integer
2	R1	Real

3	R2	Real
4	R3	Real
…	…	…

This is the conceptual scheme for the definition of restraining forces:

1. The user defines a blankholder restrain.
2. The user defines the restrain of the introduced drawbeads, as being a percentage of the standard drawbead restraining force.
3. Simex calculates the restraining force, per unit of length, of the standard drawbeads and of the material chosen by the user. Moreover, it calculates the holding force per length unit necessary to the closing of the drawbead.
4. Simex distributes the restraining force on the drawbead segments.
5. Simex takes the total holding force away from the blankholder force.

   In case the blankholder force is null, the drawbead will close anyway. No blankholder force will be applied.

Types of analyses made by Simex (elastic, elasto-plastic, plastic)

Simex suggests three types of analyses:

The elasto-plastic analysis

In this case, the results of the elastic analysis are taken as initial conditions for an elasto-plastic type of calculation.

Use this option for difficult shapes (with irregular outlines, distorted elements,…).

The plastic analysis

This one could be a standard choice to start the calculations.

Special Simex options

Define a component as a stick

At the time of inverse simulation, the final shape is known. Therefore, the initial shape has to be found.

However, the shaping of the blank by forming the sheet metal using the punch and the matrix, or using another process (for example hydroforming), does not give the same results. This is even truer if the stamped blank has marked curvatures (like the ones on a dish for instance).

The type of the simulation, which has to be made, has to be specified before starting an inverse calculation. To do this, we suggest that the user define a component called "stick". This component, to which we give particular physical properties (described later on in this paragraph), enables the simulation of deep drawing using conventional punch and die apparel.

- Physical phenomenon of the deep sheet metal forming of a dish

    As we said before, at the time of the sheet metal forming, the first part of the blank, which is in contact with the punch, is placed underneath the bottom of the punch. This part is pushed in the matrix, without being subjected to any deformations. On the other hand, the blank's parts, which are underneath the curved areas of the punch, will be caught between the punch and the matrix wall. This explains the strong deformations and the strong variations in the thickness, at the level of this area and above.

    This phenomenon will protect the blank's part, which is underneath the punch. This is another reason for the little deformations and the little thinning which it is subjected to.

- Behavior of a material without stick

    The behavior of the blank without defining a stick material is as following: the blank slides along the bottom of the punch. Thus, the deformations and the thinning appear on this part of the blank.

    Moreover, their gradient is regular starting from the bottom of the punch up to the limit of the blankholder material.

- Behavior of a stick material

    The stick phenomenon is to define a certain part of the blank stuck to the punch. This will ensure little deformations and thinning at the bottom of the dish. These will be allocated on the curved areas of the punch. Thus, we find again the behavior of the deep sheet metal forming on the whole stamped part.

The "sticking" model works at the level of the curved areas of the stamped blank. However, the "sticking" material has to include a part of the surrounding flat areas.

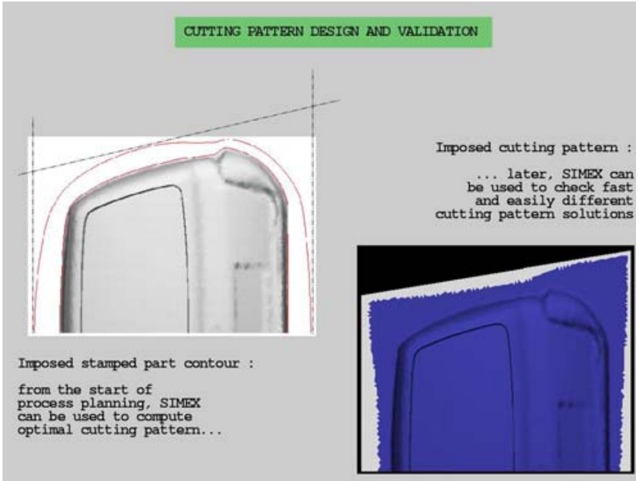
Set-up of the blank's initial shape (cutting pattern)

Die design has to enable the definition of a blank's run-offs. This means that for a part as designed (stamped blank), it should be possible to identify the blank's part which have to be added, and to calculate their ideal dimensions. These ones have to be put underneath the blankholder, or in the junction areas.

To enable this, Simex offers the possibility to define the blank's initial shape, in addition to the stamped part. Hence, there are two modes of operation:

- The user wants to impose the final part contour. This is the case for all the analysis of parts as designed. In this case, Simex performs a pure inverse analysis.
- The user wants to impose the cutting pattern. In this case, Simex performs an inverse analysis with the additional constraint that the initial contour corresponds to the one, imposed by the user.

Here, for the RENAULT TWINGO's hatchback, a first simulation is made by modeling only the part of the blank which is in contact with the punch (up to the die radius). This enables us to obtain the minimal cut's outline. This profile is then modified to simplify the trimming process. Finally, a check simulation, this time imposing the cutting pattern, is carried out to make sure that the considered process is correct.



Analysis of SIMEX® results

A Simex simulation yields the following results:

- Initial blank shape (plane or of projected on a known geometry). The material parts belonging to the blank and to the run-off can be seen on this shape.
- The distribution graphs of a certain number of quantities typical to the analysis of the sheet metal forming. These are plotted on the stamped or initial shape. The quantities that can be seen in the result of a Simex calculation are:
  - The shape of the initial blank,
  - The displacements,
  - The thinning,
  - The equivalent plastic strain,
  - The deformations mode,
  - Von Mises' equivalent stress,
  - The maximal principal stress,
  - The minimal principal stress,
  - The maximal principal deformations,
  - The minimal principle deformations,
  - The distance of each mesh's node, from the FLD curve.

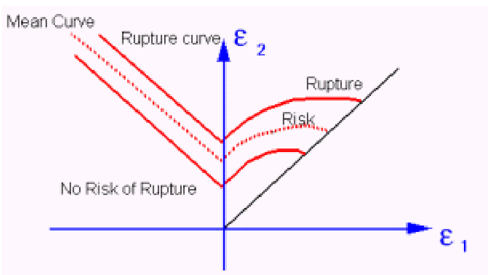
Types of defects, results analysis

There are three important types of defects to detect in the stamped part:

Rupture

To detect the risks of rupture, the following quantities have to be examined:

- FLD curve (Forming Limit Diagram). This plot is determined experimentally on the basis of normalized series of tests, or approximately as indicated above.



- Maximal thinning. This is in practice a simplified FLD plot, where the 45° left curve is extended on the right quarter-plane. Good stamping practice suggests to limit maximum thinning to 18-20%, but severe stamping conditions can lead to much higher thinning.

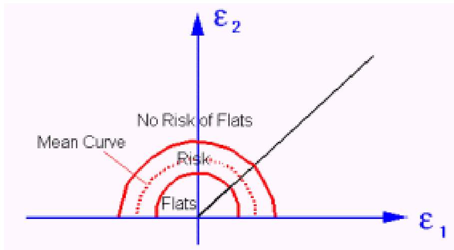
Unstretched areas (flat areas)

An Unstretched area generates many problems:

- Surface defects,
- Shape defects (undulation) resulting from the deformation difference between the adjoining areas of the part.

To detect the risks of having an unstretched area, the following quantities have to be examined:

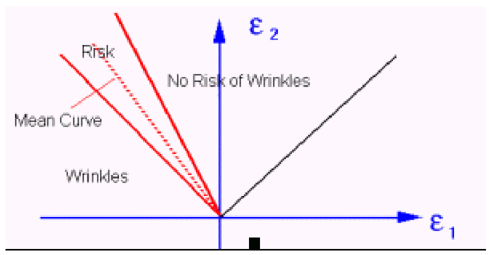
- The equivalent plastic strain. The unstretched areas are often linked to small values of the plastic deformations. The unstretched areas will be avoided for a minimal value of the equivalent plastic strain of 4%.



Wrinkles

To detect the risks of wrinkles, the following magnitudes have to be examined:

- -*The thickening*. For a finished blank, any area, which presents a thickening (negative thinning), will have wrinkles.
- The stress state. Any area, which presents compression stress (negative stress), will have wrinkles.
- The deformation state. The two conditions described above can be easily identified on the deformation plan.



Other tips

In any case, it is advised to look at the displacement distribution graph.

The displacement in the forming z direction enables to look at the nodal displacements, from the stamped shape to the initial shape. This means that this standard displacement corresponds to the distance between the two blanks.

The two other directions are interesting to consider during the sheet metal forming phenomenon, to see the material flow inside the die.

It is also interesting to look at the initial shape obtains with the Simex calculation. It enables to look at the material flow between the two states, comparing it to the stamped shape.

SIMEX® bag of tricks