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Effective Process Design and Robust Manufacturing for Hydroformed Parts

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A general trend and one of the important strategies in the automotive industry is reducing the lead time of a new car development. In order to obtain this goal the efficient use of simulation software is needed to effectively design a hydroformed part. The stages of the design chain are integrated in one simulation tool. The outcome of this feasibility analysis is a virtual prototype saying that it is possible to produce the part. In fact one process point has been defined whereas when going into production a process window must be know to guarantee a stable production process. In order to achieve this latter we are suggesting a process performance analysis. Based on multiple simulations the influence and sensitivity various process parameters on the forming process can be identified. Besides combining the analysis with statistical process control evaluation the process capability (Cpk-values) can be defined. This design chain analysis will be applied on a hydroformed part. The process performance analysis is the identification of the process window and process capability in advance, so before any tool has been milled. This will be demonstrated on a second hydroformed part.

Key Words : Process Design, Virtual Prototype, Robust Manufacturing

1. Introduction

Nowadays, hydroforming is a widely accepted technology. More and more applications in the automotive industry have been seen. A general trend and one of the important strategies in the automotive industry is reducing the lead time of a new car development. To meet this strategy a new engineering practice is needed (Kim and Hwang, 2002). The processes in the design chain must be aligned with each other resulting in a smooth transition from one stage to the other. Also every stage must generate reliable results in order to avoid stepping back to previous phases.

An approved method is the usage of simulation software. The use of simulation software will also be needed to make reliable statements during the definition phase of hydroforming production lines on feasibility and lead-time (Treude, and Engel, 2001).

As we all know hydroforming simulations are at a high industrial standard but it must be possible to increase the efficiency in the whole design chain (Hora and Skrikerud, 2002). The design chain can roughly be divided into three phases :

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Part design, Tool design and Process design.

When a part is designed its geometry is created in a CAD system. This part needs to be checked on feasibility through the rest of the design chain. All data transfer from the part feasibility to the tool design and further transfer to the process design takes time. During this iterative process, data communication and ease of transfer are essential to speed up the whole design chain. This process including the time line is illustrated in Figure 1.

Despite of the detailed analyses it still happens that parts fail during production. This part failure even occurs when the feasibility simulation turned out to be successful. In a simulation, a single set of parameters (tube wall thickness, lubrication, axial feeding, etc.) is defined whereas in real life these parameters vary. This variation can be the difference between success and failure. Fact is, when we are applying one simulation we are only defining one process point. But, when going into production a process window must be known to guarantee a stable production process (Hora, 2004; Carleer and Zwickl, 2004).

This paper deals with the efficient use of simulation software to effectively design a hydroformed part. The design chain will be illustrated in the next three sections by using an axial component.

The first part deals with the part design that mainly looks at the part feasibility. The second part deals with the tool design. How must the hydroform tool look like? The third part deals with the process design. This is the sequence of all subsequent forming steps needed in the manufacturing process. In the fourth part some simulation results will be examined. Finally this paper shows an analysis methodology in order to define the process capability (Cpk-values) with respect to varying parameters like process settings and material variations which always exist.

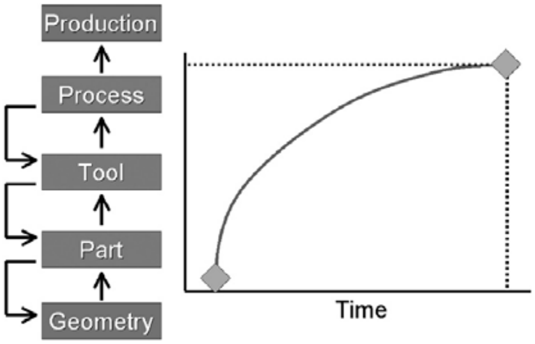


Fig. 1 Design chain sequence with effort against time representation

2. Part Design

The part is designed to fulfill its requirements. These requirements are listed in the specifications. The feasibility must already be checked in this phase.

A checklist for feasibility must contain the following elements (N. N., 2002):

(1) Geometrical data
(2) Hole geometries
(3) Section analysis: Tube diameter, tube shape
(4) Definition of the bending line
(5) Required internal pressure

The geometrical data are created in a CAD system. These data must be handed over easily to the analysis program.

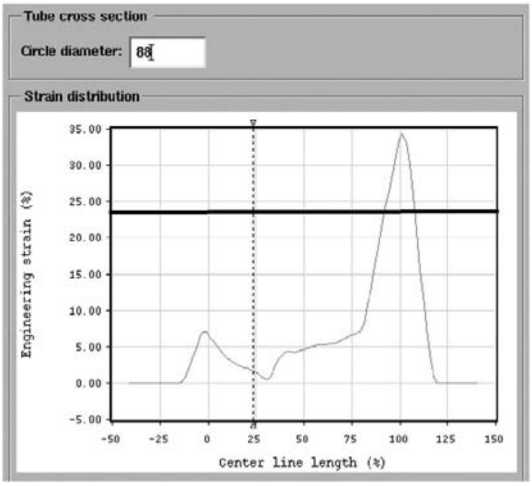
Figure 2 shows the axial component with the tube start and the tube end indicated. Also the holes are indicated, which are automatically filled.

A section analysis is used to determine the theoretical average strain based on the perimeter. These sections have to be generated automatically without any manual input to avoid essential mistakes. However, keep in mind that the average strain is a first rough estimation. In general, due to friction the strain at a straight side is lower than the average value whereas the strain value in corners can be much higher.

Fig. 2 Picture of the axial component with the tube start, the tube end and the indicated filled holes

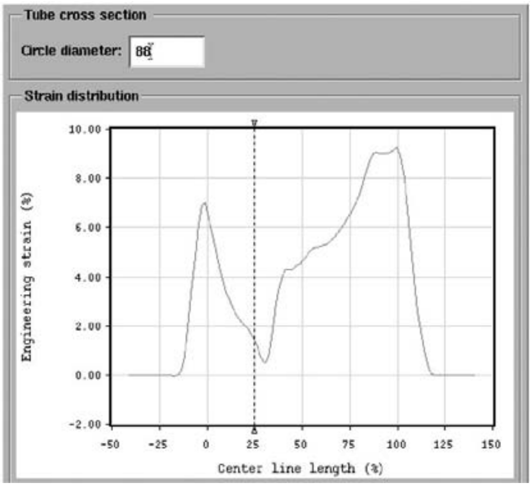
In the pictures below, the section analysis is illustrated. The sections are always perpendicular to the automatically generated center line.

At this point the initial tube diameter can be defined. For this example a tube diameter of 88.0 mm is chosen. In case the material is known, the plane strain point of the FLC can be plotted in the section strain graph to check feasibility. If the average strain is already larger than the plane strain point, successful hydroforming is very difficult. For the axial component the material H340LA with a thickness of 2.00 mm is chosen.



Circle diameter: 88

Fig. 3 Section analysis strain graph of the original part



Circle diameter: 88

Fig. 4 Section analysis strain graph of the modified part

Figures 3 and 4 both show a cross section distribution, Figure 3 of the original part design and Figure 4 of the modified part design. As can be seen in Figure 3 the maximum strain is over 30% whereas the plane strain point of the FLC is 23%. So, already at this moment the design can be modified to obtain a feasible part. Figure 4 shows the cross section distribution of the modified part where the maximum strain is slightly below 10%.

In case the tube must be pre-bent to fit in the die, the bending line has to be defined. The bending line is generated automatically based on the center line. Manual manipulation is possible and very often required.

The required internal pressure can be determined when knowing the material, the tube wall thickness and the minimum radius of the part. This determination done with analytical models gives a good first estimation (Birkert, 2000). With this estimated internal pressure and the part projected area the maximum closing force can be defined. With that the required press can be defined.

The steps performed now already give a first estimation whether the part is feasible or not. In case the part is not feasible, step back to the CAD system. In case the part is feasible, step into the next phase, the tool design definition.

3. Tool Design

The tool design definition can be performed with the same user interface as the part design feasibility. The tool design definition contains the following elements (N. N., 2002):

(1) Addendum (Transition zone and guiding zone)

(2) Die Split Line

The addendum is generated automatically. The addendum is an extension of the part and consists out of two zones, the transition zone and the guiding zone. The transition zone is the zone starting at the end of the part and evolves to the shape of the base tube. The guiding zone has the same shape as the tube. It is the area where the tube is sealed and where the tube is fed. In the figure below the automatically generated addendum and the original part are shown.

The last element of the tool design is the definition of the die split line. It must be possible to open the tool to put the tube in and take the part out. The part must be tipped first in order to avoid undercuts. The split lines are generated automatically.

Figure 6 shows the two die-halves and Figure 7 shows a section of the part with the two points of separation indicated. If required you can manually manipulate the points of separation.

At this stage of the design phase, we have both the part- and the tool surface-design. If satisfied with the results, you go into the process design phase if not you step back to a previous phase.

Fig. 5 Part with automatically generated addendum

Fig. 6 Upper and lower part of the die

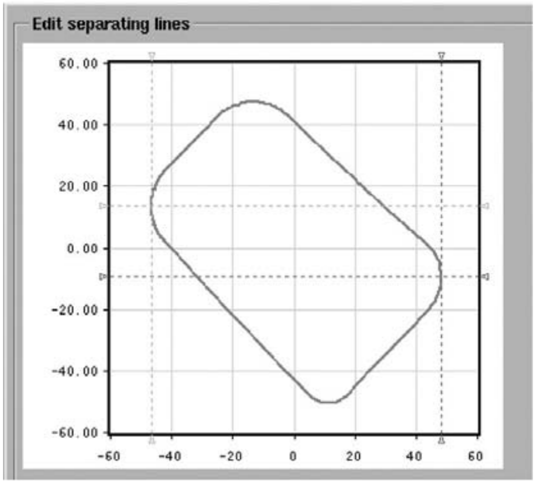


Fig. 7 Section of the part with points of tool separation

4. Process Design

In order to define the process parameters, simulations are used. The simulation can be set-up with the same interface as the part- and tool-design. The process definition contains the following elements (N. N., 2002):

(1) Bending
(2) Pre-forming
(3) Process curves

The bending line has already been defined in the part design phase. Also with help of the bending graph, it can be analyzed how critical the bend is. Here you have to decide how precise the bending process must be analyzed.

In case of non critical bending, a simplified bending model is good enough. Only the strain hardening and the thickness changes are incorporated in the simulation. This simulation can be done without the generation of bending tools.

In case of critical bending a detailed bending simulation needs to be done. All bending tools are generated automatically and an incremental simulation is run. This simulation gives also information on geometrical deviations like falling in at the outer bend or even wrinkles in the inner bend.

In order to place the bended tube into the hydroforming die occasionally the tube must be preformed. The pre-forming mainly is a geometrical change, most of the time little plastic deformation occurs. But the risk of (irreversible) wrinkles exists. In case the tool cannot be closed without the risk of pinching, a separate pre-forming step is required.

Once the tube is in the closed die-set the actual hydroforming can start. The main process parameters are the internal pressure and the axial feeding, occasionally counter punch movements are required.

The simulation can be started in the same user interface. In the next section the simulations itself will be looked at.

5. Simulations Results

As defined in the process design the simulations of the axial component exist of the following steps:

(1) Bending
(2) Tool closing
(3) Hydroforming

These subsequent step will of course be simulated subsequently.

Since the bending of the part is a non-critical bending, a simplified bending simulation is performed in seconds. The result of this bending simulation is plotted below. The inner bend shows a thickness increase whereas the outer bend shows a thickness decrease.

In this first simulation the tube is only calibrated. No axial feeding is performed during the hydroforming. The result is plotted below in Figure 9. Although the section analysis showed only relatively small strains the part splits. The splits occur at the corners of the part. With an average strain of 9% at the largest cross section the part looked very safe. But the thinning on the straight wall at the cross section with the split is almost zero. Whereas the thinning rapidly increases towards the corner of the part till it splits. The local thinning in the corner exceeds the 23% mark which is the lowest point of the FLC.

Luckily the critical area is at the end of the part so axial feeding may be applied to solve this problem.

But before having a look at a simulation with axial feeding a look will be taken at the die closure.

Fig. 8 Bending strains

Fig. 9 Fracture; hydroforming without axial feeding

As said before die closure can be interpreted as a pre-forming operation. The pre-forming mainly is a geometrical change with the risk of (irreversible) wrinkles.

Figure 10 shows the part geometry after die closing. The part fits quite well in the die cavity. This simulation is performed with a bending-enhanced membrane element. The membrane element calculates fast but has only approximate bending stiffness. For that reason no geometrical deflection will occur.

In case the same simulation has been performed with a shell element some geometrical deflection will occur. Due to its accurate bending stiffness the shell shows the occurrence of wrinkles or deflections.

Figure 11 shows surface deflection at the flat side of the part during die closure. The calculation time for the shell element is of course larger than for the bending-enhanced membrane element.

The axial feeding can be added in the process design definition. Including axial feeding the hydroforming process leads to much better results. The first simulation is performed with membrane elements. For this simulation not only the inner bend thickens but also both tube ends because of

Fig. 10 Die closure with membrane element

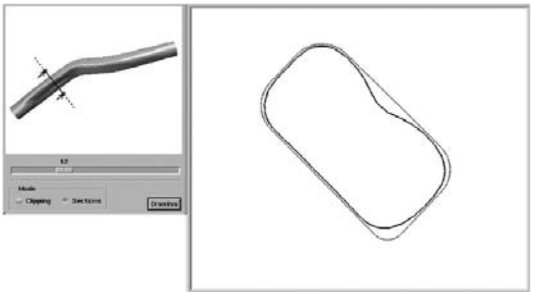


Fig. 11 Die closure with shell element; Part shows deflection in flat area

the axial feeding. In case the same simulation is performed with shell elements, the result looks slightly different. As you can see in the figure below the part wrinkles at the flat tube end because of the axial feeding. So, to make the part feasible the axial feeding at the tube start must be reduced.

After reducing the axial feeding, the part seems feasible. The axial feeding is tuned in such a way that on the one hand no splits occur and on the other hand no wrinkles occur.

Looking in more detail at this last simulation, another irregularity can be detected. At the back side of the part a small irreversible deflection occurs. This deflection can be seen in Figure 13.

At this smallest cross section only 0.5% average strain is needed to form the part. As seen before the tube slightly deflects during tool closing. During hydroforming the tube expands and the strain exceeds the 0.5%. As a consequence a surplus of material occurs. During the calibration it is impossible to totally form the part and an irreversible deflection occurs.

In order to overcome the problem with the irreversible deflection a smaller tube must be used. When reducing the tube diameter from 88.0 mm to 86.0 mm, the strain needed to form the part in the smallest cross section increases from 0.5% to 2.8%. The maximum average strain changes from 9.3% to 11.8%. This maximum value is still far below the lowest point of the FLC. The result, a feasible part, of the last simulation is plotted in Figure 14.

Fig. 12 Wrinkles because of excessive axial feeding ; with shell element

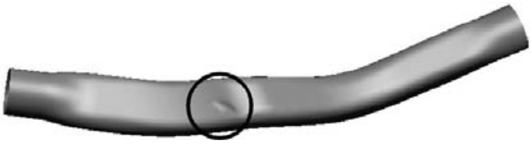


Fig. 13 Irreversible deflection because of a too large a tube diameter ; with shell element

Fig. 14 Part feasible with smaller tube diameter

6. Statistical Process Control

Statistical process control is normally applied during production in order to validate the productivity and capability of the production process. Due to variation or scatter of various parameters the production process can fail. Typical scatter parameters are the mechanical properties and the thickness of the tube. These properties must fulfill the given tolerances but within these tolerances a variation is allowed. Also process settings like axial feeding and lubrication (coefficient of friction) are not as constant as we want them to be.

Since we have the possibility to perform multiple simulations taking into account the above described scatter it is only a small step to apply the statistical process control on the simulation results. By doing so, we can evaluate the success rate of the proposed production process already in an early stage without manufacturing any of the tools.

In this study a nitrogen spring housing is evaluated with respect to various scatter or noise parameters. These noise parameters vary according to a normal distribution defined by the center- and standard deviation-value within the min-max-interval. The noise parameters including it's distribution are listed in Figure 15.

	center	standard deviation	Min	Max
axial feeding at start [mm]	30	0.333	29	30
axial feeding at end [mm]	30	0.333	29	30
lubrication (coefficient of friction) [−]	0.11	0.0033	0.10	0.12
Thickness [mm]	1.5	0.0033	1.4	1.6
Rp02 & Rm [MPa]	0	8.33	−25	25

Fig. 15 Noise variable definition

For statistical process control in this study we use the process capability or process precision Cpk. The process precision indicates the controllability of the process around the given specification limit. It indicates the probability whether the result will exceed the specification limit because of the given variation of the input. In this example the specification limit is defined at −0.20 thinning. The Cpk value is plotted as a discrete result variable on the part geometry in Figure 16.

The traffic light color scheme directly expresses the process precision according to DIN 55319. The explanation of the discrete color ranges is given in Figure 17.

Figure 16 shows one small zone where the process is not reliable indicated by the yellow/orange/red colored zone. To have a closer look at how unreliable the process is and which parameters are responsible for this result, the histogram and the Pareto chart for this zone are shown in Figures 18 and 19 respectively.

Fig. 16 Process precision Cpk

Green (reliable)	1.33 =< Cpk	No more than 0.004% of the results are outside the limits
Yellow (control required)	1.00 =< Cpk =< 1.33	Between 0.004–0.14% of the results are outside the limits
Orange (unreliable)	0.67 =< Cpk =< 1.00	Between 0.14–2.25% of the results are outside the limits
Red (unacceptable)	Cpk =< 0.67	More than 2.25% of the results are outside the limits

Fig. 17 Explanation of the process precision appraisal

The histogram shows the frequency of how often a thinning result has been obtained due to the variation of the input. The vertical black line shows the defined specification limit of −0.20 thinning. It can be seen that in some cases more than −0.20 thinning occurs. With help of the frequency plot one can more precisely analyse how reliable or unreliable the process is. In this case one can see that for the most critical area about 10% of the results exceed the specification limit.

The Pareto chart shows the influences of the considered noise variables sorted in decreasing

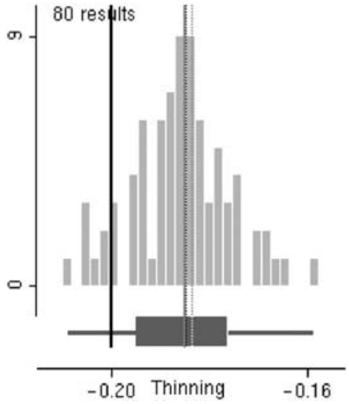


Fig. 18 Histogram

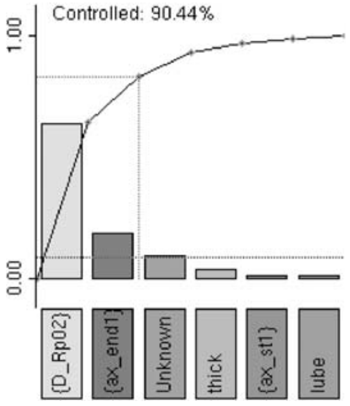


Fig. 19 Pareto chart

order. For the critical area analysed here one can clearly see that the thinning is mainly influenced by the mechanical properties (Rp02 and Rm). The second most influence gives the axial feeding at the tube end. Those two parameters influence the thinning for more than 80% which is indicated with the black dotted box.

For a more detailed analysis we will have a look at the relationship between the mechanical properties and the thinning. Figure 20 shows the scatter plot for the critical area. The scatter plot shows the raw result variable value and the selected noise variable value in a *xy*-scatter plot for all simulations. The *x*-axis represents the value for the mechanical property variation; the *y*-axis represents the resulting thinning. Again the specification limit of −0.20 thinning is indicated with help of the black horizontal line.

A clear trend can be seen that for softer material (negative value of mechanical property deviation) more thinning occurs. The relatively small deviation of the red circles from the thick sensitivity line shows that a correlation between the mechanical properties and the thinning exists. At a first thought this result is a bit astonishing since normally one would expect for softer material better formability and as a result a more reliable process. But this graph shows the opposite. Directly the question rises: how can this be?

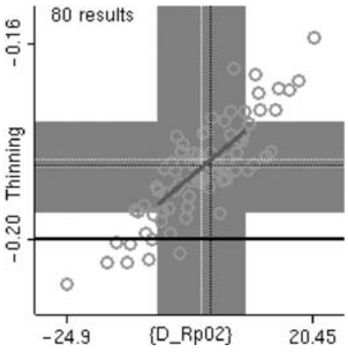


Fig. 20 Scatter plot of the unreliable zone

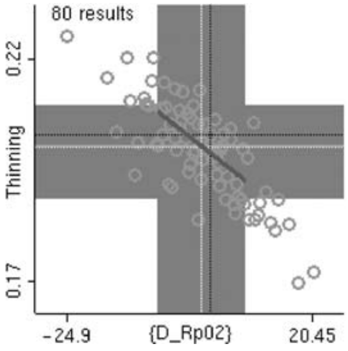


Fig. 21 Scatter plot at the tube end

In order to explain this phenomenon the scatter plot at the tube end is plotted in Figure 21. The material at the tube end thickens. Here we see a descending trend, meaning that for softer material the material thickens more than for stronger materials. So in case of soft material the axial feeding has been absorbed by the material in the feeding and transition zone. As a result the effective axial feeding at the critical zone is much smaller resulting in more critical thinning values.

The results of the process capability show one small critical area. The main cause for the failure are the mechanical properties, the softer the material the more critical the thinning. The analysis also showed that the axial feeding only has a small influence on the thinning behaviour. The influence is that small that failure cannot be overcome with it.

7 Summary

The entire design chain from part design via tool design to process design can effectively be analyzed when using an integrated tool.

The simulation itself must also be reliable and accurate. Depending on the part geometry and the stage in the design chain and therefore the required accuracy, either the bending-enhanced membrane element or the shell element can be used.

With this complete solution the whole design chain can be effectively and efficiently analyzed resulting in a considerable time reduction of the development time (Figure 22).

The process precision Cpk has been analysed during simulation analysis. The process precision indicates the controllability of the process around the given specification limit.

When performing one simulation we are only

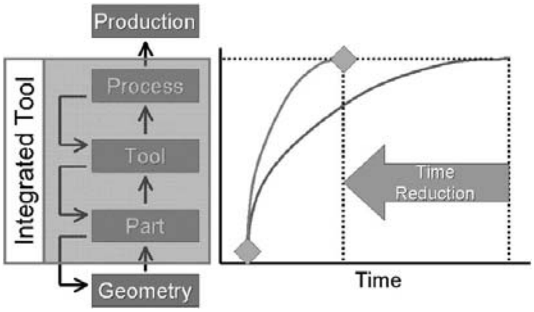


Fig. 22 Reduction of development time because of function integration

defining one process point. But when applying and evaluating multiple simulations, a process window can be defined and it is possible to achieve robust production processes.

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