Automatic solutions for Hydroforming processes

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1 Abstract

The need for fast design and delivery of concepts for hydroformed parts has become important to address tight vehicle development cycles. The use of finite element simulation for the hydroforming process has helped to address some of the issues but not for the full design validation phase. The need for a fast full solution tool that helps to address from product feasibility to various stages of bending, performing and hydroforming tooling Design, process development and validation become critical.

This paper will discuss different automatic solutions for hydroforming processes, included in current or future releases of “PAM-TUBE 2G”, such as automatic bending curve, automatic tool design for preforming, bending and hydroforming and automatic process design and optimization. This makes "PAM-TUBE 2G" a complete tool for streamlining the full forming process; from upfront tool and process design, through formability to validation and quality control in order to avoid downstream problems related to quality, tolerance and performance.

2 Introduction

Understanding hydroforming

The first patent on hydroforming came in 1903 (“Apparatus for forming Serpentine Bodies”). The first high volume production in automotive industry came in the early ‘90ties (1990 Chrysler Minivan IP Beam, 1994 Ford Contour, Engine Cradle). It took a long time from the fundamentals of hydroforming were discovered until the methodology was introduced to high volume production. Of course lack of proper machine and controlling mechanisms play a big role here, but also the understanding of the hydroforming process is not easy. When the dies close, we don’t see anymore what is “going on in there” – and the understanding of why things happen, and what influences there are is not clear at all.

Still today one can observe difficulties in managing problems that occur during setup of complex hydroforming processes. Using finite element method to simulate the processes can give a good help in understanding the process, and both avoid problems and solve problems that occur.

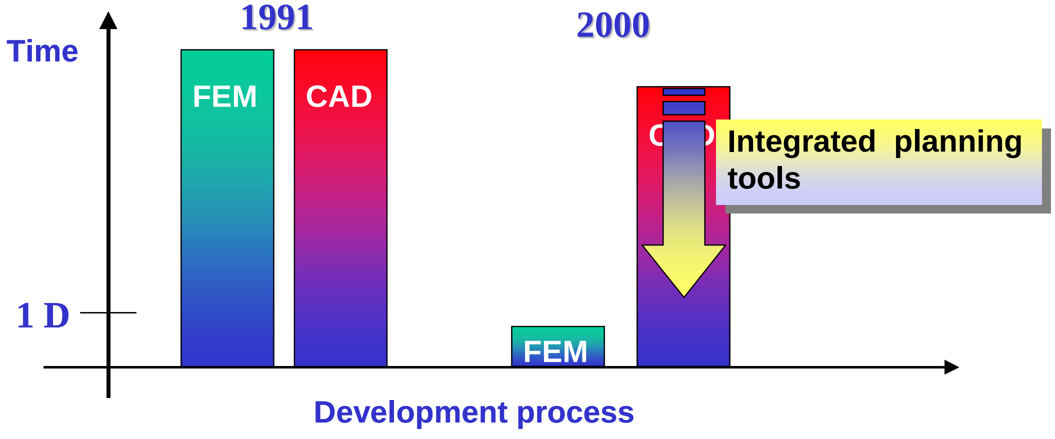
Development of FEM for forming simulations

Since the early ‘90ties, the FEM method has developed rapidly from being a tool for investigating processes to become a tool for validation and quality control. For the forming processes, this has mainly been driven by the sheet metal forming industry, but also for hydroforming developments have been done, but normally after new developments had been tested in sheet forming first. During all this time, the FEM method has helped to gain understanding on the process, and has helped solving problems. But in the same time, some "bad habits" of FEM method were recognized which meant that the reliability of the simulations was not always good enough to base the decisions on it. – samples being the use of one-step-solvers for hydroforming, use of membrane elements and simplified contact algorithms. In the later years, we have seen a development towards increased accuracy, with more realistic modeling of reality. Especially the fact to be sure to model the real world, and not model something almost like real makes a big difference towards the improvement of the results. This allows the user to base the process definition on the simulation results and helps cutting time and costs.

Development of integrated solutions

Once FEM started to be used industrially, soon the users run into other problems than just FEM-related. The pre-processing and the process setup is not at all easy for complex processes such as tube bending and hydroforming. More is needed than only a good solver in order to make the simulation as a tool popular to industrial users. As described in [Hor], it was shown that "FEM-Simulation is only a brick in the complete planning chain", showing that combining a normal CAD with a FEM-solver is not a suitable solution in order to solve the complete planning process.

Another reason for why integrated solutions should be used is the time factor. Since the beginning of FEM simulation, the increase of computation power has reduced the time needed for FEM simulation drastically, whilst this effect for CAD systems has not been as significant because the time consuming part here is the manual labour. The use of integrated planning systems meant that it was possible to cut the time spent for CAD work significantly:



Integrated simulation systems reduce total time of process design significantly [Hor2].

At ETH Zurich, the program Hydro-Plan was developed back in the second half of the 90'ties [Skr]. This tool included a complete chain of tools from the import of the final part geometry via a fast solver for feasibility checks to the accurate explicit solver and post processing. This program was used by several industrial companies. AutoForm presented a similar solution with AutoForm Hydro [Car] in 2001. ESI Group presented a solution for stamping in 2002 which is called 2nd generation software.

Need for automatic solutions

Looking at the situation today, we have reached a good level of accuracy, we do have what we call 2nd generation software. It seems this should be a good solution for industrial use? But still there is a significant amount of manual work involved setting up a hydroforming process. Why do we need automated solutions?

- Higher pressure on development times
  The time-to-market factor is also important for hydroformed parts. This puts a pressure on the development department – is there enough time for simulation – or go directly to prototyping? Automated solutions help speeding up the simulation setup. You cannot risk having to redo the tools because of no time for simulation.
- Higher variety of models / variations
  In recent years the number of models in the car industry has increased at the same times as the number of sold cars per model has decreased. This can mean that a small change in the geometry of a part is needed at one point in the production cycle. Would you risk this small change without a simulation? Automated solutions help changing parameters quickly in order to rerun the case with the changed boundary conditions so that you can ensure that you can safely produce the modified part.
- Manual FEM too difficult?
  Using FEM the “hard way” setting everything up manually is a task which requires a certain amount of understanding of the process and the way FEM works. Offering automated solutions can help people who not have a deep knowledge in these fields to still use FEM-simulations.
- Speed
  Automated solutions will certainly help speeding up the process of the virtual try-out by reducing the amount of manual work needed.
- Ensure quality of simulation
  Automatic solutions can help ensuring the quality of the simulation by automatically selecting and proposing the “best solution” and by ensuring the process is always set up in the same way – so that if comparing 2 simulations you are sure you compare the actual differences and not differences introduced by a small difference in the process setup.
- Ensure that we simulate reality
  For some aspects automated solutions can help ensuring that we simulate closer to reality than what we would have done if all the setup had to be done manually. Imagine a task of generating and setting up a multi-bending simulation before a hydroforming simulation manually – here you tend to simplify. With an automated solution, this can be done automatically – with a higher level of realism.

As shown above there are many reasons to introduce automatic solutions. Some people might now think “no – I don’t want this – I want to control the process”. This is an important point! Therefore, automatic solutions should be of a character that they can be controlled by parameters and that they should be modular – so the user can choose what automatic solutions he wants to use.

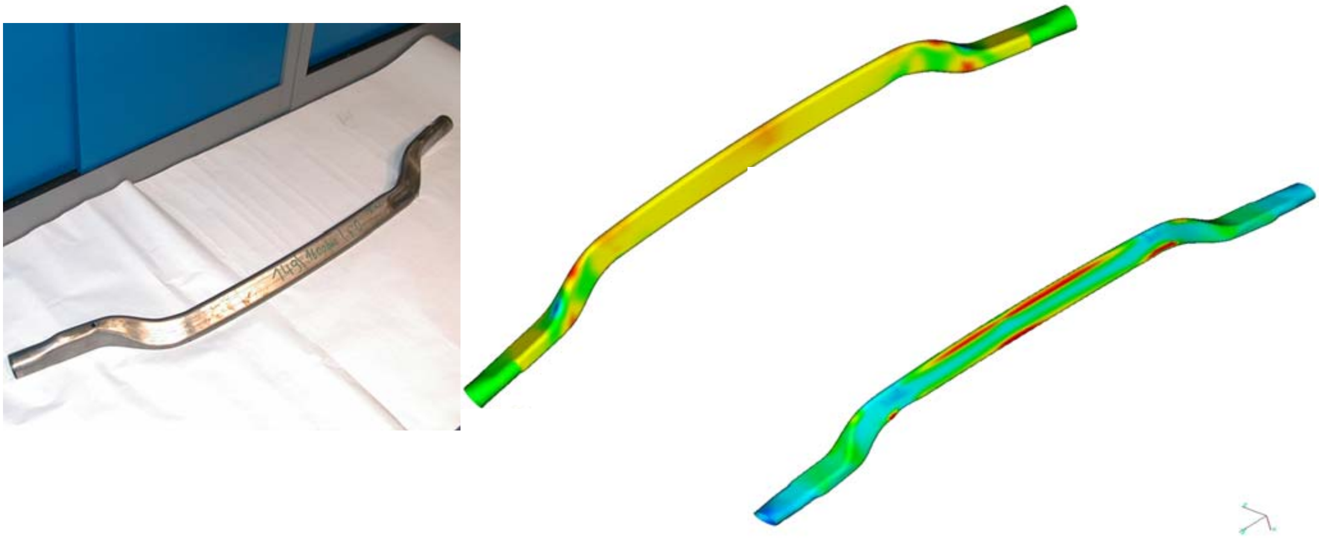
In the following 2 chapters, we will show which automatic solutions are currently available, and which we think can be become available in the future.

3 Current solutions

All samples shown here are based on available functionality in Pam-Tube 2G V2006, released March this year. Other software will offer same or similar functionality.

Automatic formability analysis

For feasibility checks, there has always been a search for finding fast approximate calculation methods, such as one-step-solver. But experience has shown that these fast calculation methods are far too unreliable to make sense to use. The danger here is that they will not show failure where it occurs:



Part from Schuler hydroforming [Skr]
Middle: one-step-calculation – no failure
Right: incremental calculation – red areas indicate failure

For hydroforming processes therefore at the moment there seem to be no fast feasibility calculation method. The best solution seems to be the expansion analysis, where the circumferential expansion is analyzed. In order to perform such an analysis, the tube ends and the centre of gravity have to be identified, and then cuts need to be done in order to be able to analyze the expansion. Pam-Tube 2G does all these steps automatically:

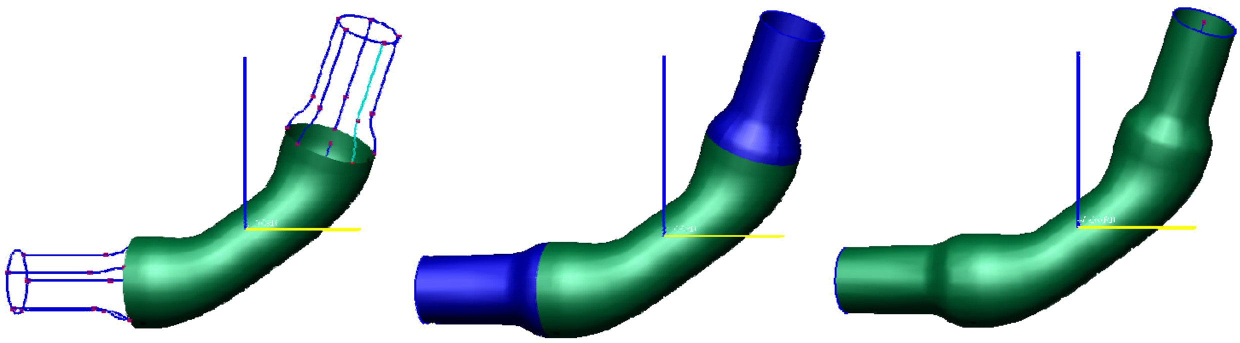
Part: hde Solutions GmbH
Left: centroid (centre of gravity) and cuts generated
Right: expansion analysis for the use of 55 or 60 mm base tube and curvature analysis

This expansion analysis coupled with the curvature analysis (indicates which areas will get strain from the bending operation) gives a valuable help in the job to determine the feasibility of the part. Of course it is not an exact simulation but the advantages are:

- It's fast – normally this is available within couple of minutes
- It does not try to make you believe you have done a calculation which does not predict cracks

Automatic addendum

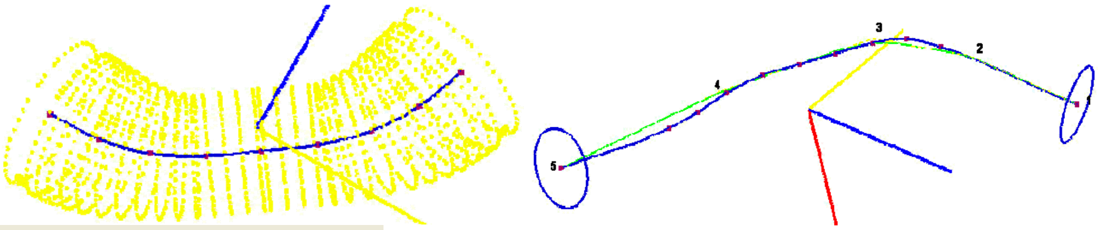
Generating the addendum is a essential part of the design process. It very much describes the possibilities of feeding for the given part. Pam-Tube 2G has a automatic solution which is called one-click addendum. Click once on the part outline where you want to generate an addendum, and the addendum profiles are generated automatically. Then the surface generation and the combining of the surfaces (CAD-based) with the part geometry is done automatically.

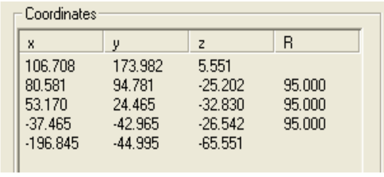


3-step addendum generation (left to right):
1. define the addendum profiles
2. Generate the surfaces
3. Combine part and addendum

Automatic bending curve

Finding the bending curve is one of the difficult tasks when designing the hydroforming process. Allowing an automatic detection of the bending curve can save a lot of time. Even if the user has specific whishes on how to arrange the bending curve, it's normally faster to modify an automatic generated one than to start defining a 3D-parametric bending curve from scratch.





Coordinates

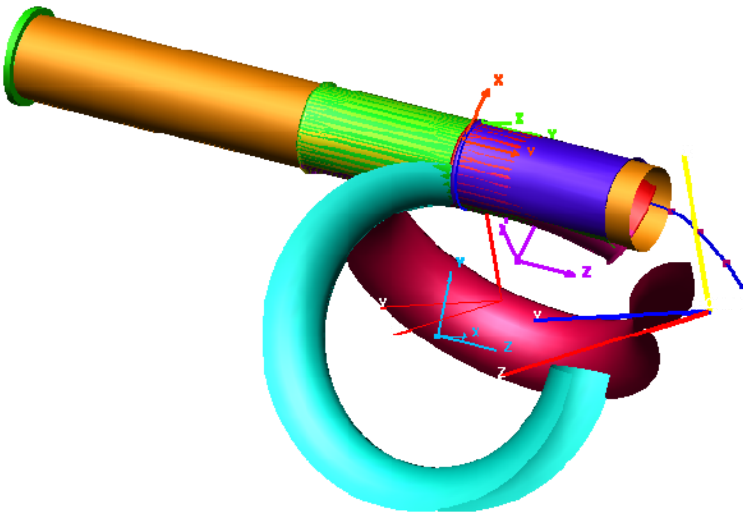
x	y	z	R
106.708	173.982	5.551	
80.581	94.781	-25.202	95.000
53.170	24.465	-32.830	95.000
-37.465	-42.965	-26.542	95.000
-196.845	-44.995	-65.551	

Bending curve generated automatically.

Automatic bending tools

Setting up a multi bend calculations – maybe containing compound bends is such a big task in itself that many skip this part of the calculation. But this is a dangerous habit, as the thinning and strains introduced in the bending process very much influence the formability in the hydroforming step.

Pam-Tube 2G includes an option to automatically generate all the needed tools based on the bending curve and the tube parameters. This even includes advanced compound clamp dies which are designed slightly flattened to better grip the bent tube and to better reflect reality.

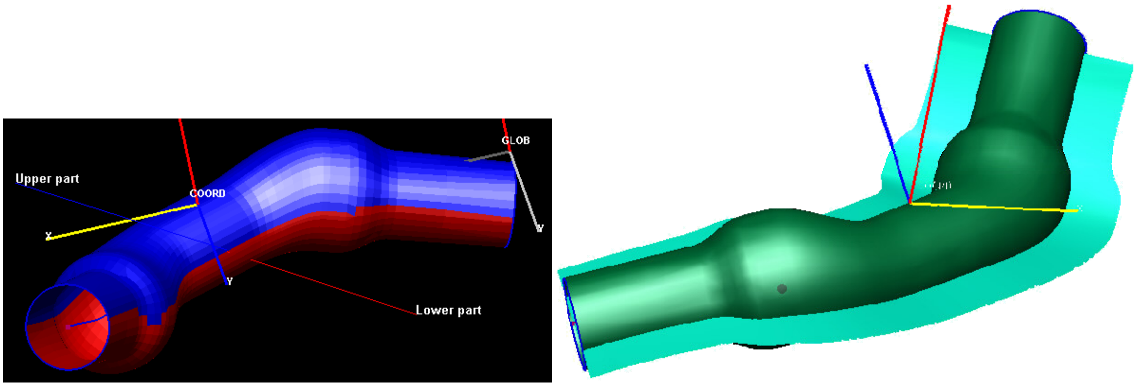


All needed tools for 2 bends including advanced compound clamp die.

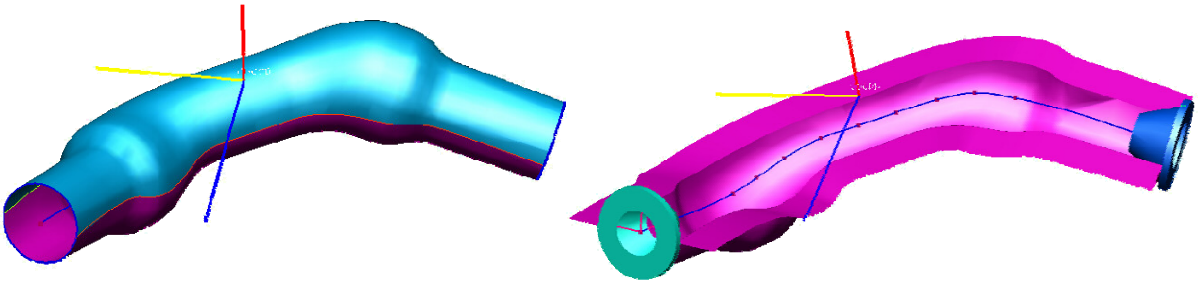
Automatic hydroforming tools

Defining the optimal hydroforming tools is for the upper and lower tool down to finding the optimal separating plane – and splitting the part including addendum surfaces with this given tipping direction.

Pam-Tube 2G includes an automatic tipping function and separating plane generator with the objective to minimize back-cut and minimize problems during tool closure.



Left: optimized tipping with indicated upper / lower tools.
Right: separating plane



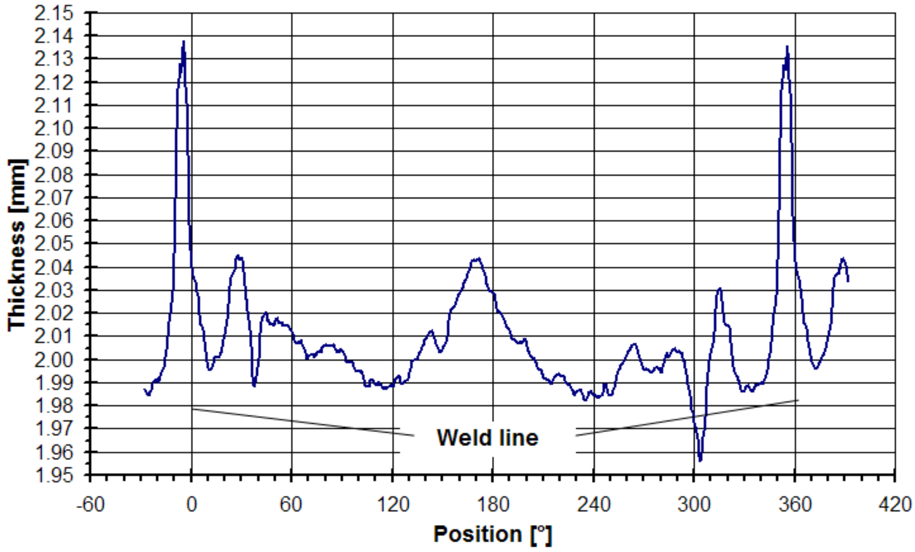
Left: part & addendum surfaces split into upper and lower tools.
Right: lower tool with left & right piston.

4 Where to go?

All samples shown here are ideas and/or prototype developments for Pam-Tube 2G V2007.

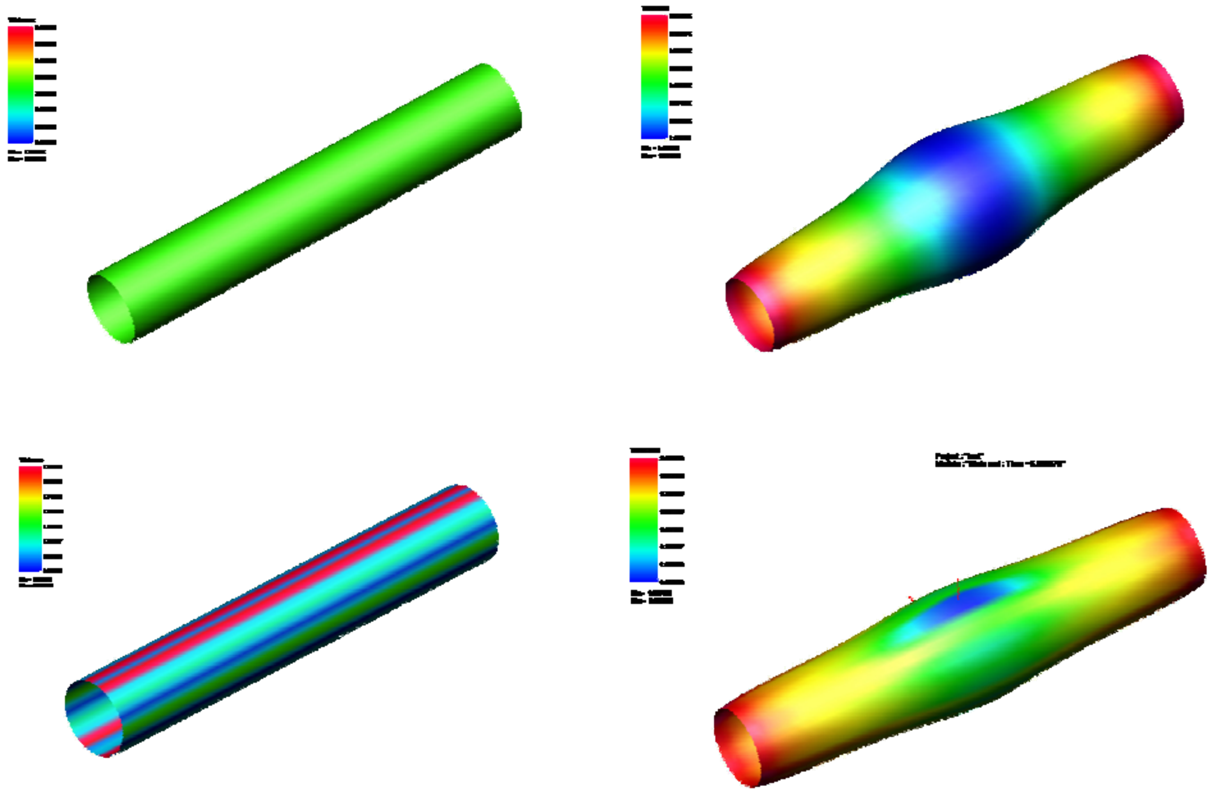
Influence of roll-forming

In current simulation of the bending & hydroforming process a “virgin” tube is assumed. In reality this is of course not the case. Considering the striven to reach more accurate simulations, this is an important fact to keep in mind. The formability and behaviour of a virgin tube is quite different to a tube that has been roll-formed.



Sample of measured thickness distribution of a roll-formed tube.
Source: Technische Universität Darmstadt

The thickness distribution around the circumference is not any more homogenous – and the rollforming process introduces strains. This can easily be illustrated by looking at a burst test of a tube:



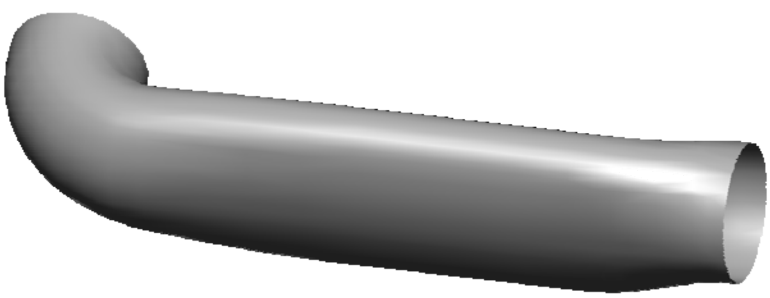
Simple burst test – thickness distribution.
Top: without influence of the rollforming.
Bottom: with influence of the rollforming.

As seen on the images above, the influence is clear: both the shape of the failure mode and the pressure at failure is quite different. We think this can be important factor to incorporate in future simulation programs.

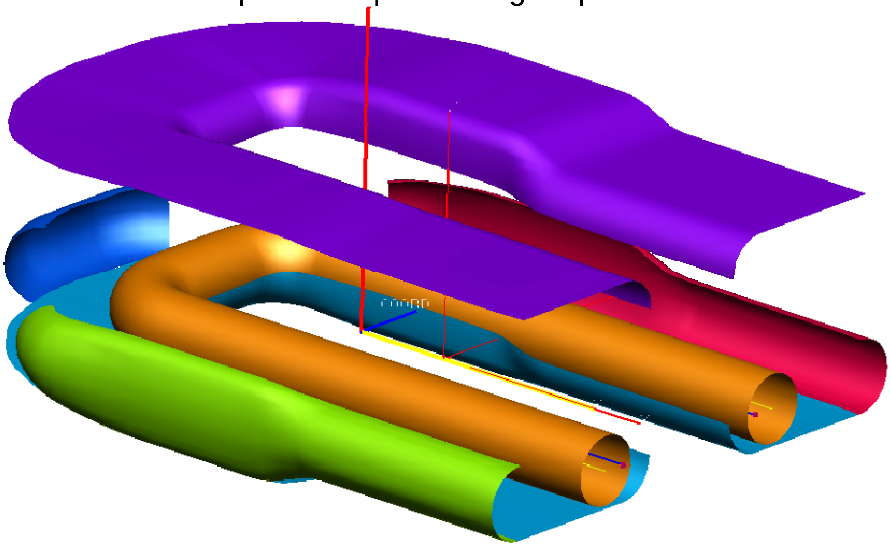
Influence of preforming

Many parts that are hydroformed do not fit into the dies, or it is not possible to close the dies without pinching the tube. A preforming operation is needed. This is a operation which sometimes cause some problems – it's a crucial one in order to succeed with the production process and it is difficult to generate some good tools. Often this is down to experience of the process designer – they will find a method to perform the tube, so that it fits into tools. This can vary from just giving the tube a couple of good hits with a hammer to very high-tech methodologies. By sure it is a possible risk factor, and can delay prototyping period massively.

Looking into this sample from hde Solutions GmbH:



This part is produced as a double part, and is not possible to manufacture without preforming. A flattening operation is needed. After idea from hde Solutions, a possible – automatic generated tool concept for the preforming step could look as follows:



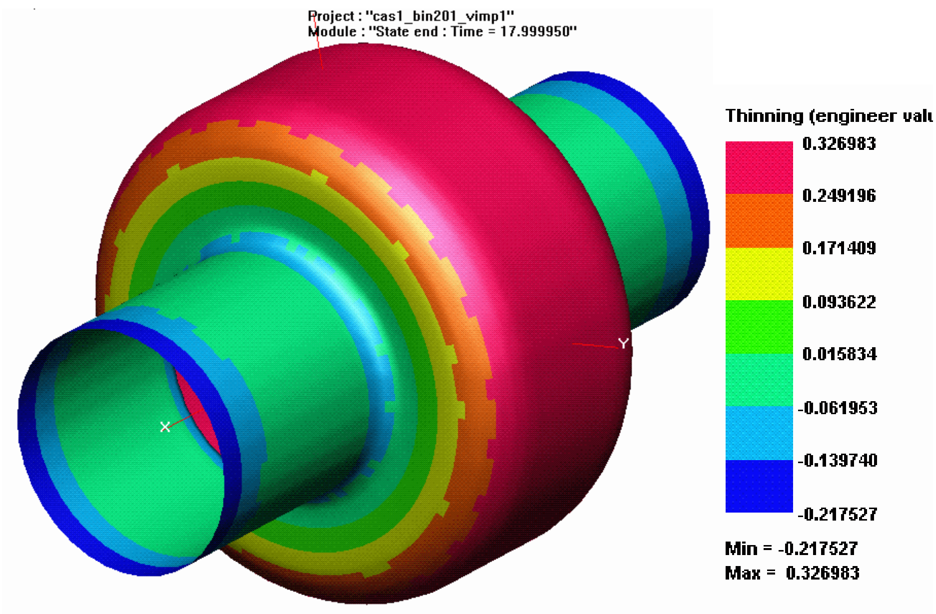
The fact to have an automatic option to generate the preforming tools we believe will decrease the risk found today in the good design and setup of preforming steps significantly. Also an automatic solution here will help the user to quickly do a simulation to check if the concept is feasible.

“Automatic” solver

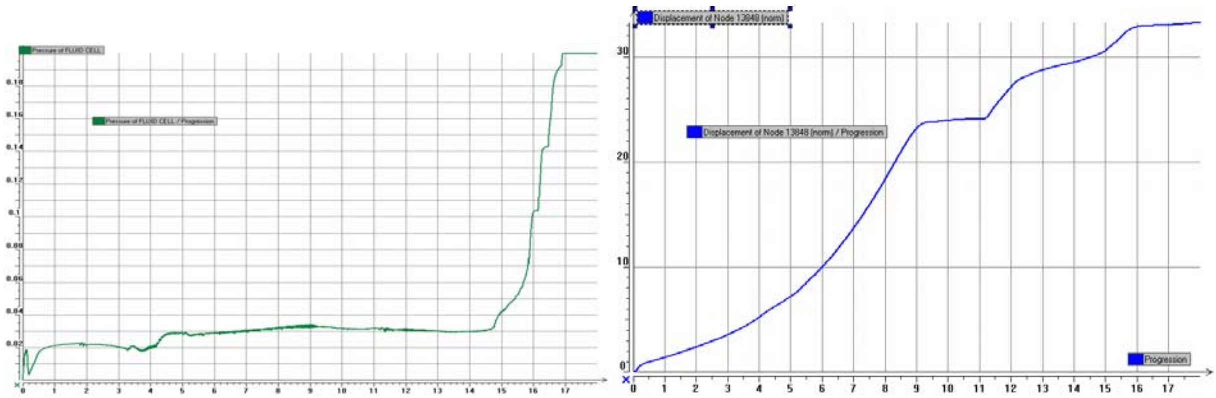
Determining the pressure-feed-curve for complex parts that are on the limit of the formability has always been a time-costly process. Normally several simulation-loops are needed in order to find a pressure-feed-curve that makes the part feasible. You could solve this problem by using stochastic optimization – which will be mentioned in the next paragraph. But often there is no time for running dozens of simulations – the more elegant solution would be to have an “automatic” solver, which can monitor the process while calculating. A lot of work has been done on this field which has resulted in several papers – e.g. “Determination of Proper Loading Paths in Tube Hydroforming and Stamping using FEA Simulation” by Altan et al from Ohio State University.

So the idea is not new, but has not really found industrial use. So there is still some improvement to be done obviously. But maybe also the objective is not correct? Looking at this as an automatic solution– it is probably not realistic to be able to hit the optimum in only one run? But still – if we could make this automatic solution superior to any human made first try – we have increased the quality of that first run. So changing the objective slightly to not be “find the optimum in one simulation” to “find a very good solution in one simulation” it should be possible to develop such an “automatic solver”.

Continuing to work in this direction, we are testing different possibilities using fluid cell calculation technology. The solver will automatically vary the volume feed rate and the displacement of the punches in order to minimize thinning and avoid wrinkles. A sample below shows the use of such a methodology:



Sample part, thinning.



Left diagram: pressure vs. time, Right diagram: displacement of the punch.

Obviously there is still some testing to be done, but basic testing shows good results, and we surely believe this will be a great added value for future hydroforming process setup. Also once this is solved, looking into the bending process might be interesting, as the demands for tighter bends combined with high-strength materials continue to grow.

Non-linear optimization

The above described methodology of an "automatic solver" will have limited area where it can work –only the feed-pressure curve can be optimized. Using a more global approach, will allow the user to optimize also other parameters of the process, this being for instance for the bending process the pressure or the feed of the pressure die etc. or addendum surface for the hydroforming process.

A more general approach means looking into the basics of optimization. In [Bec], Becker proposes to define the optimization problem for process optimization as follows:

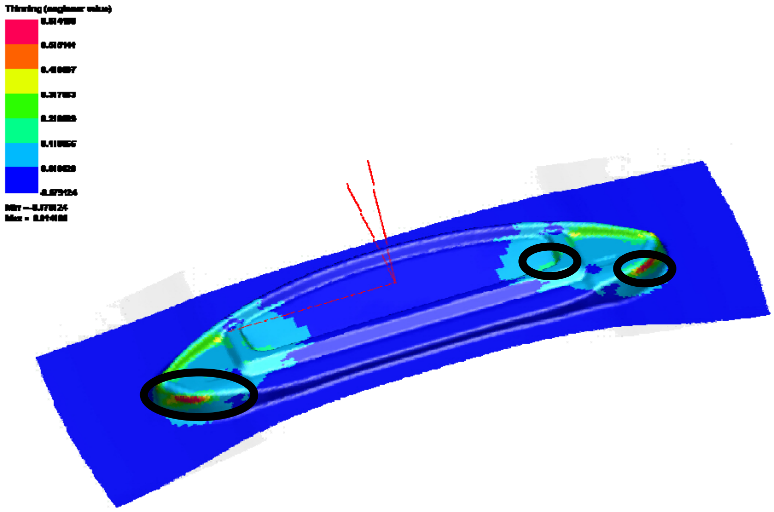
$$
\begin{array}{lll}
\text{min} & z\,(q_1, \ldots, q_n, e_1, \ldots, e_m) & \\
\text{with} & e_j = f_j(q_1, \ldots, q_n) & (j=1,m) \\
\text{under} & r_k(q_1, \ldots, q_n, e_1, \ldots, e_m) >= 0 & (k=1,l) \\
\text{whereas} & \quad z = \text{objective function} &
\end{array}
$$

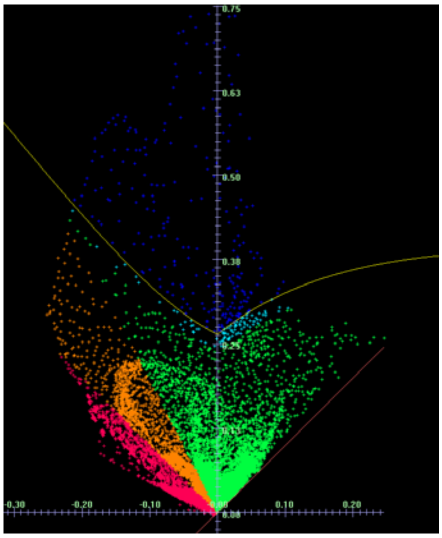
q_i = process parameter
r_k = restriction
e_j = output result
f_j = calculation model

Here „$e_j = f_j(q_1, \ldots, q_n)$“ represents part of the process model.

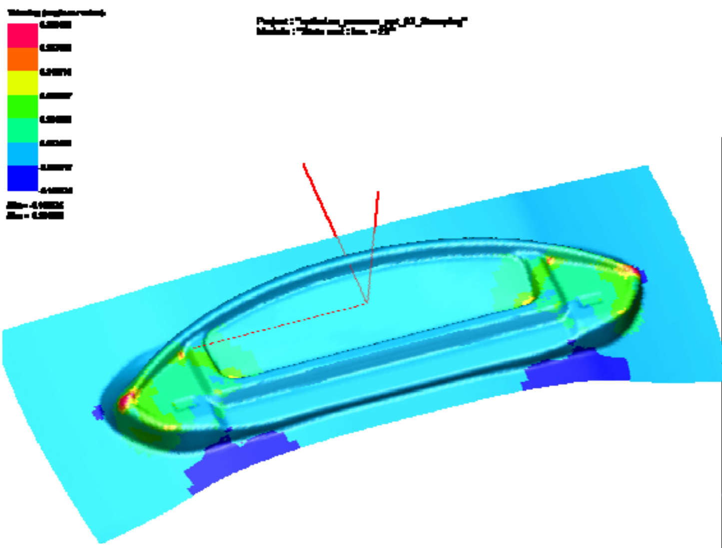
As you can see, the optimization problem is highly non-linear – which means that solving the problem is highly CPU-intensive. There are different methods to implement a solution for this problem with the objective to minimize the number of solver calls. At the same time the user wants to be sure that the solution converges, and that the found optimized solution really represents a good solution. The objective to find the global optimal solution cannot be a realistic objective here, as that would mean extremely costly calculation times – but normally it is sufficient to know that the found solution is good enough.

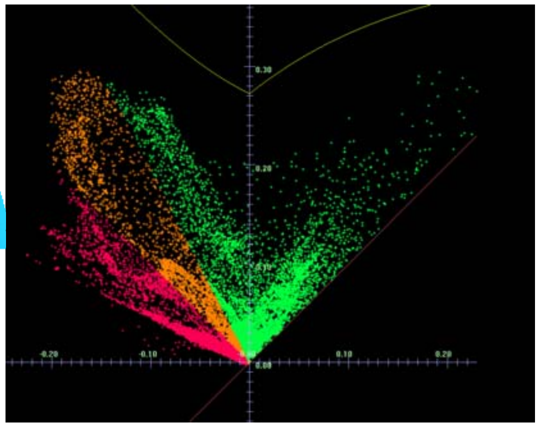
Pam-Opt is such a program, which acts like advanced, general non-linear optimizer. A sample for the capabilities is shown in a stamping example [IDDRG]:





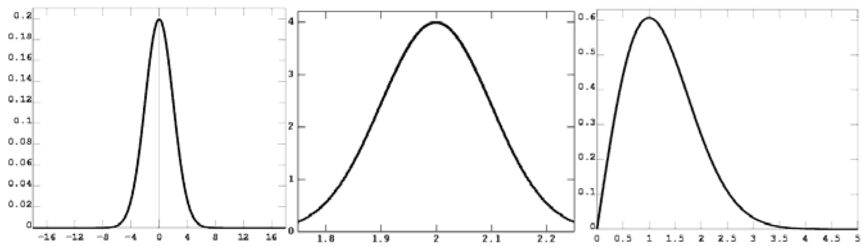
Objective is to avoid cracks (which you see in initial design) and to minimize wrinkling and unstretched areas. Parameters to vary were blankholder force, blank size, blank thickness and the friction value. After 13 iterations including 60 calculations, a result was found:





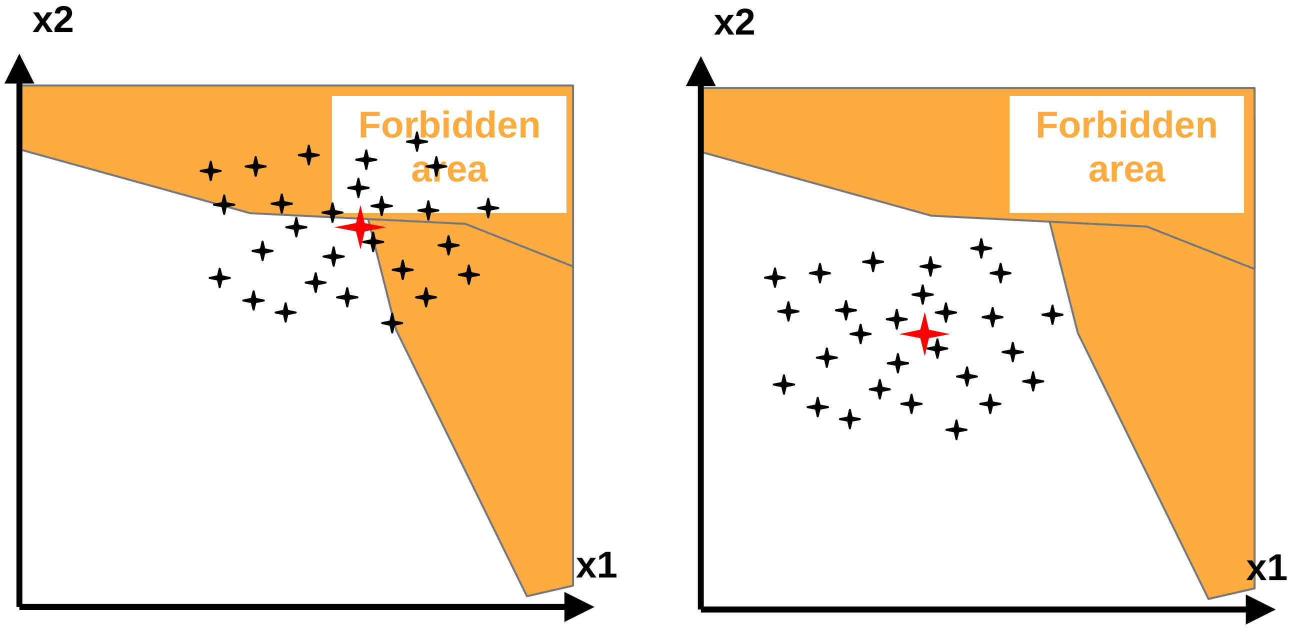
The cracks have been eliminated! Similar runs have also been done for bending and hydroforming applications, where keeping the same objective (no cracks and minimize wrinkling trend) parameters like feed-pressure curve or boosting for bending can be optimized.

Another strong field of Pam-Opt is the robustness analysis. Even if you have found a process setup, you don’t know how robust your solution is – because in real life, the material properties will change, the lubrication will change, the thickness will vary the feeding might vary etc. If you then go into production and end up with a high scrap rate, the original simulation is not worth a lot. The optimization tool can easily analyze these variations by generating several inputs based on given distribution laws.



Different distribution laws (for material, load, friction etc.)

The results can be images like this:

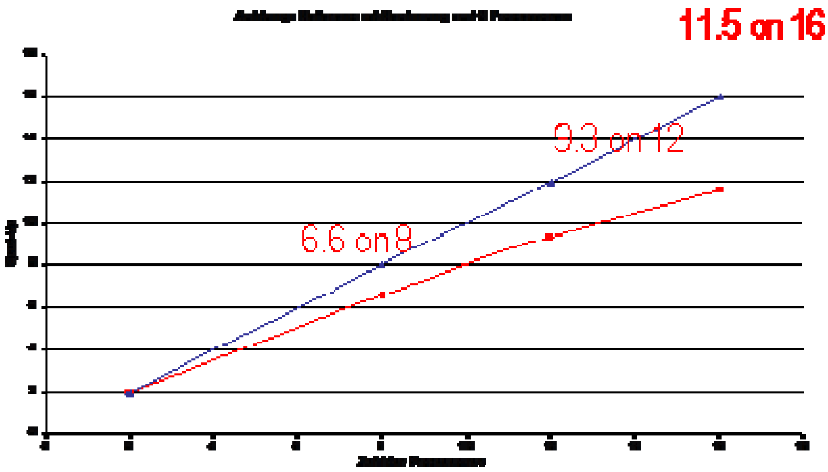


If the initial design (red cross) shows ok simulation results, but varying parameters will mean that half the runs will fail, that is not a robust design – whilst if also simulation runs with variations in the parameters will be ok, a robust production can be expected. [IDDRG]

We believe this is an area where for complex processes still a lot can be gained. High scrap rates are costly and also may delay production if blown parts destroy tooling parts. Also for high volume parts production, being able to deliver the high volume can be crucial.

Use of multi-core processors for DMP-calculations

Going towards more accurate simulations and more use of optimization / robustness analysis -> the need for more computational power increases. The increase of the computational power of a single processor has slowed down the last years – as modern processor design runs into limitations. At the same time both AMD and Intel are launching multi-core processors – which again opens up a new perspective – parallel computing gets available and affordable for everyone. Parallel computing means that the computational power can continue to increase even if the single processor itself does not become faster. In order to make use of this, Pam-Tube 2G offers so called DMP capability – distributed memory parallel processing. This means that the calculation job will be distributed between a given number of processors – the number being what is available. The DMP computing methodology offers superb scalability:



Scalability of DMP using several processors. Note: the reference here is 2 processors. For 8 processors this will results in a scalability compared to a single processor of app. 6.

Linux clusters become more and more popular – which is understandable as this offers “supercomputer performance” for a small budget. The multi-core processors seem to be the perfect fit for DMP calculations of simulation processes. This will certainly speed up the calculations times without having to sacrifice accuracy as you would do when simplifying the model.

We believe this will open up the possibility for more than those affording “super-computers” to look into the world of optimization and validation. Once the process design is decided it will be possible to run a stochastic validation to see if the process can be expected to be stable within couple of hours.

5 Conclusion

As has been shown in this paper, there are different methodologies which can help the engineer in the process of designing bending and/or hydroforming processes. There is still no automatic solution available to do all the work – for that the hydroforming process is too complex. But combining the know-how and the skills of the engineer with intelligent automatic algorithms to solve isolated tasks, a better way of work is possible.

Pam-Tube 2G offers an advanced CAE system with automated solutions for isolated jobs including one of the most advanced simulation tools on the market today. Offering these type of advanced tools is only possible when the tools are tailor made for the specific process – including know-how on the process in the basics of the CAE tool. In the future, we believe these tools will continue to develop, allowing the engineer to save time and cost and ensuring the quality of the process setup.

Using advanced CAE systems in the early stages of the process design for such complex processes as hydroforming is essential in order to reach:

Do it right the First Time, On Time, at a Predicted Cost!

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