STATE-OF-THE-ART IN THE USE OF (LS-DYNA) FORMING SIMULATION IN HYDROFORMING AND PRECEDING PROCESSES

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Rapid and reliable methods for component development and economic manufacturing layout are today crucial factors for the application of hydroforming techniques in mass production of lightweight components for the automotive industry. Optimum design of components taking into consideration special process-specific factors enhances safety and also the cost-effectiveness. The feasibility study, the component configuration and definition of a production sequence are closely interlinked. Once the approximate product geometry or component design, respectively, is known, a FEA (Finite Element Analysis) simulation has to be performed to study the forming process and appropriate die design. The FEA has become an established feature of hydroforming technology. The objective of FEA study is to replace costly and elaborate experimental testing by fast, low-cost computer simulation.

Benefits of FEA Simulation

Introduction

Modern systems for the development and manufacturing of new products are strongly connected to market demands. To achieve fast and effective response to market needs, the concept and design phase must take place in a virtual CA-x environment. The development time of new products can be reduced by these integration of computer aided technologies into design, process planning (layout) and product optimisation of hydroforming components. Concurrent Engineering has to be performed to ensure optimal ratio between development times and development costs.

In a market oriented system of product development, modern CA-x technologies are combined with technologies of rapid prototyping, rapid tooling and production planning. Market demands, such as batch size, product geometry and functionally or fashion trends have to be considered when development cycles and production layout are planned (Figure 1).

Mainly in the development phase, but also in production layout planning of hydroforming components the CA-x technology play an important key role. CAD/CAM and FEA techniques enable the shape design, final product design and determination of manufacturing technology in a virtual environment.

The use of FEA forming simulation provides several key benefits:

- it can provide a more detailed insight into the real behaviour of a structure, by representing accurately the material behaviour, contact and friction, and geometric nonlinearity.
- it allows the number of physical prototyping tests to be reduced. Detailed FE forming analysis can be used in place of prototyping tryouts, provided that the engineer has confidence that the analysis can produce reliable results.
- it provide an accurate estimate of the limit load for limit state design of part and process designs(Figure 2).

In the following sections of this paper the use of FEA, especially LS-DYNA, in several key areas of hydroforming technology and preceding processes is considered.

FEA Process Sequence

Figure 3 shows in principle the methodology for the development of a hydroforming component by means of FEA forming simulation. In a second step, after the project initiation and technical layout discussion, the FEA calculation supports permanently the die design process and manufacturing of the complex tools or dies. Within the product development of complex hydroforming parts the simulation of the forming steps utilising FEA has gained increasing importance. FEA technique in manufacturing layout of hydroforming processes is used:

- to check the production feasibility of the component
- to analyse and optimise the final component quality and expected process reliability
- to determine an indication of the required process forces for the die and machine design

First, by help of the configuration layout tool an analysis of the component takes place, where the component cross sections with their circumferences and radii as well as the course of the component centreline are checked regarding their hydroformability. On the basis of the results from the component analysis the definition of the starting tube dimensions and the interpretation of the additional manufacturing steps take place. In order to determine failure and quality aspects in the later on explicit forming simulation, a single step solver simulation should be done first, to check the general feasibility of the component. For very complex components and manufacturing processes a validation through an explicit simulation program, such as LS-DYNA, is necessary by an detailed look to each of the individual forming steps, followed by an implicit calculation, where the springback behaviour, the residual stresses and if necessary, piercing or punching operation are calculated. The whole process methodology for FEA calculation can be seen in Figure 4. The effect of this methodology is, that a reduction of the number of the tools and respectively the costs of tools can be achieved by the application of the FEA feasibility study. For example, it is possible to reduce the necessity time for the prototyping from 6 to 1 or 2 weeks. That means, that no die modification is necessary by using FEA study’s in prior. This fact leads to an obvious shortening of the development time as well as to savings of development costs.

Die and Process Development

The economic and efficient design of dies for hydroforming and preceding processes is increasingly being supported by the application of LS-DYNA. This is especially the case for the preforming and hydroforming operations, where LS-DYNA has proven to be quite valuable for the prediction of important process parameters, including axial forces and stress or strain distribution.

The more accurate predictions of structural response obtained from FEA can mean that each design iteration is more effective. Once the important features of a component have been established, fewer prototypes may need to be constructed. Prototype manufacture and real testing (prototyping) is expensive and time-consuming. Although prototypes are still required, the reduction in the number of variants tested may help to reduce the cost and duration of the design phase.

Fundamentals of Preforming Processes

In designing the hydroforming process for the production of automotive structural components, a number of factors must be taken into account to ensure technically and economically production methods. The layout of the preforming process and preforming die respectively, determine both the process flow and the final component quality as well as the required machines. In the following a few general methods of preforming and their necessity are discussed. The development and the validation of these preforming variants is done by means of FEA simulation techniques.

Preforming

Introduction

Preforming is necessary to load the prebent part into the hydroform die , all square sections of the bent tubes have to be tighter than the opening of the hydroform die. Considering the positioning tolerance of handling systems like robots or CNC-feeder systems and the bending process usually means that the gap between outer tube surface and hydroform die should be between 0.5 and 1.5 mm. Only at the tube ends the outer shape of the tube is similar to the die cavity. Very often the necessary tube circumference and thereby the tube diameter itself has to be adjusted to the square section with the maximum expansion in hydroform process. Three different cases can be distinguished:

Faultless loading of the bent tube into the hydroform die means that sufficient circumferential gap around tube for save loading is available. Normally in this case after bending (rotary draw bending or press bending) the tube can be hydroformed without intermediate processes. This is most economic way to produce engine cradles with hydroforming technology. If, for instance, only a flattened tube is necessary as a starting part (bending not considered) for hydroforming it is possible to use elliptical tube material made by extrusion forming. During closure of the hydroform die, a slight bending in second plane of the prebent tube is possible (see Figure 5).

a) If after bending, loading of the prebent tube is not possible, because the tube width in the split plane of the hydroform die is wider than opening of the die cavity. The tube is not bent in this specific forming area (Figure 6), a preforming operation is necessary to flatten the tube in the described area. Sometimes the flattening operation can be integrated in the hydroform die with so-called pusher units (Figure 7) which are activated by special hydraulic, gas or wedge slide units. In general this methodology is very problematical for most die shapes and for aluminium material because of extremely complex die setup and inevitable gap's between this sliding units, in which aluminium material moves by internal pressurising within hydroform process.

b) After bending a loading of the prebent tube is not possible for above mentioned reason but the contour of the hydroform die is tighter than the tube in a prebent section or in a few other areas. In this case a flattening procedure is sometimes not possible; this leads to a preforming process in a die with tapered sides (Figure 8), in which the tube can either be flattened or drawn within such an operation. The operation allows a pre-distribution of the material in many different ways to guarantee the optimum wall thickness distribution in the hydroform process to achieve a high variety of different square section geometry's as shown in Figure 9. As an advantage in comparison to case B is that there are more possibilities to change the contour of the prebent tube but as a disadvantage a press operation including handling and lubricating is necessary. In comparison to case B the die contact friction is relatively high [5.8] which leads to press forces in a range of about 500 to 3000 kN depending mainly on the die design, tube material and dimension.

Figure 10 shows the different possibilities for preforming die layout to produce starting parts from straight tubes for hydroforming:

- Flattening
- Conical radial preforming
- Conic radial preforming with synchronously bending operation of the tube centre line

In practise, a combination of these operations is often required. Figure 10 also shows a fictitious example for a workpiece produced by means of a combination of all the mentioned forming possibilities. With regard to the conic radial preforming, attention must paid, as already mentioned above, to the press forces and tool loads that may occur. For sidemember parts for truck rails with workpiece length from 1500 to 4000 mm and reductions from d0 = 140 mm to d = 125 mm using a wall thickness between 3 and 4 mm very often forces are expected up to 5000kN. Further, contact stresses up to 1200 N/mm2 occurred due to material movement along the tool surface. A reduction of the friction force between tube and die surface using optimised coating (TiC, TiN) and lubrication systems has to be carefully carried out. This also applies to conic radial preforming with superimposed bending (Figure 10 – variant 3).

Design Guidelines for Preforming Processes and Parts

How can a hydroform process oriented geometry be obtained starting from a given part design that can be manufactured from a (round) tube and economically produced? The known requirements are:

- The starting part must be perfectly placed in the hydroforming tool.
- After tool closing, a defined position of the workpiece ends must be ensured (so that no "sliding" occurs thus avoiding an inaccurate starting position for the hydroforming process)

The two following examples illustrate further design guide lines:

- The centre of gravity of the starting part cross section should be situated at the centre of gravity of the hydroformed workpiece cross-section.

This leads to a homogeneous wall thickness reduction during the hydroforming process with regard to the part circumference and also minimises the risk of a local tube failure (bursting). If the said requirement does not apply the risk of bursting in areas with excess material persists. In Figure 11 cross- sections of an engine cradle preformed in a preforming die are shown. Figure 11 further shows the result of the real hydroforming operation for the different preforming variants 1 and 5.2. The preforming process was been optimised by using FEA simulation technique, after failure mode wrinkling was detected in the real prototyping. The starting geometry for hydroforming is shown in Figure 12 whereas a) shows the result for preforming die “variant 1” and b) illustrates the optimised variant 5.2. Figure 13 shows the wrinkle formation in FEA (plastic strain distribution) in these problematical area after hydroforming operation. Figure 14 shows the problem-free forming out by optimised preforming die.

A further design guideline for a starting part in the hydroforming process is:

- All cross sectional radii of the starting part must be greater than or the same as the radii of the hydroforming workpiece.

If this is not been realised in component design, the inner parts of these radii are subjected to tensile stress during hydroforming and are enlarged again. This can lead to micro cracks at the inside surface which may be impossible to detect (Figure 15).

Figure 16 shows a combination of a bending and a preforming operation taking place in a hydroform die as a preforming operation with tool optimisation by using FEA technique. The basic suitability of different tooling variants with and without “tube holder” at the tube ends and different segmentation of these active die units are first checked. In a first step three different preforming die layout were investigated by using FEA. Die concept, no “tube holder” and no segmentation of the die cavity as well as the resulting part geometry is shown in Figure 16. It can be clearly shown, that these die layout leads to part radii after preforming which are smaller as the radii of the hydroforming workpiece. Further a excessive wrinkle formation can be expected. Figure 17 shows the concept of die layout 2 and the resulting preforming operation. Within this die concept, a segmentation of the upper die was done. The use of the “tube holder” guarantee a better preforming shape; also with a wrinkle formation but no “sharp” radii. In Figure 18 the most expensive die layout is presented. The upper and the die layout is segmented. As expected, the preforming part looks best with these die layout. Cost reasons, almost double the costs as for die concept 2 (+ 35.000 Euro) , have lead to an decision which bases on concept 2 with some ideas of concept 1 and 3.

The second step of the FEA feasibility study consists of optimising more precisely the tool cavity of the concept 2. Figure 19 shows a relatively simple die concept which was built according to the results from these investigation step. No die segmentation was done within these concept. Both tube ends have a straight vertical end area. These vertical end area is only built in the lower, not in the upper die, where a tangential tube end area is built. Figure 20 illustrates the comparison of FEA feasibility study and achieved part geometry in real prototyping. As can be seen, all failure areas have identical shape in real prototyping or virtual prototyping, respectively.

Summary

Preforming currently advanced to a stage where the various process variants can be used to produce a wide variety of starting parts for hydroforming. The decision as to which production steps are to be integrated in the preforming process depends on a wide variety of factors. Some of these were discussed in the above, such as the different cases of preforming and general die and part layout. Accurate predications of the local deformations observed in the preforming process were obtained by the FEA simulation in prior and also afterwards to the real tool set-up. From this point of the study it can generally be concluded that explicit FEA simulations of preforming operations are reliable, efficient. Today, such optimisations can be performed within relatively short periods of time and result in a high planning reliability.

Hydroforming

Production processes in the wide field of metal forming, especially hydroforming, are time consuming (Figure 22, 23) and expensive. Usually the necessary studies relating to the practicability of the hydroforming process and to the design of the dies and parts are done experimentally with high expenditure and loss of time. The main goal in hydroforming technology is the reduction of costs during the prototyping and the shortening of the development cycles including optimising tooling or die geometry, respectively.

The designing of the tooling for the production of automotive structural components must taken into account a number of factors to ensure technically and economically viable production (Figure 21). The design of the die and the general die layout determine quality and the accuracy of the final hydroformed component.

Introduction

Regarding the accuracy, one must bear in mind that the metal forming technology have different boundary conditions than machining. In machining the generation of a geometry is an incremental process with a small interaction zone between tool and workpiece. Effects of wear, thermal expansion, and so on can be detected and corrected during the process and accounted for in each workpiece. In metal forming, especially hydroforming, the shape of the workpiece is stored in the die geometry as a whole and therefore transformed to the workpiece as a whole. Due to that, the ranges of accuracy in hydroforming and in machining are quite different, e.g. IT 6 to IT 16 and IT 0 to IT 10, respectively. A high accuracy, i.e., a low IT-number, is obtained in machining processes, while in hydroforming the accuracy is lower. In hydroforming i.e., typical values concerning the shape of calibrated extruded profiles were deviations of ± 0.25 mm. The deviations increase with increasing complexity of the processes and parts.

Additional effects are:

- the die geometry due to wear,
- the errors in the machines which lead to an offset and tilting, and
- distortion of the parts due to residual stresses.

Especially the combination of the requested precision in combination with the complex geometry’s lead to an increase in high-quality hydroforming processes with optimised process and die technology to close the gap between the desired and achievable tolerance.

Die Design in Hydroforming Process

A common comment heard within the industry is: For hydroforming you just need a good machine and a simple tool which is mainly made by two die halves similar to the outer shape of the final component and some axial cylinders. Unfortunately this is wrong ! The mentioned “one die = two halves” – procedure might work for some prototyping samples but is far away from mass production application.

The major task of the die is the production of the designed components shape and profile. This is achieved by the machined shape of die cavity providing a "barrier" to the expansion of the raw material caused by the interior pressure and axial forces being applied to the workpiece.

Together with trouble free production, the die must also ensure the required component quality with particular regard to external dimensions. So, the die is still the key element of every hydroforming process and therefore an important aspect of the

- availability of the whole system
- production safety, and
- part quality.

Regarding the hydroforming die, the achievable shape is greatly influenced by the general die layout, the manufacturing accuracy of the form imparting surfaces and by the rigidity of the die components.

A number of other factors that also have an important influence in finished part quality are

- the manufacturing concept
- preceding forming operations
- tube material
- friction condition

Die Design in General

On the one hand hydroforming dies must be suitable to produce the required component properties, on the other hand a cost-effective design must be aimed for, with size a determining factor. When it comes to die design, an optimal balance must be found between these contradictory parameters.

With regard to die size, the horizontal forces arising from the interior pressure are of major significance. Whereas the forces exerted in clamping direction are compensated by the machine force, horizontal forces acting on the die result in stresses and corresponding die deformation. Rigidity of the die itself can be ensured by careful design. Solid guides (Figure 24) along the die ensure the absorption of potential lateral stresses. Both stresses and deformations should be kept to manageable levels through suitable die design, as the stresses can cause damage to the die over the operating period and deformations can lead to undesirable variances in component dimension [5.9].

Figure 25 shows a square section view of an example of a mass production hydroform die with insert technology. In general, to achieve the best possible hydroforming part quality, the whole die system should be as strong as possible. This includes a rigid guiding of the upper and lower tool halves:

- pillars are pre-guide the upper and lower die during closure
- during hydroforming the upper and lower die are guided by guiding plates (Figure 4.50)and the contour of the wear resistant inserts all along the length of the component. Separate guidance of the press system itself is not necessary or contrary to this.
- pressure and matching plates allows the optimisation of the stiffness behaviour of large hydroform die sunder loads within a range of more than 20.000 kN especially if the press ram is not loaded in centre or non-symmetrical.
- wear resistant inserts allows the replacement of areas with higher wear without excessive downtime or appreciable machining costs. The insert size depends on the coating method (TiC / TiN) used. For safety reasons the inserts and pressure plates should be available as spare parts which means that a complete spare tool is not required. Every inserts causes split planes within the die which usually causes no reduction of part quality if the inserts are designed and machined according to the state-of-the-art. However, extra split planes over and above this ideal can generate split line marks on the part surface, i.e. for the use of tubular aluminium material.

Designing Dies with Help of Finite Element Analysis

The complex nature of die geometry’s makes analysis of the stress and elastic strain conditions in the die virtually essential. Finite element analysis is a useful aid in the design of dies. At University of Aalen programs such as Pro/Mechanica, ANSYS are used. Figure 26 shows a problem zone within a die inserts with regard to maximum stresses. The sharp edges and small drainage wholes in the ground of the die cavity result in very high notch stresses which would probably cause die fracture in volume production. Special insert design must be used at these points to alleviate the stress condition.

Finite element analysis can be used to compute the optimum dimensions and geometry of basic die plates, inserts and sliding units as well as axial punches or punch caps (Figure 27). The integration of openings to accommodate hydraulic piercing units and active forming cylinders for sliding or pusher units is of particular importance in the FE analysis. In addition to the sharp contour edges of the inserts, zones of this kind are subject to high stress concentrations. In extreme cases it is necessary to dispense with the piercing of particularly critical points during the hydroforming process.

The Application of FEA for the Development of Hydroforming Parts

The task of the process simulation is to execute general feasibility studies for industrial applications of hydroforming technology by using the FEA in order to obtain a reduction of the production development phase (time to market) or a reduction of the development costs (brake even point).

Crucial starting points for the optimisation of time, costs and quality of the configuration of the procedure are situated during the first stage of the hydroform component development, where a modification of the process-influencing parameters is possible still without time-consuming and expensive steps, e.g. die modifications.

In general, hydroforming parts have complex shapes with variable cross-sections and centrelines. This requires, as mentioned above, that additional preforming operations must be considered together with the hydroforming process itself. The simulation of the forming steps utilising FEA has gained increasing importance for component and process design. It serves to examine the production feasibility, to analyse and optimise the final component quality and expected process reliability. In Addition, it supplies the initial information about the required process forces for the die and machine design.

A further substantial function of the FEA manufacturing simulation is to carry out early predicates concerning the adjusting product properties (wall thickness distribution, stress- ,strain distribution, cold hardening). In addition the inspection of the time course is of crucial importance during the forming. Also the calculation of the influence of any elastic strains referring to the springback behaviour of the components formed by use of interior high pressure is not to be ignored regarding the measurement and form tolerances.

Figure 28 shows in principle the methodology for the development of a hydroform component on the basis of the CAD data of the component design. In a first step of the component analysis, the component cross sections with their circumferences and radii as well as the course of the component centreline are analysed by hand. On the basis of the results from the component analysis the definition of the starting tube dimensions and the interpretation of the additional manufacturing steps take place.

In order to determine the manufacturing sequence in the following FE analysis for their feasibility, the knowledge of a set of boundary conditions is necessary.

To these boundary conditions belongs essentially the

- material parameters
- tube dimensions
- component geometry
- friction model (Coulomb)

For very complex components a repetition of the individual development steps can be necessary both during the theoretical process (procedure) configuration as well as at the prototyping. Such iteration loops are not drawn in this figure.

The effect of this, that a reduction of the number of the tools and respectively the costs of tools can be achieved by the application of the FEA feasibility study. Hence a reducing of the time for the prototyping (real tryout) from 6 to 1 or 2 weeks can be achieved. This is possible because there is in 95% of all cases no die modification necessary during the real prototyping. This fact leads to an obvious shortening of the development time as well as to savings of development costs. An increase of the quality accompanied by an increased manufacturing integrity for batch production can be derived additionally by the analysis of the FEA manufacturing simulation (Figure 29).

Figure 30 shows the results for the hydroforming process of the Bumper-part which was already regarded in the preforming section. Considering the preceding forming steps, reasonable agreement between analysis and real tryout is found. Accurate predications of the local deformations observed in the hydroforming process were obtained by the FEA simulation in prior to the real tool set-up.

Right, to sum up, as was shown, process simulations with FEA technique can be used successfully for improvements of the die design and die layout. A reduction of time and costs by an simultaneously increase of quality can be achieved.

Conclusion

Constant optimisation of the whole or overall production steps of a hydroforming component, e.g. preceding forming operations, hydroforming dies, presses and hydroforming production line technology today ensures the economic application of the hydroforming process. In addition, successful efficient methods are available for component and process development by using FEA techniques. Future research and development work is appropriate for further improvements in the FEA technology by using valid input parameters as well as the numerical aspects on the solution quality of FEA feasibility studies of hydroforming processes.

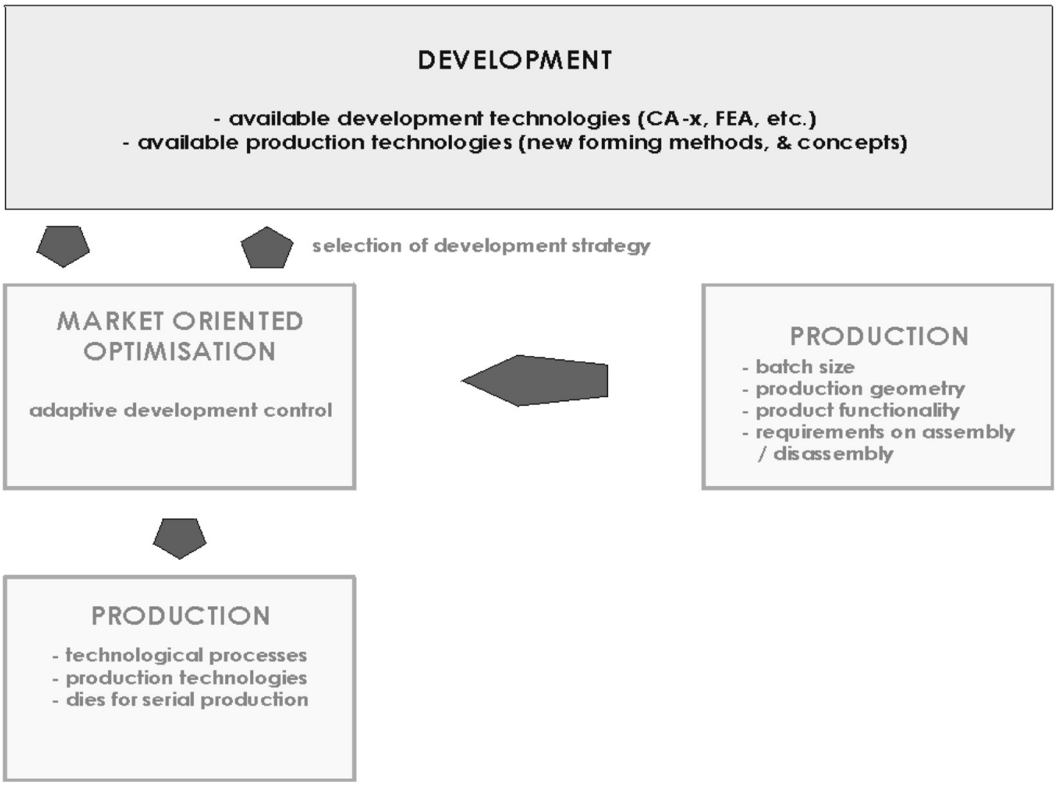


Figure 1: Market oriented Development Optimisation

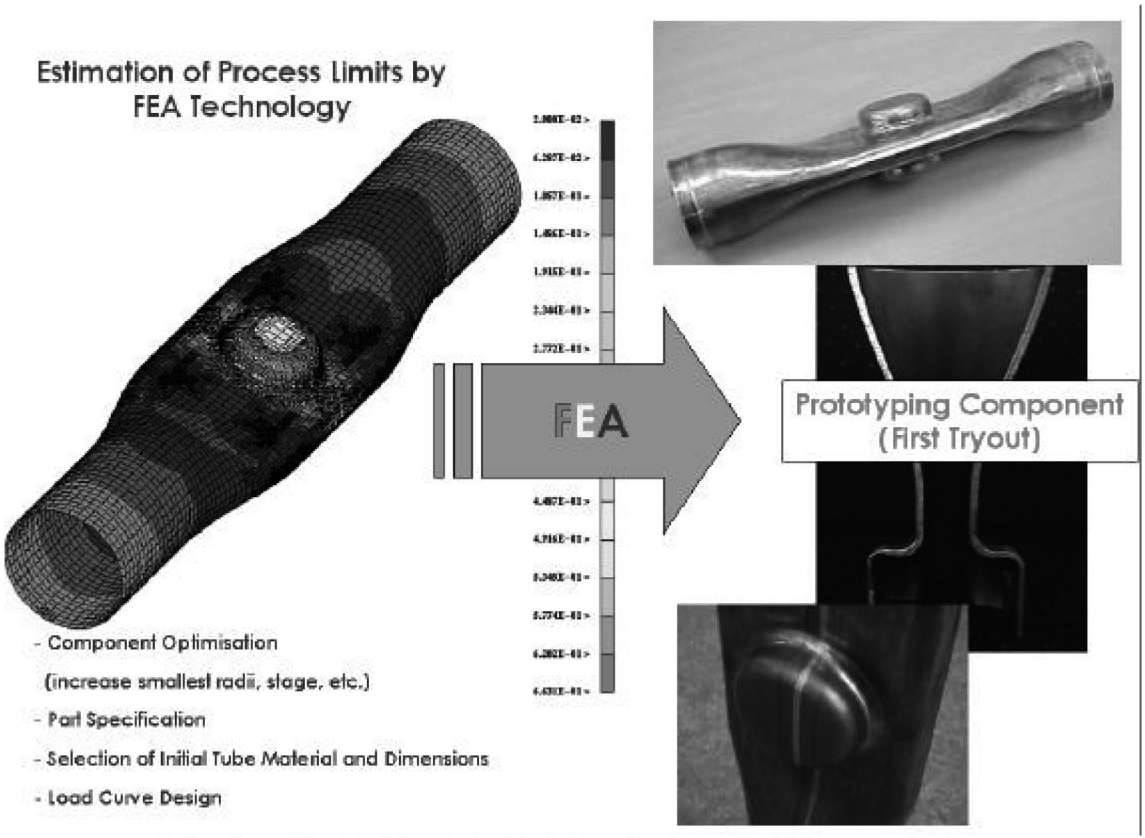


Figure 2: Estimation of the Limit Loads for Limit State Design of Part & Process Design by means of FEA

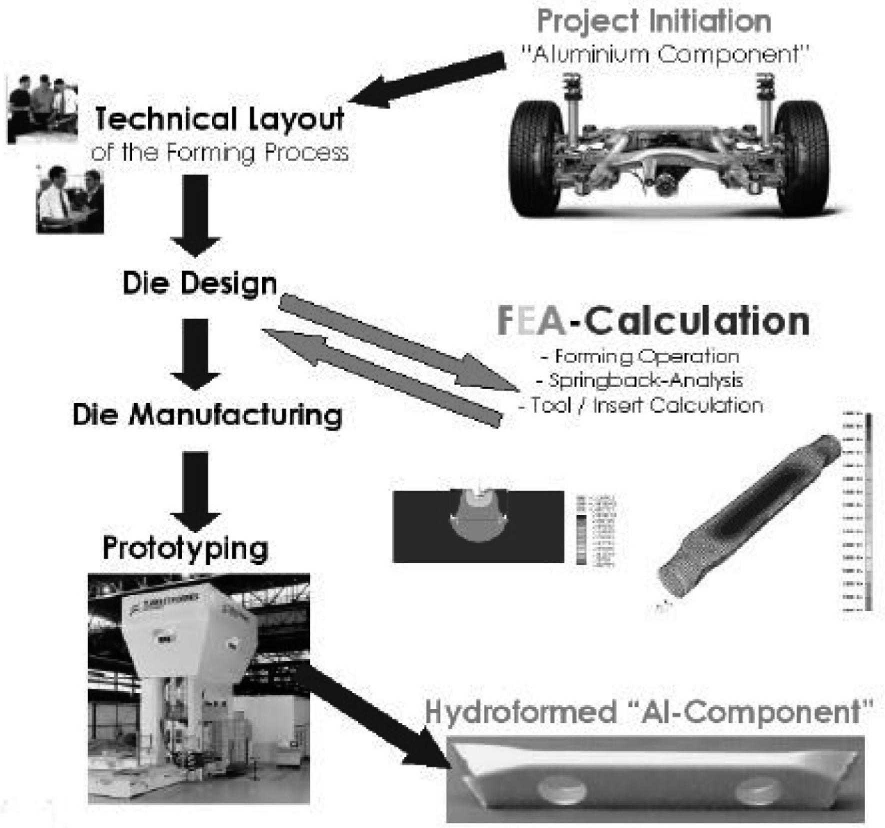


Figure 3: Methodology for the Development of a Hydroforming Component by FEA

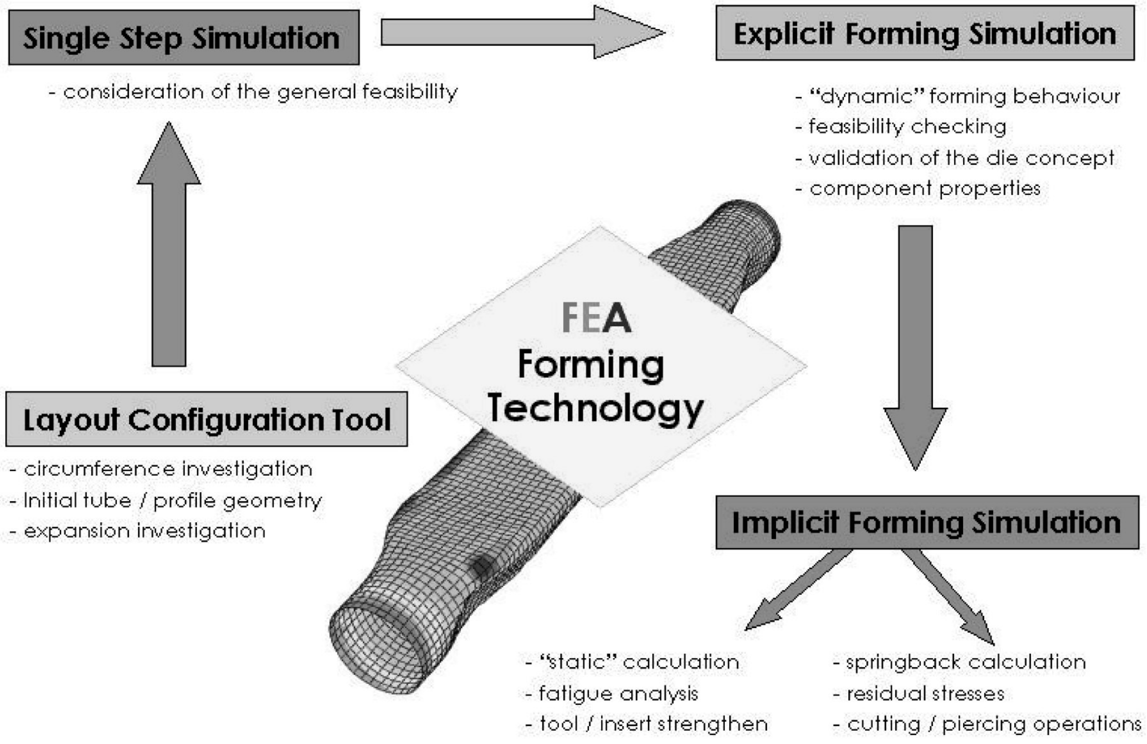


Figure 4: Process Chain FEA Simulation

Figure 5: Process Step "Hydroforming" without Preceding Forming Operation

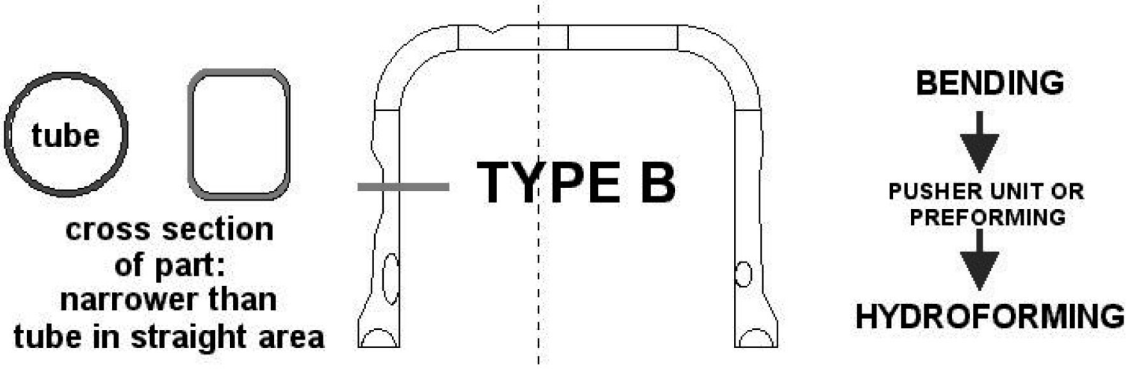


Figure 6: Engine Cradle, Variant 1

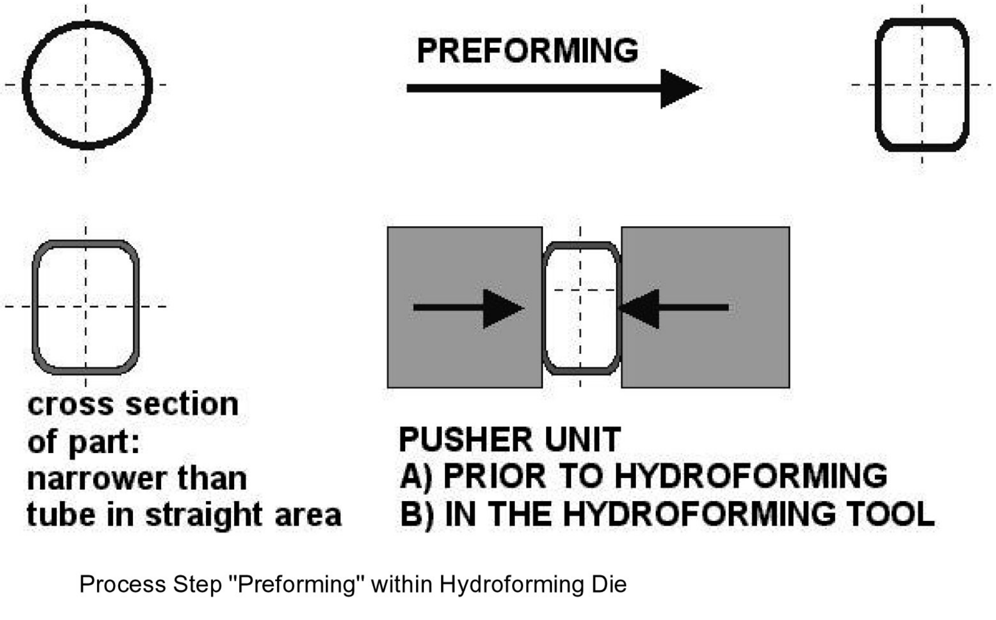


Figure 7: Process Step "Preforming" within Hydroforming Die

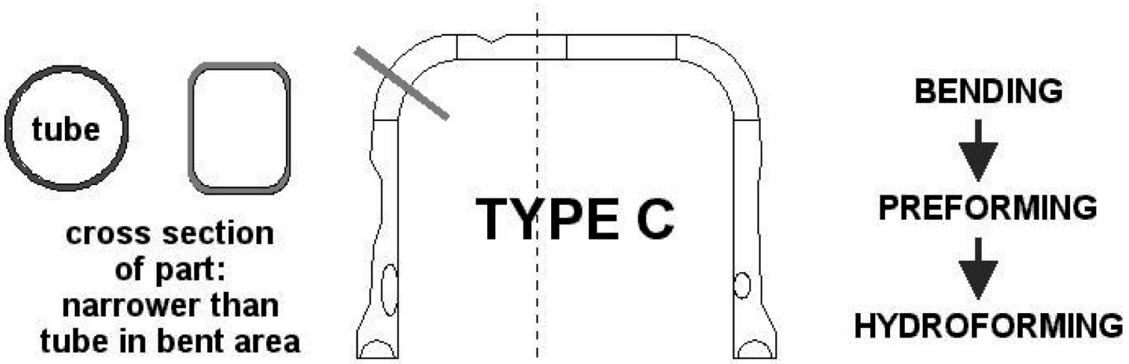


Figure 8: Engine Cradle, Variant 2

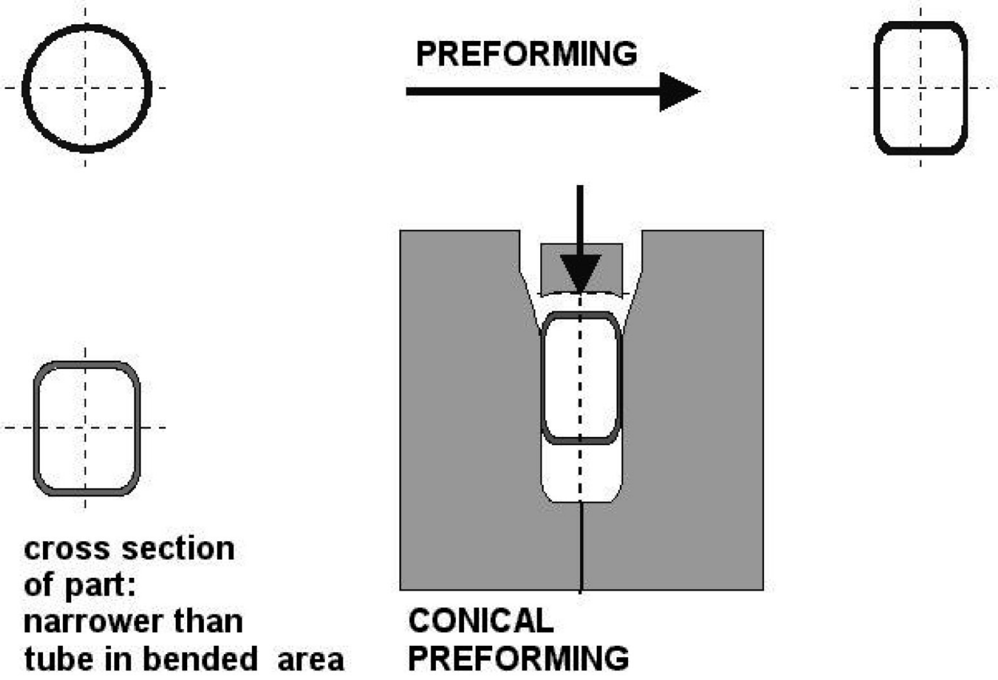


Figure 9: Process Step "Preforming" with separate Preforming Operation (Tapered Die)

Figure 10: Preforming in Die: Selected Process Variants – Fictitious Component

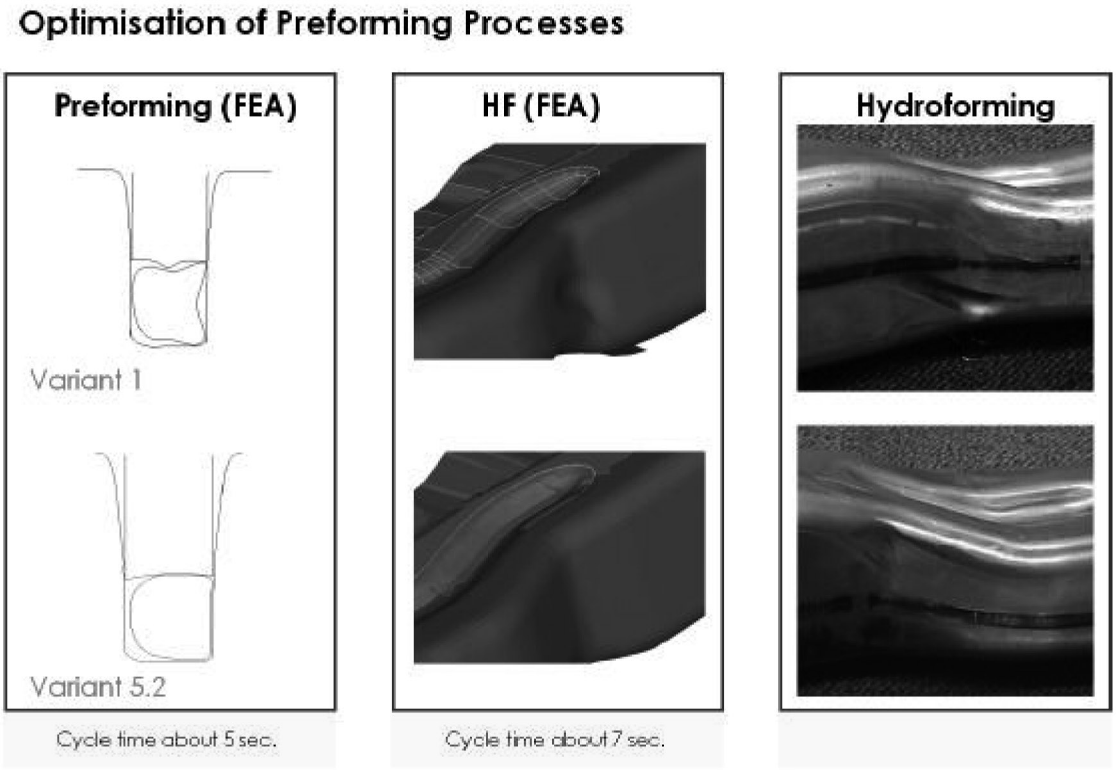


Figure 11: Optimisation of a Preforming Process by using FEA, Result of Hydroforming Operation (Defective Workpiece [Variant 1] and Perfect Workpiece [Variant 5.2])

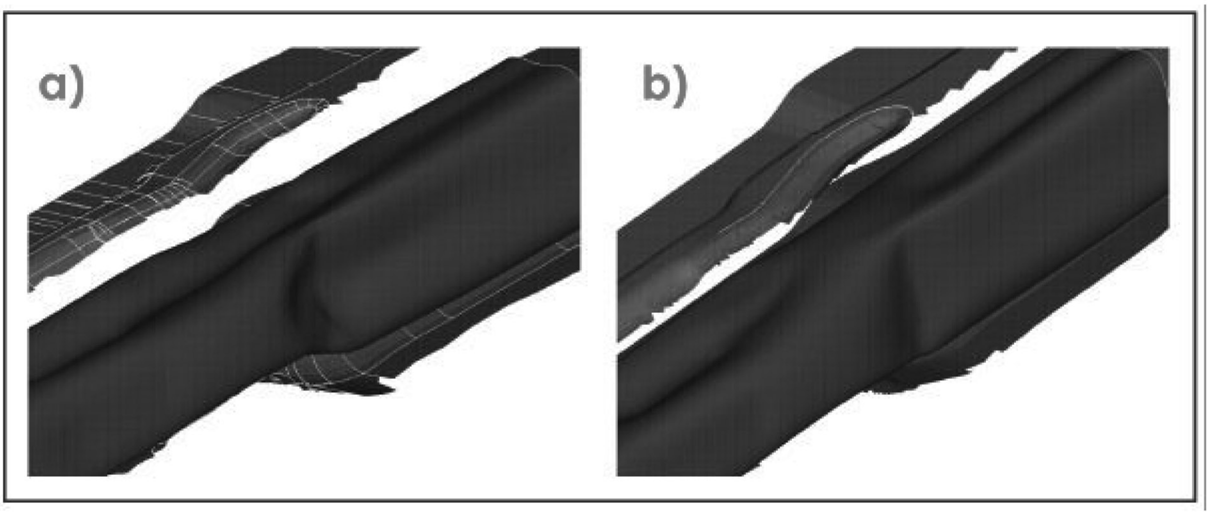


Figure 12: Starting Geometry for Hydroforming a) Variant 1 b) Variant 5.2.

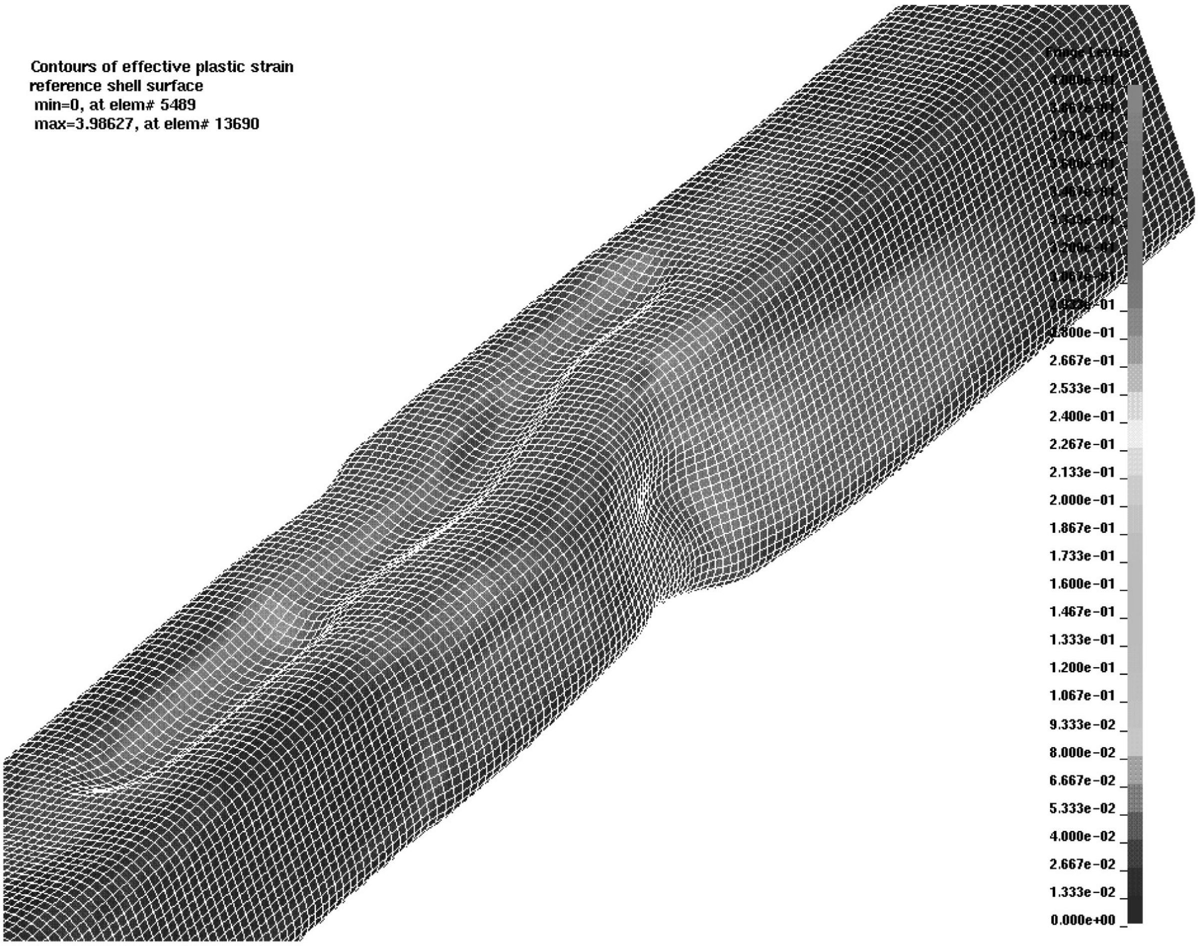


Figure 13: Wrinkle Formation in FEA (Plastic Strain Distribution) after Hydroforming

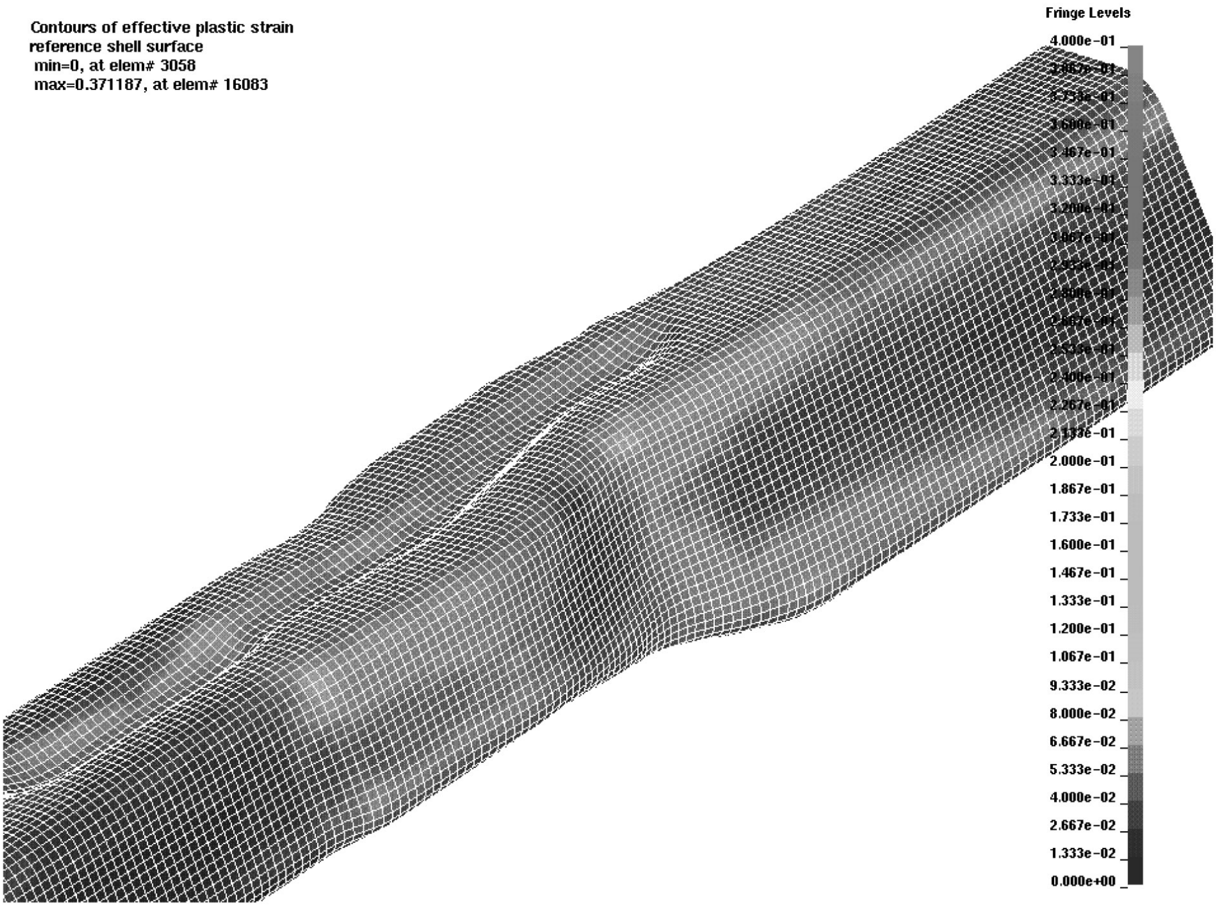


Figure 14: Problem-free Forming Out by optimised Preforming Die

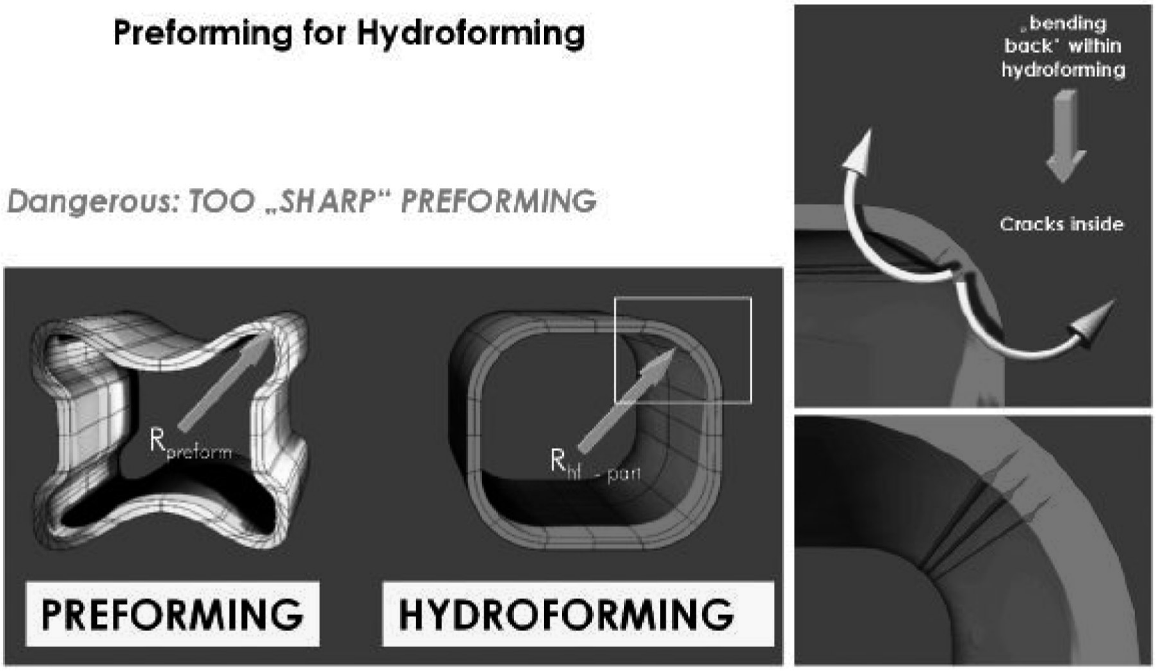


Figure 15: Requirements on Starting Parts for Hydroforming:

All Radii after Preforming greater or same as the Final Component Radii

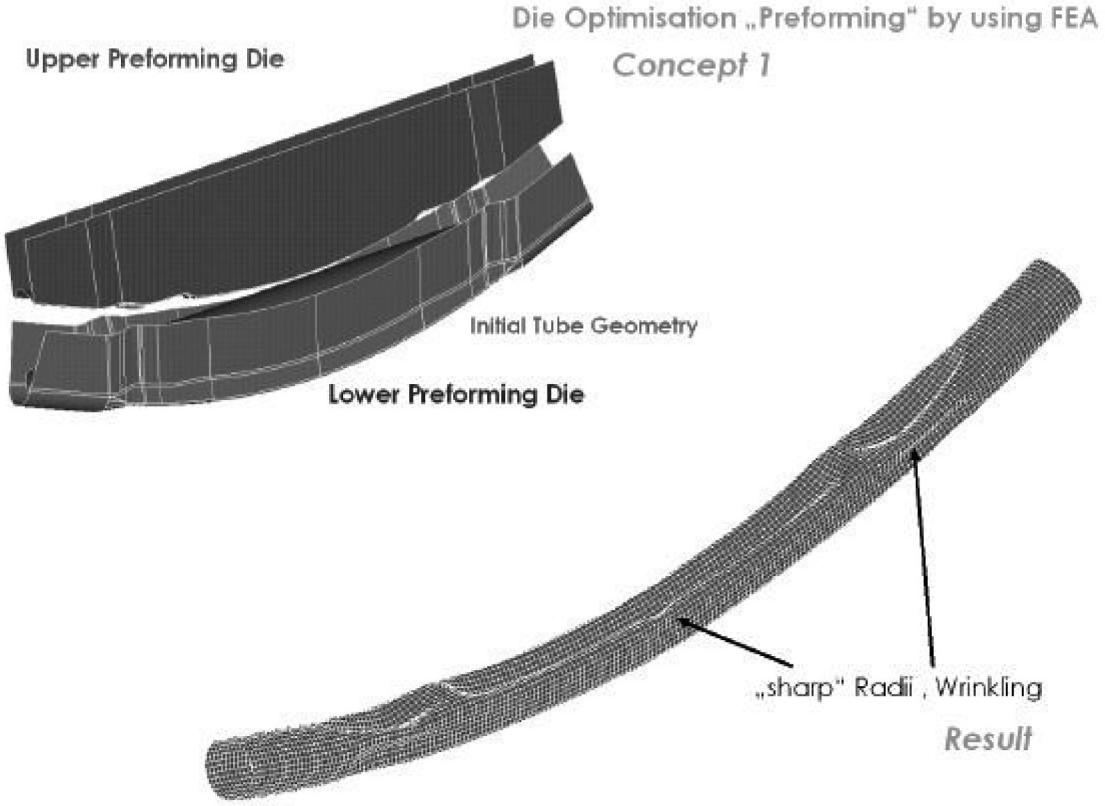


Figure 16: Preforming “Bumper”, Die Concept 1

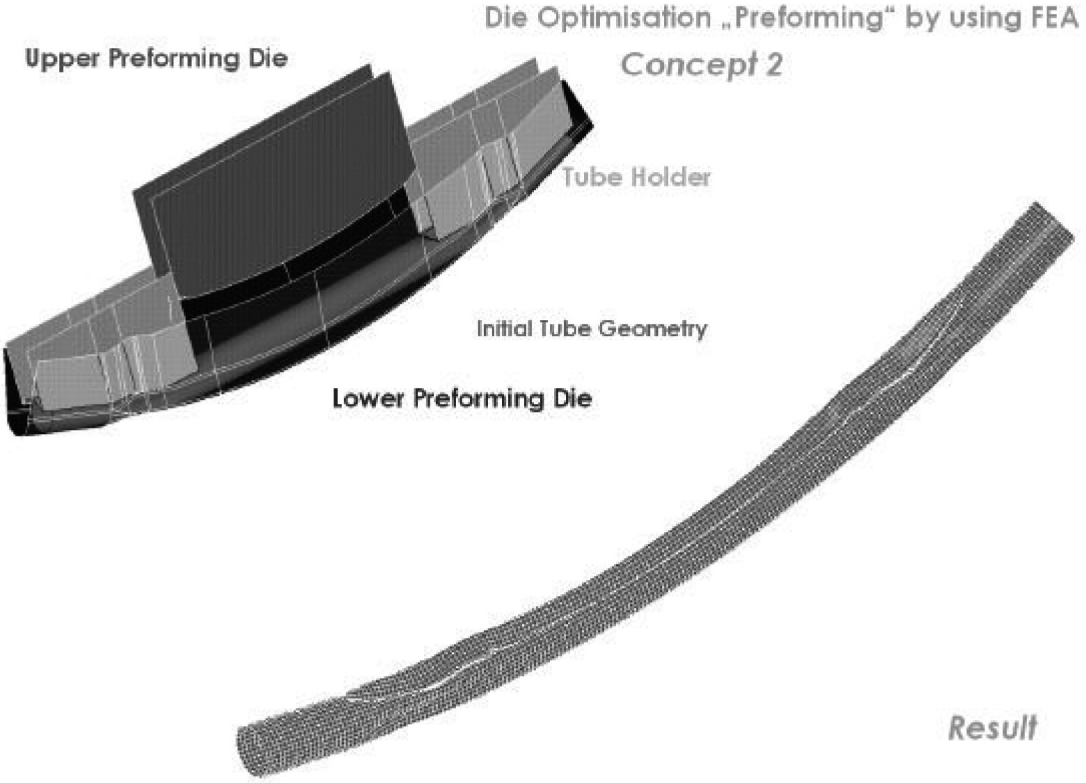


Figure 17: Preforming “Bumper”, Die Concept 2

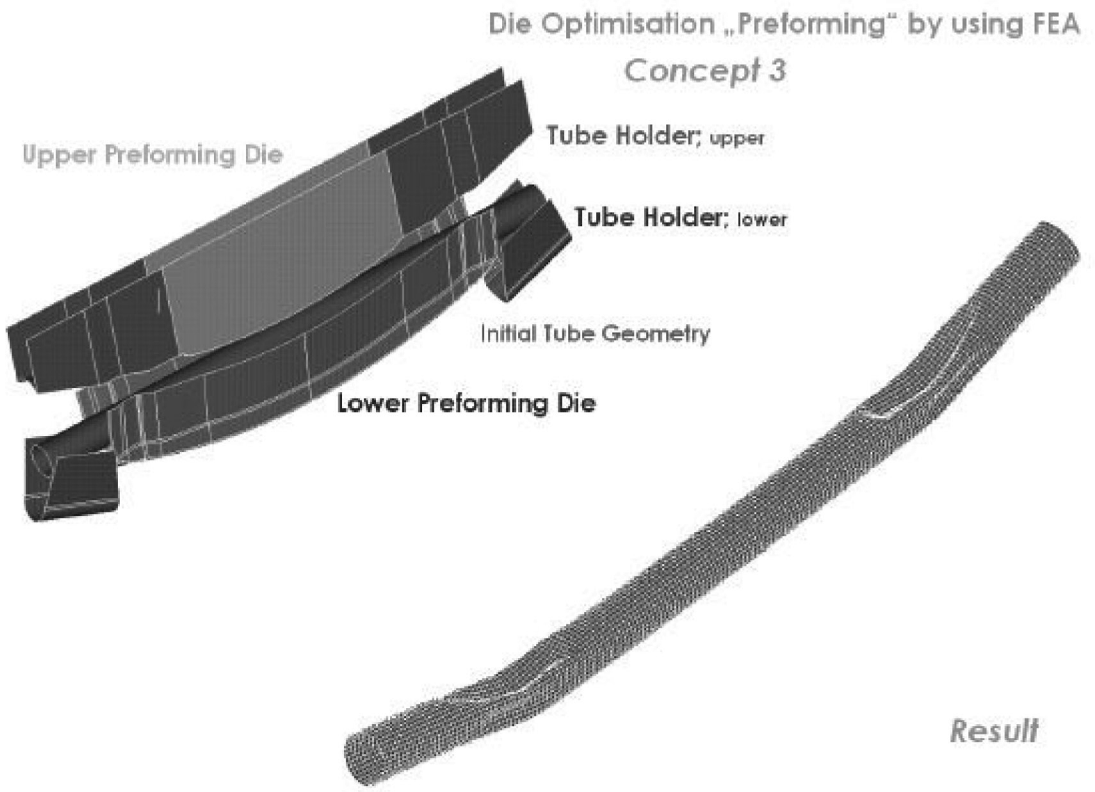


Figure 18: Preforming “Bumper”, Die Concept 3

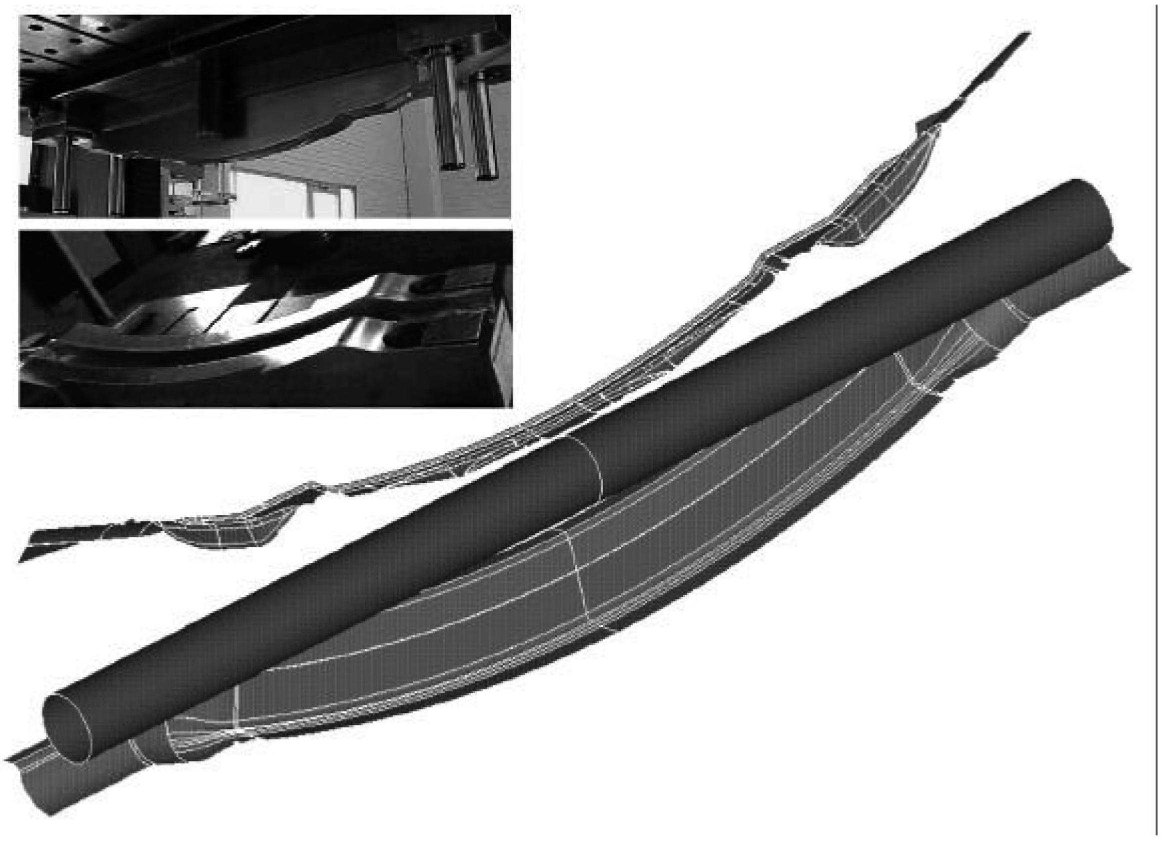


Figure 19: Preforming “Bumper”, Final Die Concept

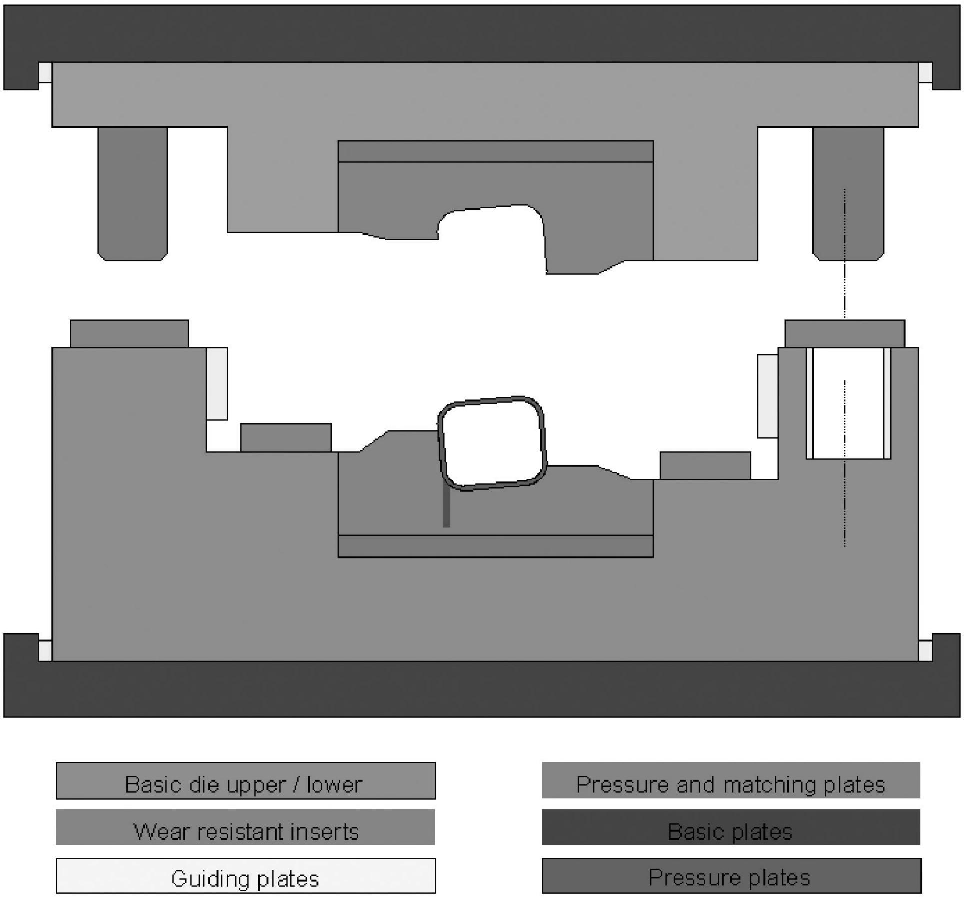


Figure 20: Schematic Crosswise Cut of a Horizontal Die Layout

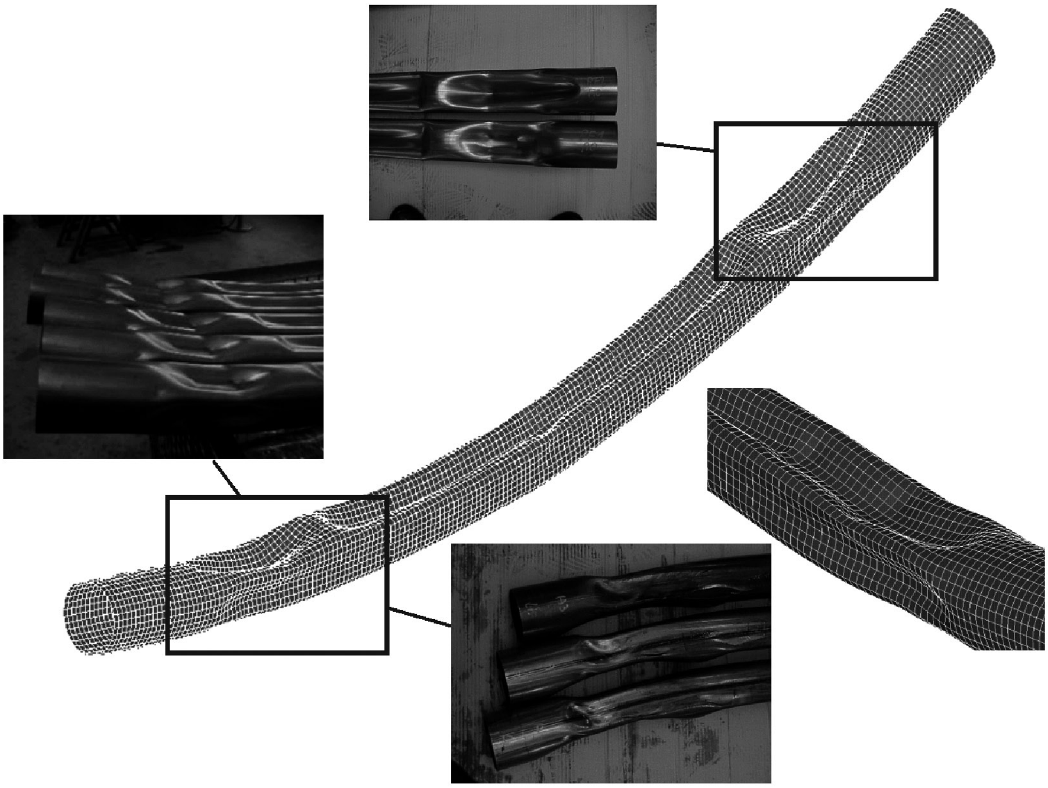


Figure 21: Comparison Real Prototyping and Virtual Prototyping - Preforming "Bumper"

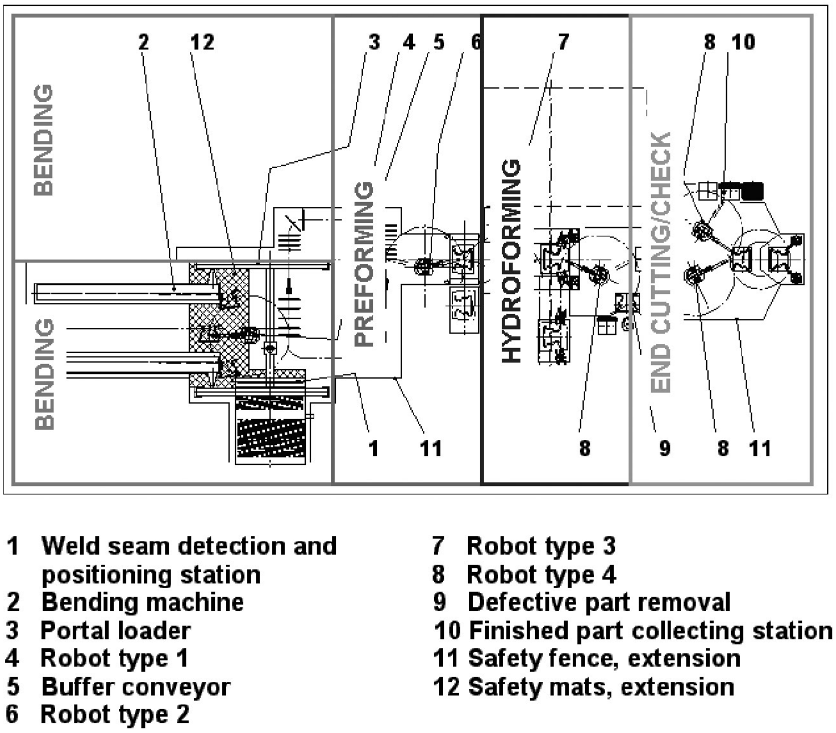


Figure 22: Production Line Layout for the Production of an Engine Cradle

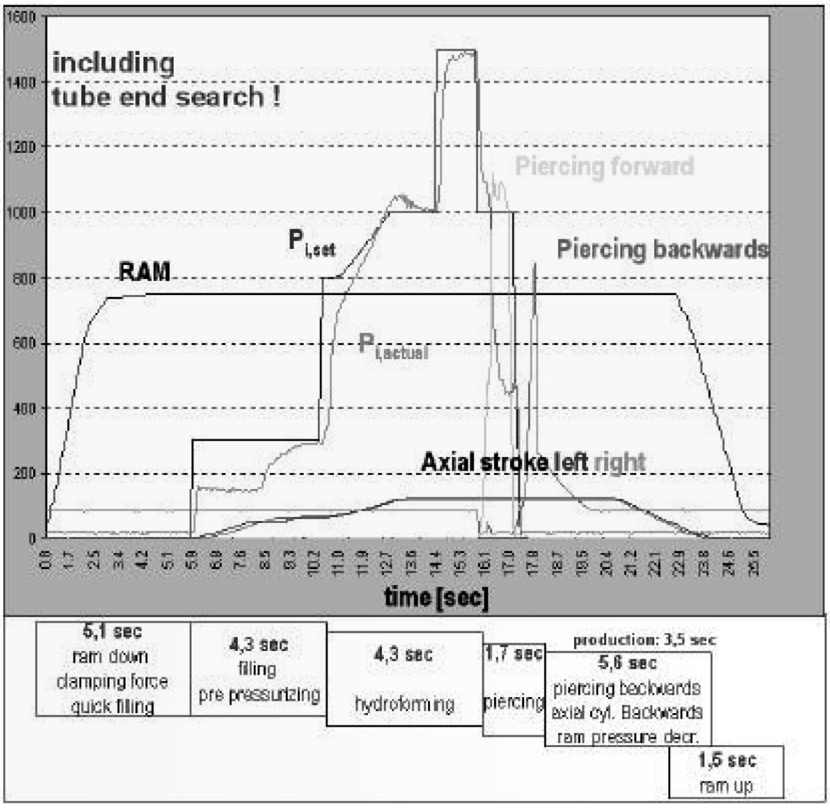


Figure 23: Recorded Process Parameters "Hydroforming"

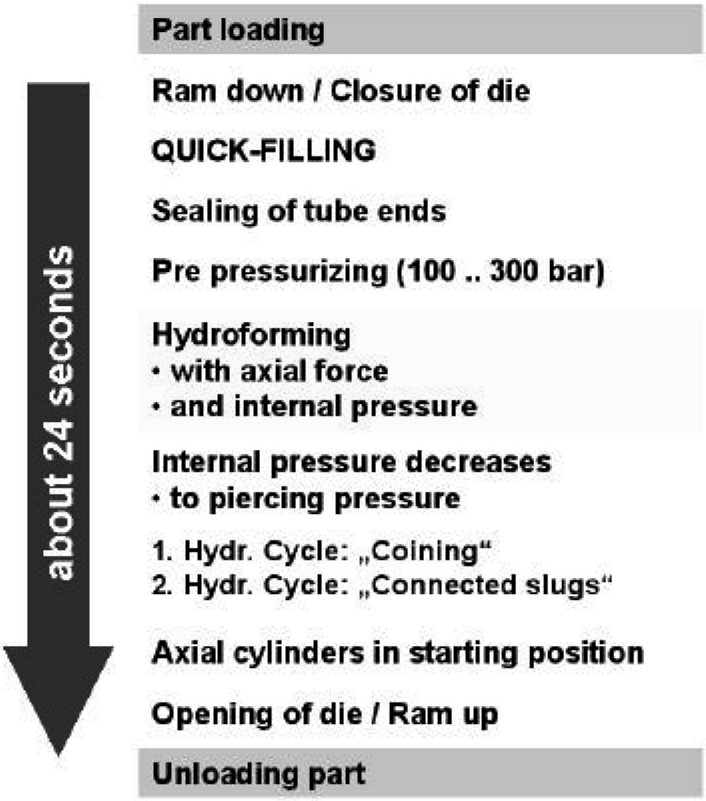


Figure 24: Hydroforming Process Sequence

- steel piping of all hydraulic components
- all connections to one side

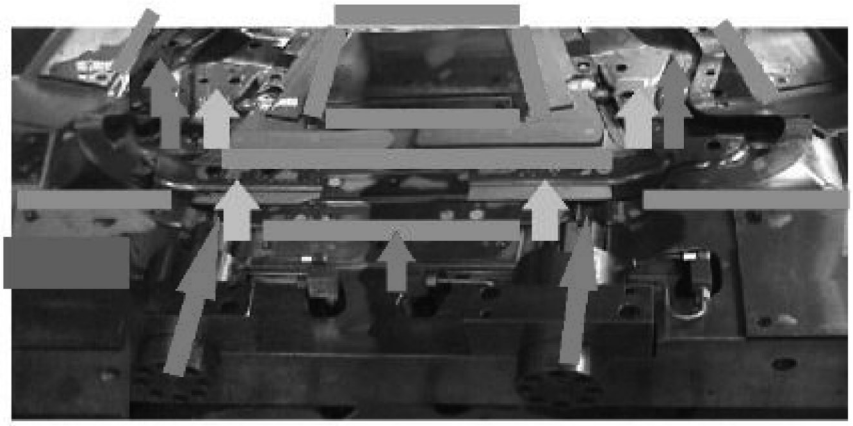
- axial cylinders
- stiffness !
- guidance !

Figure 25: Hydroforming Die Example: Audi A8 - Profile Calibration Die

Ejectors

Guidance

Piercing Units



24 Piercing Units
6 Ejectors
2 Axial cylinders
> 50 Inserts in contour area (active)

Figure 26: Hydroforming Die Example: Engine Cradle Rover 75

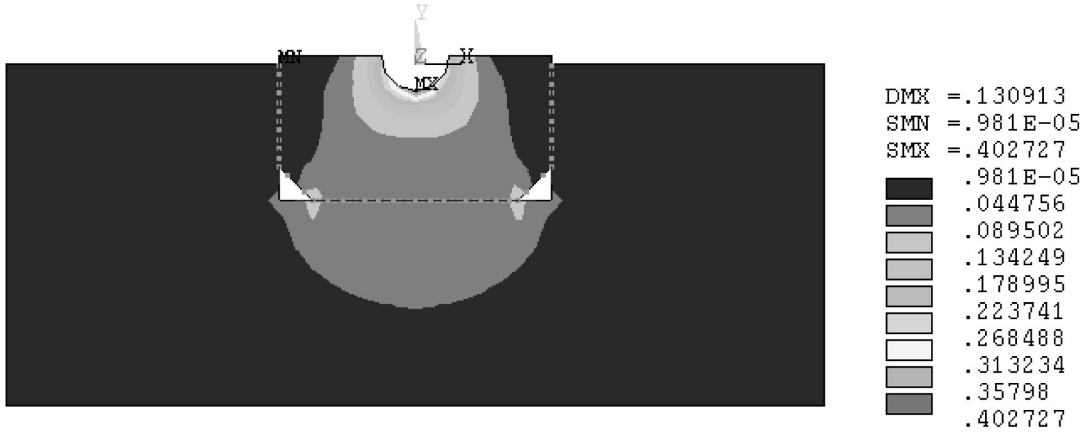


Figure 27: Structural Die Layout with FEA Technique - Insert (ANSYS)

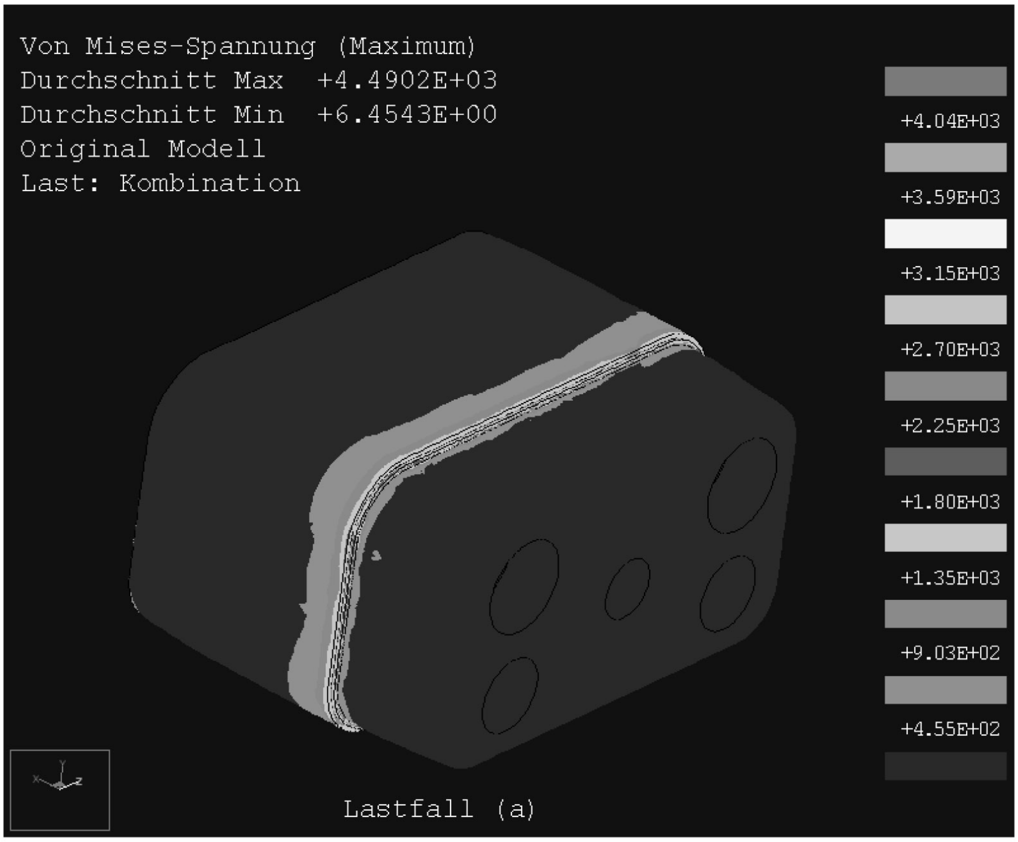


Figure 28: Structural Die Layout with FEA Technique - Punch Cap (Pro/Mechanica)

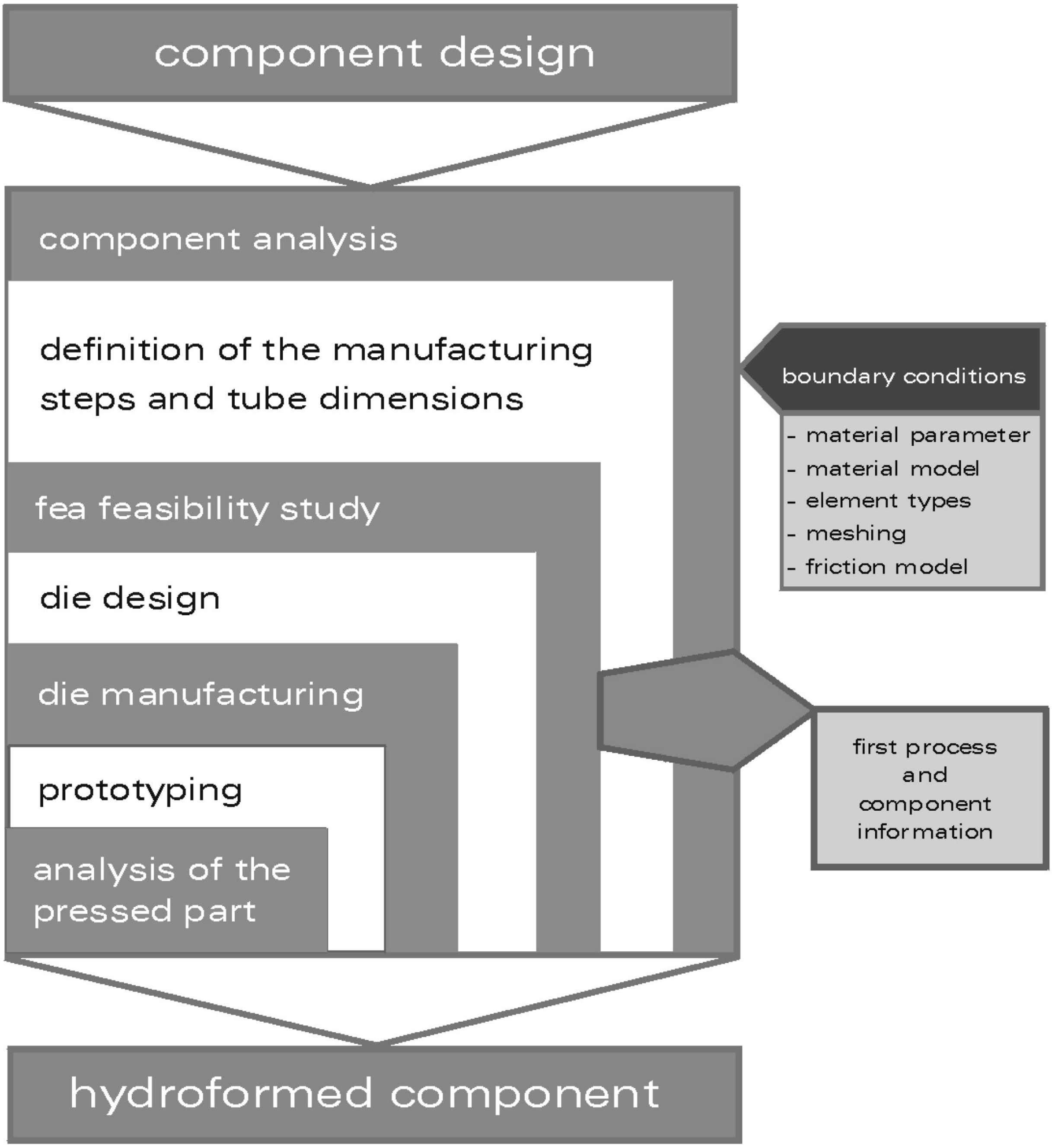


Figure 29: Principle Methodology for the Development of a Hydroforming Component

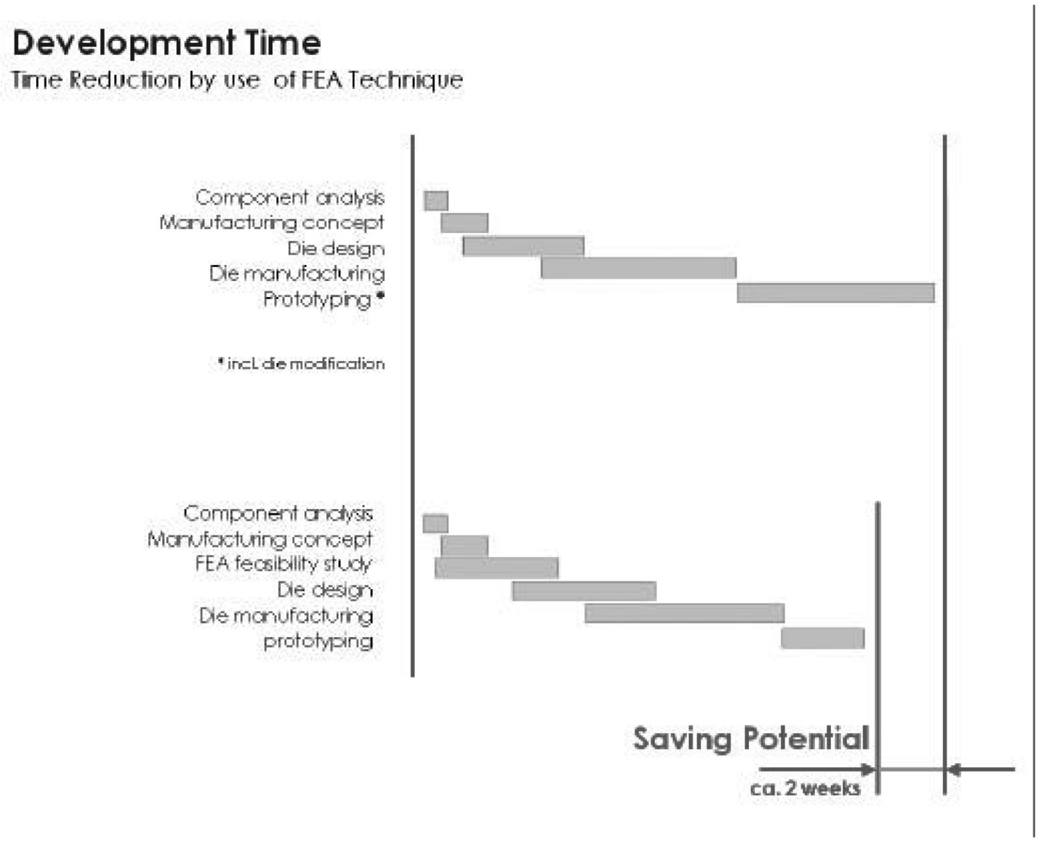


Figure 30: Achievable Time Reduction by using FEA Techniques in Part Development

Figure 31: Comparison Real Prototyping and Virtual Prototyping - Hydroforming "Bumper