ADVANCES IN HYDROFORMING FOR MANUFACTURING AUTOMOTIVE PARTS

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ABSTRACT

Increase in demand for fuel efficient vehicles along with higher safety and environmental standards has forced automotive manufactures to look for increased applications of light weight materials such as Advanced High strength steel, Aluminum and Magnesium alloys and new manufacturing techniques to reduce the total weight of the car. Also, increased competition in market place has reduced the lead time for new models forcing automotive manufacturers to move towards new economical manufacturing methods to reduce the manufacturing cost. Hydroforming of sheet and tube is one of the new manufacturing methods currently being pursued by auto makers world wide because of a) low tooling cost, b) better properties (dent resistance and energy absorption) of part after forming, c) ability to form complex shapes and integrated structures (hydroformed tube may replace an assembly from several stampings) that reduces assembly cost and time. This paper provides an overview on the advances in press (machines) & tools, tests for material and lubrication selection and strategies for process design through FE simulation in sheet and tube hydroforming. Also, warm hydroforming of magnesium and aluminum alloys is briefly discussed.

1. INTRODUCTION

Until recently hydroforming of sheet and tube was not considered for automotive manufacturing due its high cycle time. However, advances in hydraulics and intelligent press design over the time have reduced cycle time considerably making it attractive for automotive manufacturing. In addition, hydroforming of sheet and tube offers benefits such as a) low tooling cost, b) better properties (dent resistance and energy absorption) of part after forming, c) ability to form complex shapes and integrated structures (hydroformed tube may replace an assembly from several stampings). These reduce assembly cost and time thereby represent an attractive alternative to stamping in the current market trend towards smaller batch size of new models.

Metal forming using liquid media is classified as shown in Figure 1. It is broadly classified into sheet and tube hydroforming depending on the input preform. Further, sheet hydroforming is classified into hydromechanical deep drawing and high pressure sheet hydroforming depending on the male or the female die that has the shape/impression to be formed. High pressure sheet hydroforming is further classified into hydroforming of single blank and double blank depending on number of blanks being used in the forming process. This paper provides an overview on the advances in press (machines) & tools, tests for material and lubrication selection and strategies for process design through FE simulation in all the areas of sheet and tube hydroforming. Also, warm hydroforming of magnesium and aluminum alloy sheet is briefly discussed.

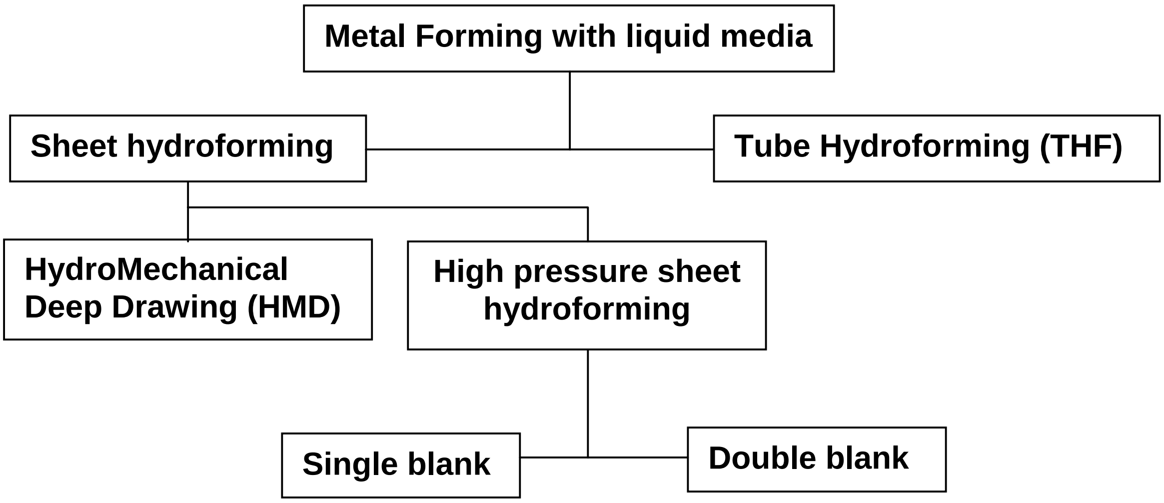
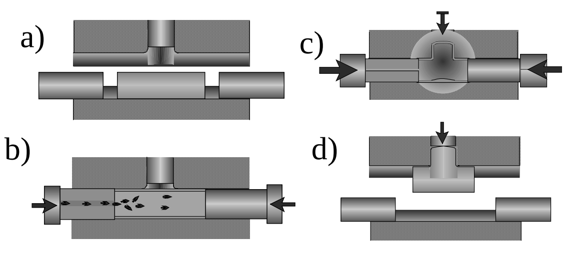


Figure 1 **Classification of the forming process using liquid media [Schmoeckel et al 1999]**

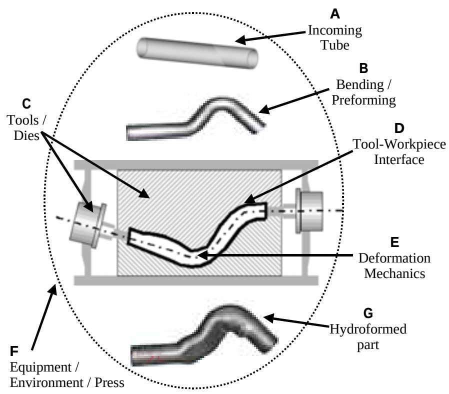
2. TUBE HYDROFORMING (THF)

2.1. Description

In THF, a tubular pre-form is placed between two dies. The dies are closed and held under pressure while the tube is internally pressurized and axially compressed to force the material into the die cavity to acquire the desired shape/impression of the die (Refer Figure 2). During this process, axial feed and internal pressure are controlled simultaneously to form the part without any defects such as bursting and wrinkling.



THF process sequence; a) place a tube, b) seal and fill fluid, c) pressurize and feed material, d) take a formed part out



THF System

Figure 2 **Schematic of the THF process and its process parameters**

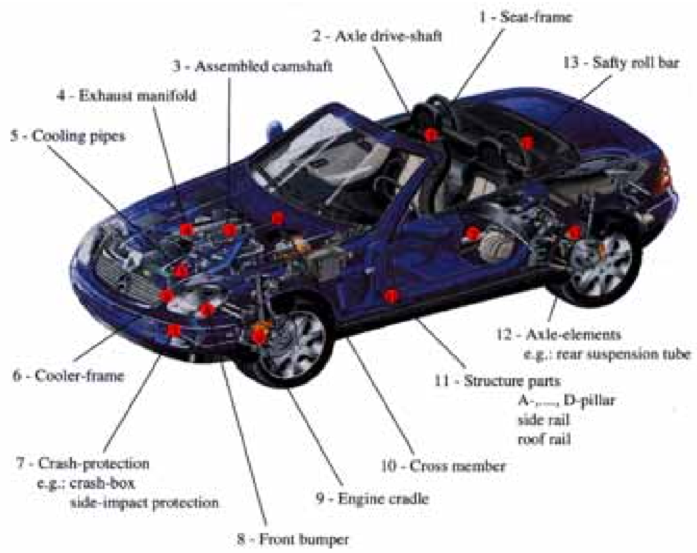


Figure 3 Schematic of the hydroformed parts in an automobile [Schroeder 1999]

THF is now widely used in making tubular parts of different configurations used in automotive industry (Figure 3) and other applications such as appliances. The rapid growth of this technology has been due to the advantages THF offers compared to conventional manufacturing via stamping and welding namely; (a) part consolidation, (b) weight reduction through more efficient section design and tailoring of the wall thickness in structural components, (c) improved structural strength and stiffness via optimized section geometry, (d) lower tooling costs due to fewer parts, (e) fewer secondary operations (less welding and punching of holes during hydroforming), (f) tighter tolerances and reduced springback that facilitates assembly, and (g) reduced scrap since trimming of excess material is far less in tube hydroforming than in stamping. [Schmoeckel et al 1999, Ahmetoglu et al 2000].

In order to successfully design and develop a THF process or operation, improvements in each area of the THF technology and their interactions should be considered. The main components and key issues of a complete THF system (Figure 2) can be listed as follows: a) Quality of incoming tubes, b) Performing and bending design and production methods, c) Die and tool design guidelines, d) Die-workpiece interface issue (friction and lubrication), e) Deformation mechanics (metal flow) in different zone, f) Equipment, press and environment related issues, and g) Dimensions and properties of the hydroformed part.

2.2. Material properties/ Tubular Hydraulic bulge test

We at ERC/NSM suggest tubular bulge test for determining the properties of tubular materials because a) stress conditions in THF are often biaxial similar to bulge test compared to uniaxial in the tensile test. The maximum effective strain achievable in the bulge test without local necking is much larger (usually twice) than that in the tensile test. Figure 4 shows the schematic of the bulge test for tubular materials. The tube held at the ends is subjected to internal pressure until it bursts. During the test the internal pressure and the height of the bulge are measured, which are used to obtain the flow stress of the material for process simulation. The burst height of the tube indicates the formability of the tube. The burst height from bulge test can be used as a indicator/ design specification for the quality of the incoming tubes to the THF plant [Aue – u- lan et al 2002].

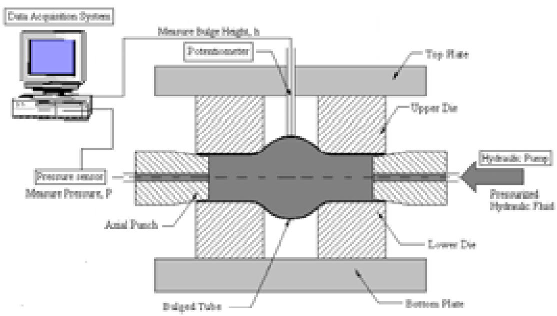


Figure 4 Schematic of tube bulge test to evaluate the material properties of tubes for THF

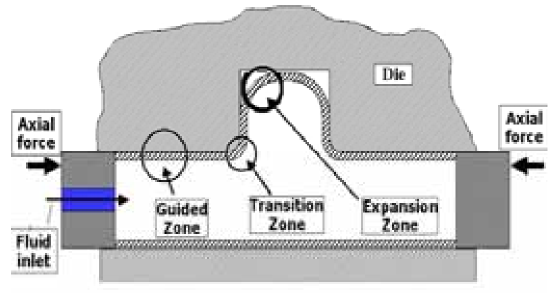


Figure 5 Different zones of friction conditions in THF.

2.3. Lubrication selection

In THF, depending on the deformation mechanism, the entire deformation area can be classified as guiding zone, transition zone and expansion zone. In guiding zone the tube is subjected to compressive axial stress due to feeding from either sides resulting in thickening of the tube and contraction of the surface of the tube on which lubricant is applied. In expansion zone the tube is subjected to biaxial tensile stress resulting in thinning and surface expansion. Transition zone mark the intermediate stage. Thus, a good lubricant in THF should be able to perform well in all the three zones. ERC/NSM has developed a) Guiding zone test b) Transition zone test and c) Expansion zone test emulating the deformation mechanism and the contact pressure in respective zones [Ngaile et al 2004a, Ngaile et al 2004b] to screen the commercially available lubricants for THF.

2.4. Press and Tooling

THF press design plays a dominant role because it significantly influences the cycle time and the economics of the process. Figure 6 shows three basic press concepts for THF a) conventional design (long stroke design concept), b) new design (short stroke design concept), and c) similar to concept (b) without any locking mechanism. Among the basic concepts, concept (b) is used widely because a) it reduces cycle time with long stroke cylinder that is used mainly to move the top die up and down fast with less fluid pressure, b) Short stroke cylinder requires less volume of fluid to generate the required high pressure thereby reducing cycle time, and c) Mechanical locking of top die eliminates the high pressure hydraulic system for top die thereby reducing cost and making design more compact [Siegert et al 1999, Osen 1999, Bieling 1999, Marando 2003]. Figure 7 shows the different types of presses available in the market that has adapted the three basic concepts. They basically differ in either the structure of press frame or typing of mechanical locking mechanism used. Figure 8 shows THF press with modular design concept. The benefits of this design are a) useful for a design that requires several step of production (performing –hydroforming), and b) multiple ram can be locked together in order to form a large part [Macrae et al 2003].

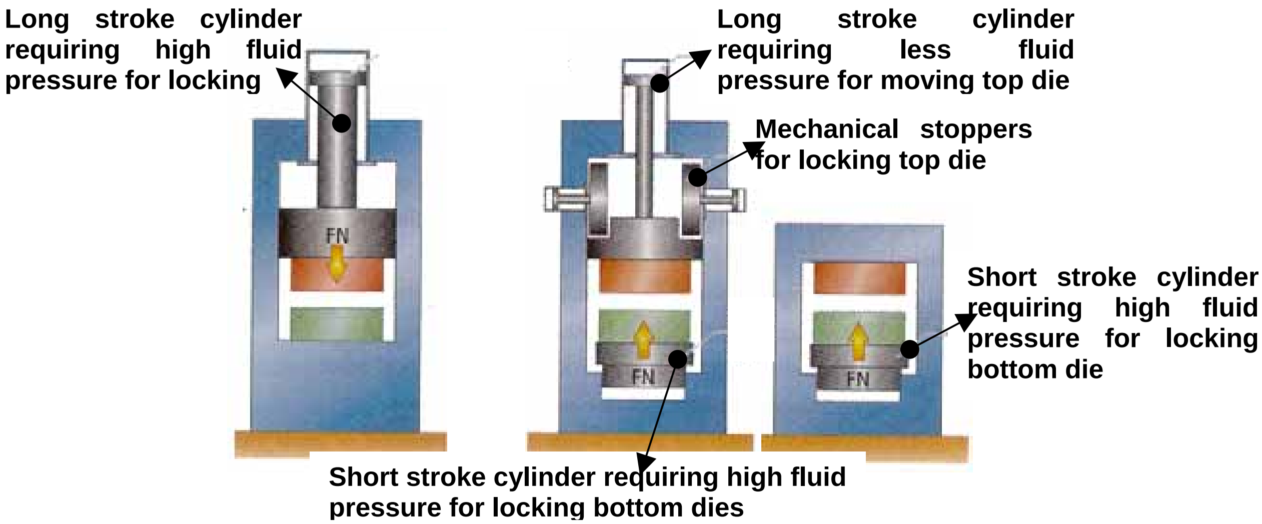


Figure 6 Basic concepts of THF presses [Breckner 1999]

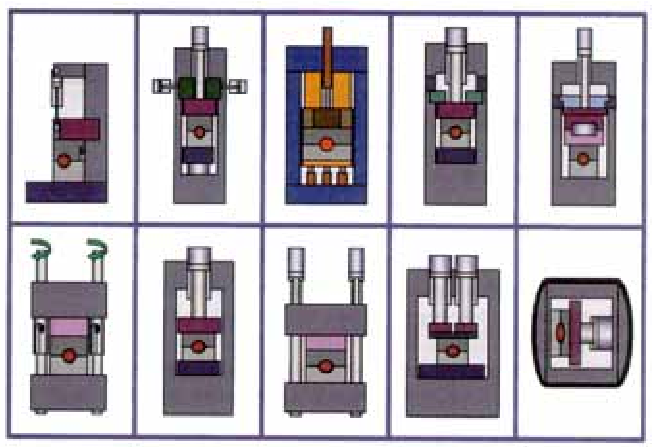


Figure 7 THF press types available in the market adapting the basic types [Schnupp et al 2003]

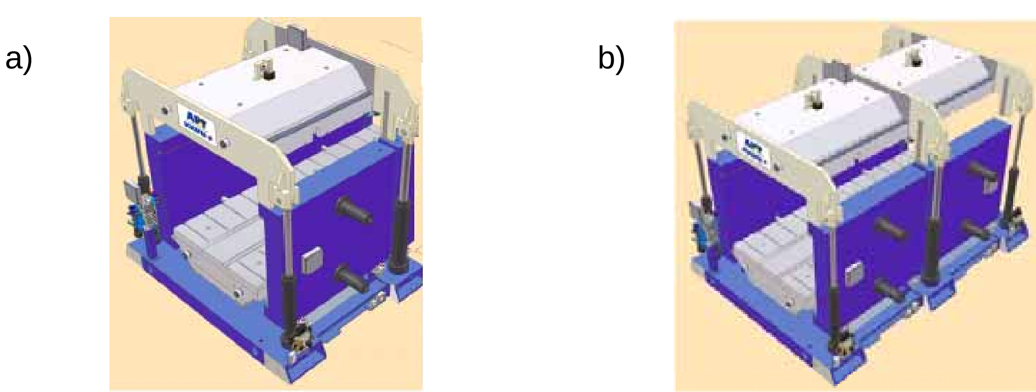


Figure 8 Modular press concept (Source: AP&T Schafer); a) single cell unit and b) double cell unit

2.5. Process design through FE simulation

Successful design of THF process requires the estimation of optimum relationship of the key process parameters; axial feed versus time and internal pressure versus time to form the part. More axial feed could result in buckling of the tube while less axial feed would result in leakage of the medium and also bursting due to excessive thinning. At ERC/NSM, FE simulation using PAMSTAMP 2000 coupled with optimization technique and adaptive simulation technique have been used to determine the loading path that results in minimum thinning and no wrinkling in the part and without any leakage of the medium during the process [Jirathearanat et al 2004]. Figure 9 shows the example optimum loading path obtained for hydroforming of a cross member part. Figure 10 shows the part geometry, die geometry and the thinning distribution in the part for the optimum loading path. Loading path estimated from FE simulations were used in experiments to form a good part (Refer Figure 11).

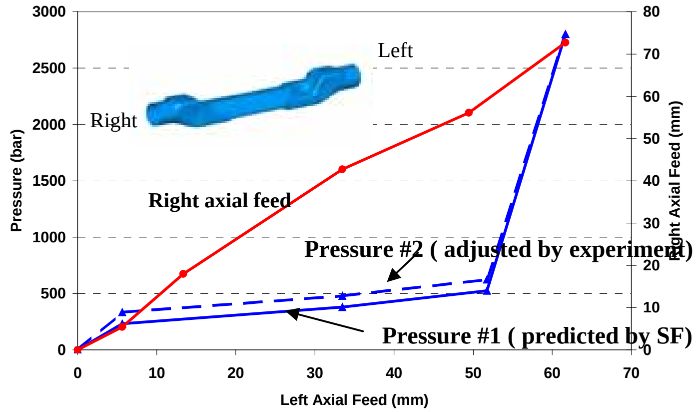


Figure 9 Loading path obtained by adaptive simulation technique for forming cross member part.

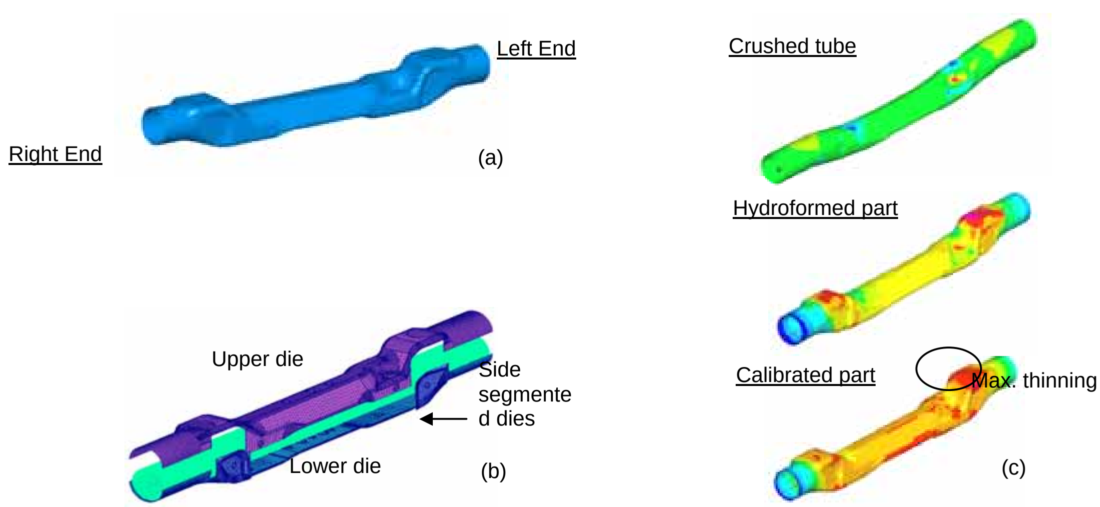


Figure 10 Schematic of the cross member part geometry, die geometry and the thinning distribution predicted by FE simulation for the optimum loading path at various stages

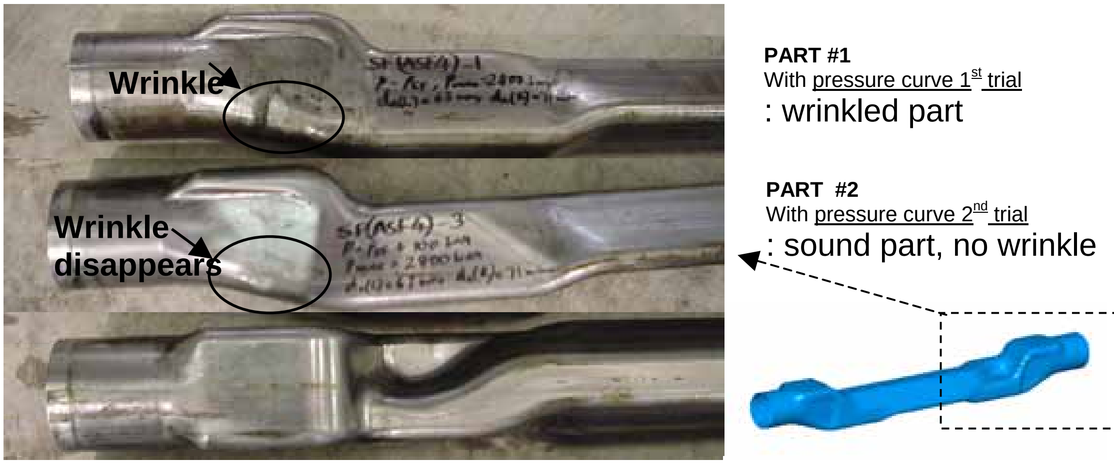


Figure 11 **Schematic of the part obtained from experiments using the estimated optimum loading path**

3. HIGH PRESSURE SHEET HYDROFORMING AND VISCOUS PRESSURE FORMING

3.1. Description

In high-pressure sheet hydroforming, the sheet is formed against female die by the hydraulic pressure of the fluid as shown in Figure 12. During the forming process, the intermediate plate acts as a blank holder to control the material movement from the flange and also seals the fluid medium to avoid leakage. Viscous pressure forming is similar to sheet hydroforming in which the pressure acting on the sheet is generated by compressing the viscous medium rather than hydraulic fluid/water in sheet hydroforming.

The forming operation in high pressure sheet hydroforming can be divided into two phases. Phase I involves the free forming where the sheet bulges freely in the die cavity until it initiates contact with the die. This introduces uniform strain distribution throughout the sheet thereby a) The formability of the material is effectively used compared to conventional stamping process where deformation is localized in the sheet at the punch corner radius, and b) Improves the dent resistance of the hydroformed part compared to stamped part. Phase II involves calibrating the sheet against the die cavity to obtain the desired shape. High fluid pressure is required in phase II depending on the material, sheet thickness, and the smallest corner radius in the die geometry. Thus, sheet hydroforming offers a viable alternative process for fabricating automotive parts from low formability advanced high strength steels and aluminum alloys.

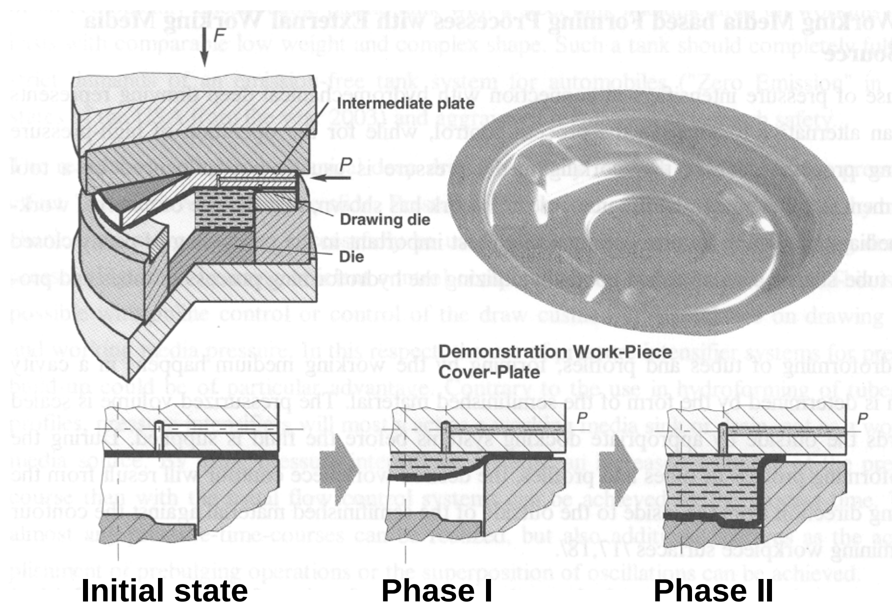
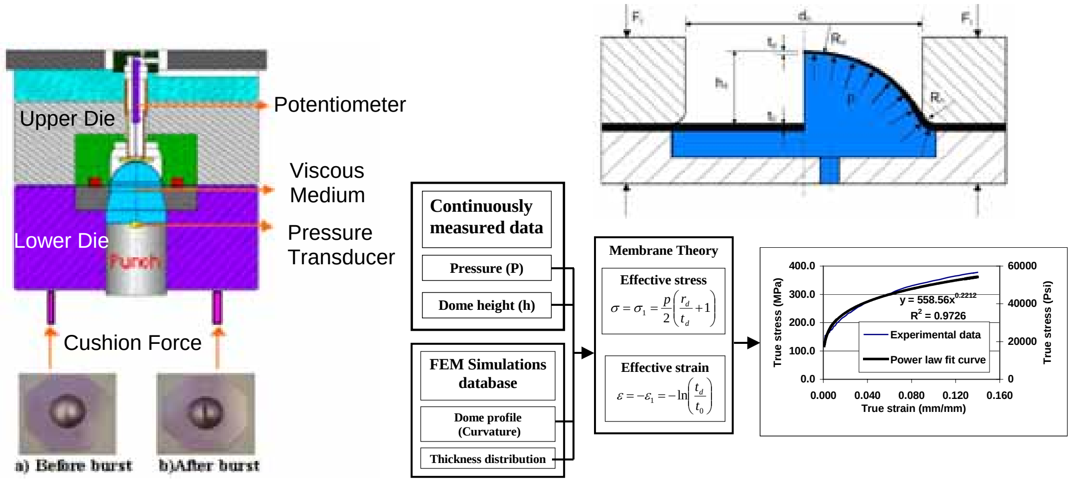


Figure 12 **Schematic of the high pressure sheet hydroforming process [Kleiner 1999]**

Successful application of high pressure sheet hydroforming requires careful consideration of all components of high pressure sheet hydroforming system namely: a) Quality of incoming sheet, b) Die-workpiece interface issue (friction and lubrication), c) Tool design for efficient application of BHF and avoid leakage d) Relationship between the internal fluid pressure and blank holder force (loading path), e) Press and tooling, and d) Dimensions and properties of the hydroformed part.

3.2. Material properties/Viscous pressure bulge test

We at ERC/NSM suggest bulge test (Viscous Pressure Bulge test, VPB test) for determining the properties of sheet materials and to check the quality of sheets incoming to the stamping plant because a) Stress conditions in stamping/ sheet hydroforming are often biaxial similar to bulge test compared to uniaxial in the conventional tensile test, b) The maximum effective strain achievable in the VPB test without local necking is much larger (usually twice) than in the tensile test. Figure 13 shows the schematic of the bulge test where the sheet clamped at the edges is bulged freely by the viscous pressure until it burst. During the test, the height of the dome and the internal pressure of the viscous medium are measured in real time. The measured dome height and pressure are used as an input to the inverse analysis using FE simulation to determine the flow stress of the material. The burst dome height is a good indicator of the formability of the material (The higher burst dome height the better formability). Also, the burst dome height can be used as a indicator/ design specification to check the quality of the incoming material to the stamping plant [Gutcher et al 2000].



a)VPB test tooling b) Procedure to calculate the flow stress from VPB test

Figure 13 Schematic of the VPB test tooling and method to determine the flow stress

3.3. Lubrication selection

Lubrication plays a dominant role in controlling material flow in the blank holder–sheet and the die-sheet interface during forming process. Failure of lubrication results in a) excessive thinning resulting in tearing of the part, b) excessive galling resulting in damage of surface finish of the formed part and c) wear of the dies. Lubricants used in sheet hydroforming usually fail due to high contact pressure at material-die interface. The pressure generated at the interface depends on the material, sheet thickness and the die geometry. Thus a single lubricant cannot satisfy the requirements of all the processes. Selection of lubricants should be made using tests that emulate the interface pressure, surface expansion close to production conditions. ERC/NSM suggests use of Stamping Lubricant Tester (SLT) [Yadav et al 2004] and Modified Limiting Dome height test [Schneider et al 2003] for screening commercially available lubricants for sheet hydroforming process.

3.4. Press and tooling

3.4.1. High pressure sheet hydroforming press

High pressure sheet hydroforming presses and tools are designed and manufactured based on the technology developed and available in THF. However, in sheet hydroforming, higher clamping force due to large area of the sheet and blank holding mechanism need to be considered. University of Dortmund, (LFU), Germany in cooperation with Siempelkamp PressenSysteme (SPS), Germany had built a 10,000 ton press for high pressure sheet hydroforming of large automotive parts (Figure 14). The press is designed to have horizontal mounting for inexpensive compact design, easy handling of workpiece, short stroke for cylinder to reduce cycle time and requires less investment for foundation in the shop floor. The press frame is cast and prestressed by wire winding to withstand dynamic load during forming. During hydroforming, large volume of fluid at relatively less pressure is required during the phase I (free bulging) and small amount of fluid at high pressure is required in phase II for calibration. Hydraulic systems in the press were designed at two different pressure levels a) max pressure of 315 bar with volume of 100 liter of pressurizing media and b) max pressure of 2000 bar with volume of 5 liter of pressurizing media to reduce the cost, cycle time and make the design more compact [Kleiner et al 2001, Lucke 2003].

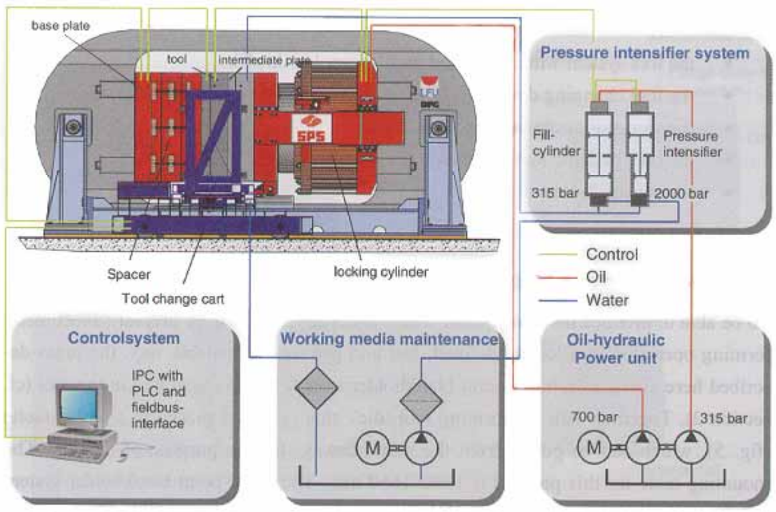


Figure 14 **Schematic of horizontal high pressure sheet hydroforming machine at LFU [Lucke 2003]**

3.4.2. Tooling system

3.4.2.1. <u>Tool design – LFU</u>

In conventional high-pressure sheet hydroforming tooling (Figure 12), The intermediate plate applies the required blank holder force to seal the pressurizing media and to control the material flow during hydroforming. Hence it is difficult to precisely apply the required blank holder force on the sheet. University of Dortmund, LFU, designed a new tooling as shown in Figure 15, where the sealing force is applied by the intermediate plate while the blank holder that is mounted in the flange portion of the die applies the blank holder force. Thus, the material flow from the flange is precisely controlled. In forming asymmetric parts, thickening in the flange is not uniform resulting in gap that causes the leakage of pressurizing media. LFU developed modular tooling design with multipoint blank holder as shown in Figure 15,where the force at each cylinder can be varied independently. The multipoint blank holder is incorporated in the tooling using short stroke cylinders that provides large force in short stroke [Kleiner et al 2001, Kleiner et al 2003,].

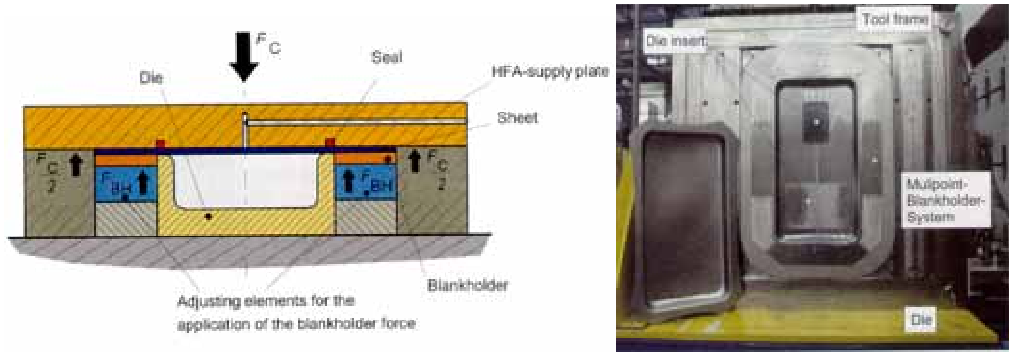


Figure 15 **Schematic of tool design by LFU with multipoint cushion system in the die for blank holder force application [Kleiner et al 2003]**

3.4.2.2. <u>Tool design - ERC/NSM</u>

The tool designed at ERC/NSM uses the mechanical action to generate the required pressure. Figure 16 shows the schematic of the tooling design by ERC/NSM for sheet hydroforming. The stationary punch is mounted on the press bed while the blankholder rests on the cushion pins and the die is mounted on the press ram. The pressurizing medium required to generate the pressure is placed in the cavity formed by the punch and the blank holder at the top-most position. Initially the sheet is placed on the blank holder. The upper die moves down and clamps the sheet against the blank holder. After clamping the sheet, further movement of the upper die results in movement of blank holder relative to the stationary piston. This relative motion results in compression of the viscous medium between the sheet and punch. Due to the incompressibility of the pressurizing medium, pressure is generated to act on the sheet. Thus by pure mechanical motion in a regular press, sheet hydroforming process is performed [Liu et al 1996].

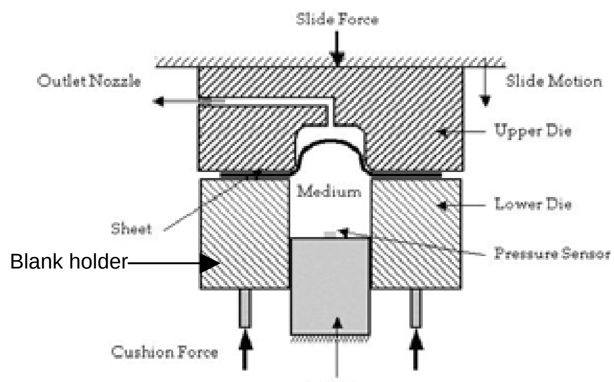


Figure 16 **Schematic of the tool at ERC/NSM for high pressure sheet hydroforming [Liu et al 2004]**

3.5. Process design through FE simulation

Successful design of hydroforming process requires the optimum relationship of the key process parameters; blank holding force versus time and internal pressure versus time to successfully hydroform the part. Higher blank holding force could result in excessive stretching and finally fracture of the sheet while low blank holding force would result in leakage of the medium. At ERC/NSM, FE simulation using PAMSTAMP 2000 coupled with optimization techniques have been used to determine the loading path that results in minimum thinning in the part without any leakage of the medium during the process. Figure 17 shows the loading path for forming a sample asymmetric part from DP 600 material of sheet thickness 0.60 mm. Figure 18 shows the thinning distribution in the part. The obtained profile would be verified experimentally using the ERC/NSM tooling.

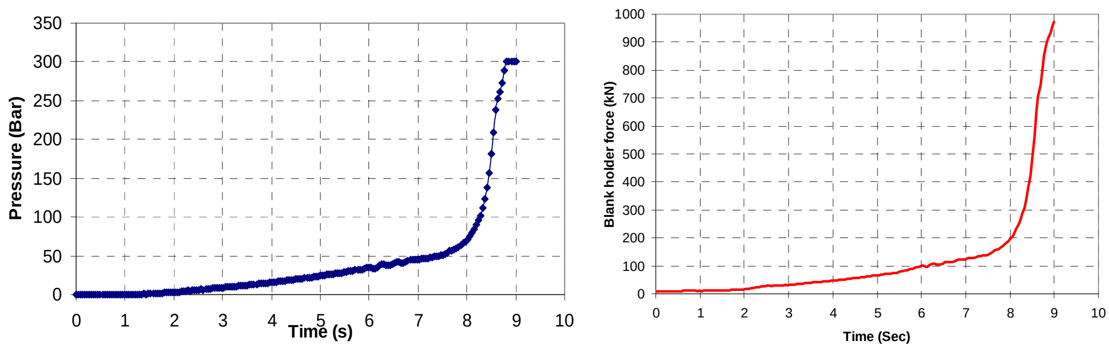


Figure 17 **Loading path obtained using FE simulation (PAMSTAMP 2000) coupled with optimization techniques.**

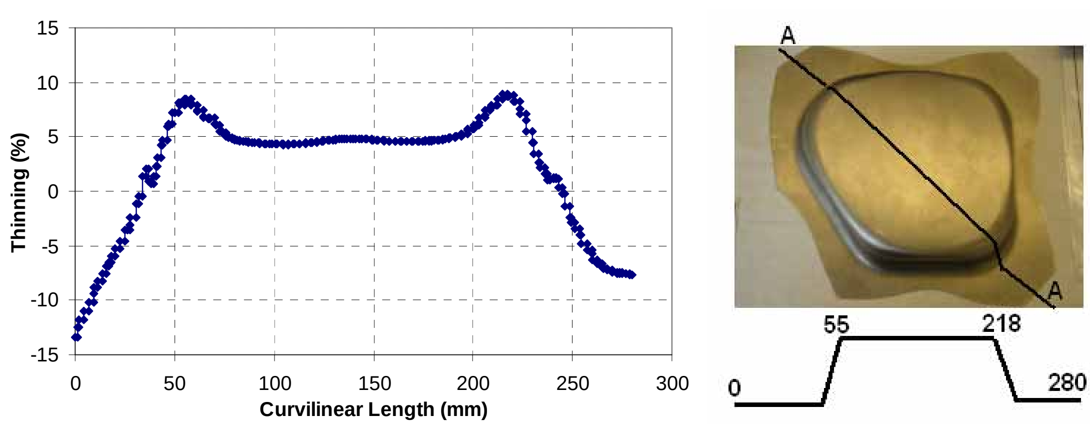
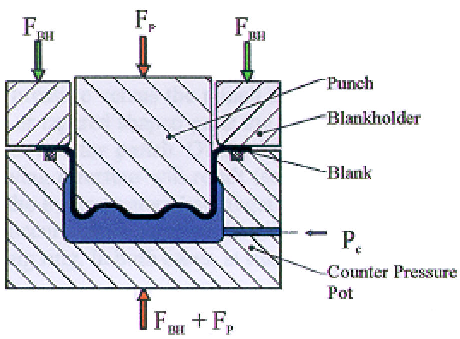


Figure 18 **Predicted thinning distribution in the formed part for the optimum loading path**

4. HYDROMECHANICAL DEEP DRAWING (HMD)

4.1. Description

In HMD, the sheet is deep drawn against a counter pressure in the pot rather than a female die in regular stamping operation as shown in Figure 19. The medium in the pressure pot can be either "passive" (pressure generated due to the incompressibility of the medium during forward stroke of the punch) or "active"(pressure generated by external pump).

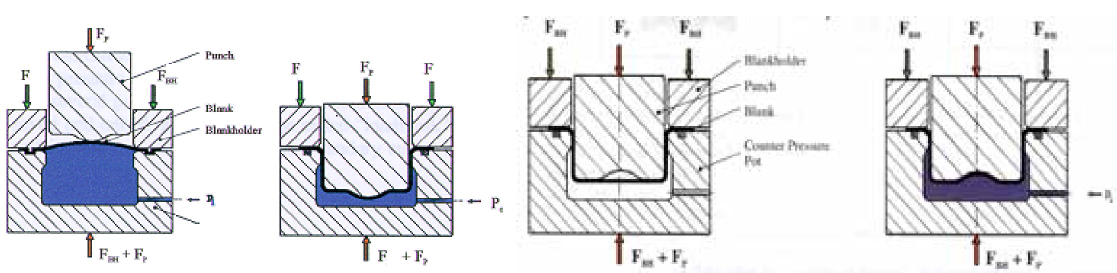


a) Process description [Aust 2001]

b) Example parts [Maki 2003], [Aust 2001]

Figure 19 Schematic of the hydromechanical deep drawing and example automotive parts produced using HMD

HMD results in higher LDR (deep drawability) compared to conventional stamping because during HMD the sheet metal is forced to form against the punch surface due to the fluid pressure. Due to the friction between the sheet and the punch surface, the sheet attached to the punch surface is not stretched during the forming process resulting in uniform wall thickness and higher LDR. HMD can be combined with regular stamping operations resulting in reduction of forming stages. Figure 20 shows the combination of HMD with regular stamping, to form complex parts.



Combination of stretching followed by HMD **Combination of deep drawing followed by HMD**

Figure 20 Combination of HMD with stretching and deep drawing to produce complex parts in less forming operations [Siegert et al 1999b]

HMD is advantageous compared to conventional stamping because a) Elimination of female die results in lower tool cost and lower die development time. b) Elimination of sidewall wrinkles during forming process due to external fluid pressure allows more freedom in designing auto body panels c) Ability to form complicated shapes and features in the sheet metal resulting in less forming operations compared to the conventional stamping thereby reduces the manufacturing cost. d) Better surface quality as the outer surface of the sheet is in contact with fluid only thereby reducing the chance of tool marks [Siegert et al 1999b, Maki, 2003].

Successful application of HMD requires careful consideration of all components of HMD system namely: a) Quality of incoming sheet, b) Tool-workpiece interface issue (friction and lubrication), c) Tool design for efficient application of blank holder force and avoid leakage d) Relationship between the internal fluid pressure and blank holder force (loading path), e) Press and Tooling, and d) Dimensions and properties of the HMD part. Details on the methods to test the quality of incoming sheets and tests to select the commercially available lubricants are given in Section 3.2 and 3.3, respectively. In the next section new developments in HMD presses and tools are discussed.

4.2. Press and tooling

4.2.1. HMD presses

HMD presses are designed using the short stroke design concept developed for THF. Figure 21 shows the operation sequence of the 3500 ton HMD press designed by Muller Weingarten at IFU, University of Stuttgart using the short stroke design concept. The top die is moved up and down using the long stroke cylinder that requires large volume of the hydraulic fluid at low pressure. The ram is indexed at the desired bottom position using the mechanical locks. Short stroke cylinders that are mounted in the top ram are activated during HMD to apply the large force required to counteract the force generated on the punch due to the pot pressure. Short stroke cylinders require less volume of fluid at high pressure. Schnupp HMT and Schuler have also introduced HMD presses with short stroke design concept. However, the short stroke cylinder is mounted in the press bed rather than the press ram as shown in Figure 22. The new machine concept allows a) independent control of the blank holder force and the pot pressure, b) reduce the cycle time and cost by decreasing the amount of high pressure hydraulic fluid to be handled by the system.

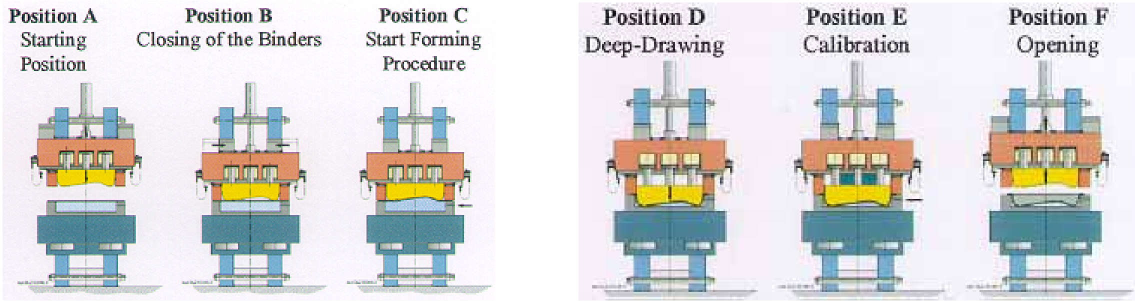


Figure 21 **Schematic of the operation sequence of the HMD press built using short stroke cylinder concept by Muller Weingarten [Beyer 1999]**

a) Schnupp HMT [Schnupp 2003] **b) Thyssen Krupp**

Figure 22 **Schematic of the HMD presses built by Schnupp HMT and Thyssen Krupp hydromechanics**

4.2.2. Tool design

The concept for tool design is similar to regular stamping. The punch and blank holder are specifically designed to the part shape while the pressure pot remains common for all parts. The pressure pot and the punch in HMD tool should be designed to withstand high pot pressure. Also, careful consideration is required for sealing at the pressure pot – sheet interface to avoid leakage of the fluid during HMD. Various advancements in tool design are;

4.2.2.1. <u>Pressure chamber at top to overcome bulging</u>

HMD of parts with tapered sidewalls result in the bulging of the sheet in the gap between the blank holder and the punch as shown in Figure 23 a (Detail A) due to the pot pressure during forming. This bulging could result in excessive thinning and fracture at higher pot pressure. IFU has developed new tooling design with additional sealing at the punch-blank holder interface as shown in Figure 23 b to create a pressure chamber in the top. During HMD the hydraulic fluid from the pot is circulated to the top pressure chamber so that the pressure in the top and bottom chamber is the same to avoid bulging [Siegert 1999b, Aust 2001].

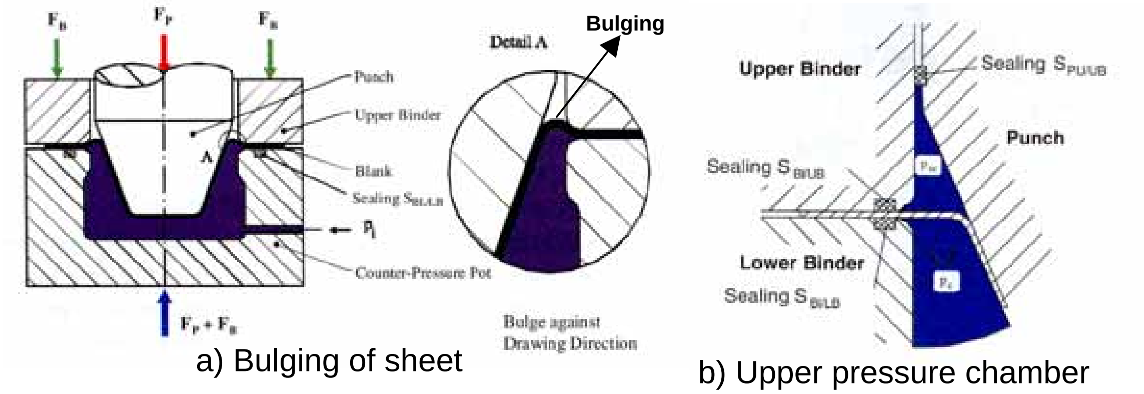


Figure 23 Schematic of the bulging during HMD using punch with tapered wall and upper chamber to compensate for bulging during HMD using punch with tapered wall [Aust 2001]

4.2.2.2. Elastic cushion to form sharp corners

The pot pressure required to completely form the part depends on the smallest corner radius in the part. Thus, parts with sharp corners require press with very high capacity resulting in increase in the investment cost. Schuler developed elastic cushions that are mounted in the pressure pot as shown in Figure 24. Towards the end of the forming process, the sharp corners are formed mechanically by the cushions rather than the pot pressure resulting in reduction of the required press capacity and investment [Stereme et al 2001].

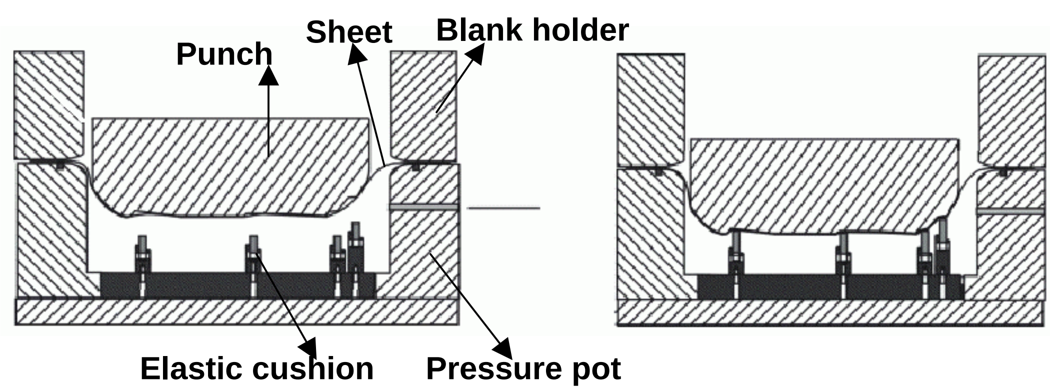
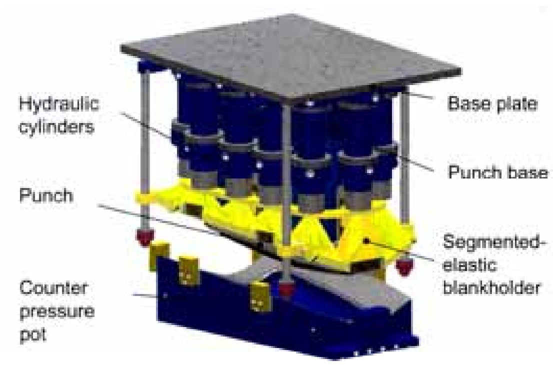


Figure 24 Schematic of the pressure pot with elastic cushions to form sharp corners in HMD [Stremme et al 2001]

4.2.2.3. Elastic blank holder

Design of blank holder plays a dominant role in HMD because the applied blank holder force controls the material flow during drawin and also applies the necessary force to avoid leakage of the pressure medium during forming process. In forming asymmetric parts using conventional blank holders, thickening in the flange is not uniform resulting in gap between the rigid blank holder and sheet at thin locations that causes leakage of the pressurizing media. University of Stuttgart, IFU developed multipoint segmented elastic blank holder similar to stamping as shown in Figure 25. The blank holder force can be adjusted independently in space at each cushion. The thin plate on the blank holder that comes in contact with the sheet deflects elastically depending on the contact sheet thickness thereby; it remains in uniform contact with the sheet. Thus, segmented elastic blank holder applies uniform pressure and avoids leakage of the pressurizing medium compared to conventional rigid blank holders.



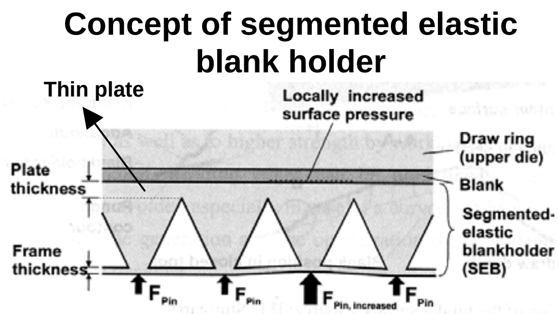
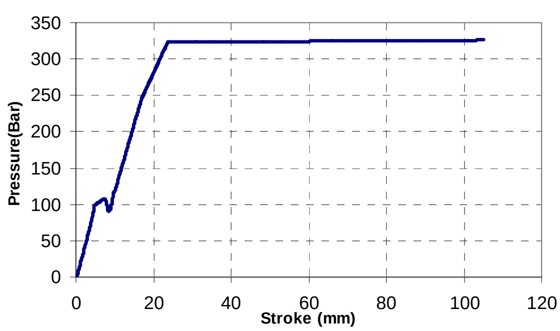


Figure 25 **Schematic of the die assembly with segmented elastic blankholder for HMD [Siegert et al 2003]**

4.3. Process design through FE simulation

At ERC/NSM, FE simulation using PAMSTAMP 2000 coupled with optimization technique and adaptive simulation technique has been used to determine the pot pressure and the blank holder force that results in minimum thinning and no wrinkling in the part and without any leakage of the medium during the process. Figure 26 shows the example optimum loading path obtained for hydroforming of a axisymmetric round cup of diameter 90 mm up to depth of 100 mm (LDR 2.5) in single operation from AKDQ steel. Figure 27 shows thinning distribution in the part for the optimum loading path. Loading path estimated from FE simulations would be used in experiments to verify the FE results [Contri et al 2004].



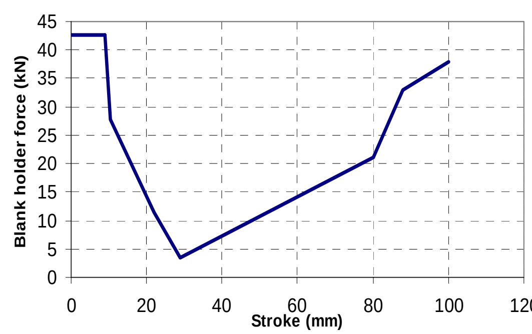


Figure 26 **Loading path obtained using FE simulation (PAMSTAMP 2000) coupled with optimization techniques [Contri et al 2004].**

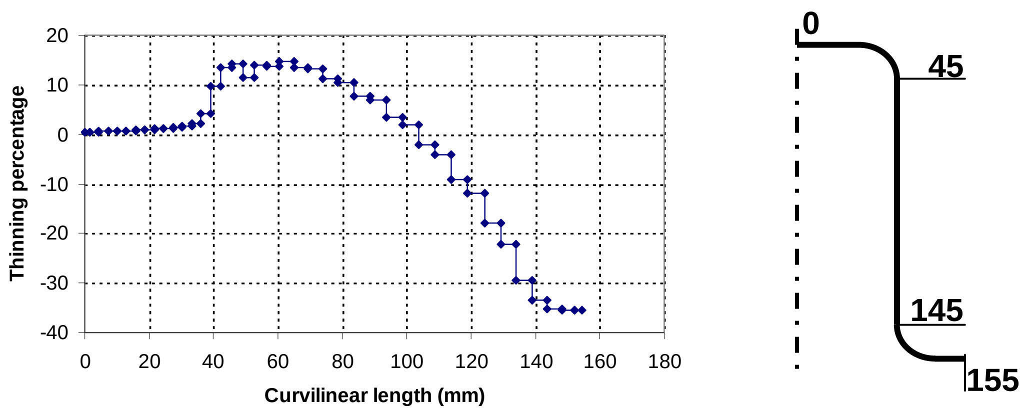


Figure 27 **Predicted thinning distribution in the formed part for the optimum loading path [Contri et al 2004]**

5. HYDROFORMING OF DOUBLE BLANKS (PARALLEL PLATE HYDROFORMING)

5.1. Description

Two flat or preshaped sheets that can be of different thickness, different shape welded or unwelded at the edges constitute the input blank for the parallel plate hydroforming process. The input blank is placed in the tool that has both upper and lower die containing the shape to be formed. The blank is held at the edges and the pressurizing media is introduced between the sheets using a special docking mechanism. The sheets are formed against the top and bottom die to get the desired shape by the fluid pressure. Figure 28 shows the schematic of the parallel plate hydroforming process. Figure 29 shows various automotive parts manufactured by parallel plate hydroforming.

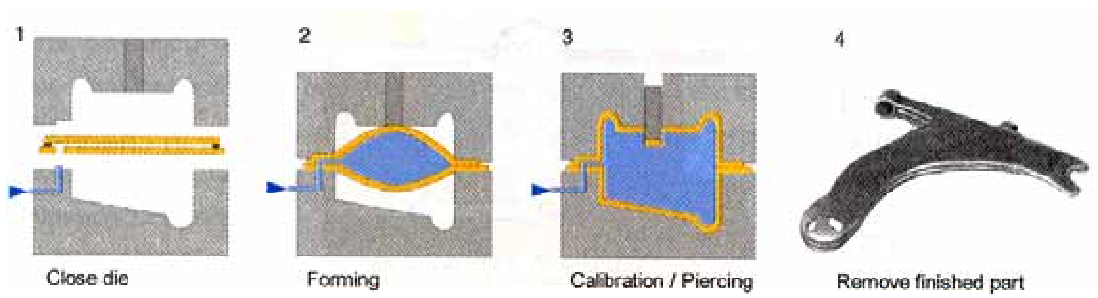


Figure 28 **Schematic of the process sequence in double blank sheet hydroforming [Birkert et al 1999]**

Parallel plate sheet hydroforming is an alternate to THF process in forming complex geometries that has different cross sections over the length of the part with large difference in expansion ratio. In THF the maximum difference in expansion ratio achievable at different cross sections in a part is limited because the input blank is circular tube with a uniform cross section over entire length. However in parallel plate hydroforming, by locally changing the blank width, cross sections with different expansion ratio can be accommodated. Parallel plate hydroforming can also be used an alternative to high pressure sheet hydroforming as in both cases the sheet metal forced against the die by the liquid medium. However, in parallel plate sheet hydroforming two parts can be produced in one production cycle thereby the productivity is increased. Parallel plate hydroforming allows top die and bottom die of different shapes. Also, it allows forming two different materials and two different thicknesses in one production cycle. Parallel plate sheet hydroforming may be economical compared to conventional stamping for production of relative small batch size. [Habil et al 2003, Schwarz et al 2003, Pasino et al 2003, Schroeder 2003, Rosen et al 2001].

Cross member below wind shield
[Habil et al 2003]

Engine support
Cross member
[Habil et al 2003]

B - Pillar
[Schroeder 2003]

Figure 29 Sample parts in automobile produced by double blank sheet hydroforming

Various factors/process parameters that influence the design of parallel plate hydroforming process is similar to the high pressure sheet hydroforming process. Therefore only the docking mechanism, which is new for parallel sheet hydroforming to introduce the pressurizing fluid between the sheet, is discussed.

5.2. Docking systems

Figure 30 and Figure 31 shows the various patented docking systems being used in industry to introduce the hydraulic medium between the sheets. The docking system by Krupp-Drauz and Schuler are used for process in which the sheets are welded and only stretched during the forming process. In both cases the fluid is sealed mechanically by deformation of the sheet at the location of docking and by the welding at other locations to avoid any leakage. The docking system developed by University of Dortmund can be used when the sheets are not welded and the sheet metal can be allowed to drawin. The sealing is provided by the clamping force of the dies [Krei 1999].

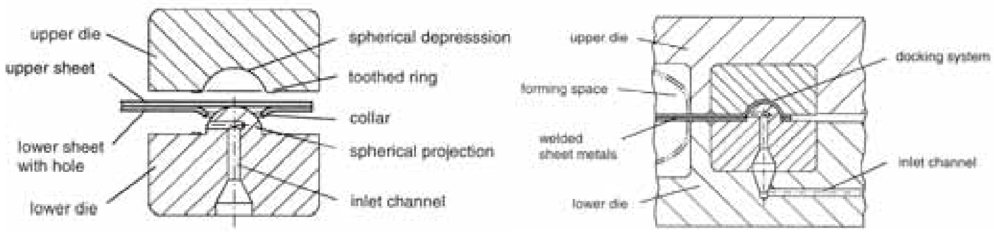
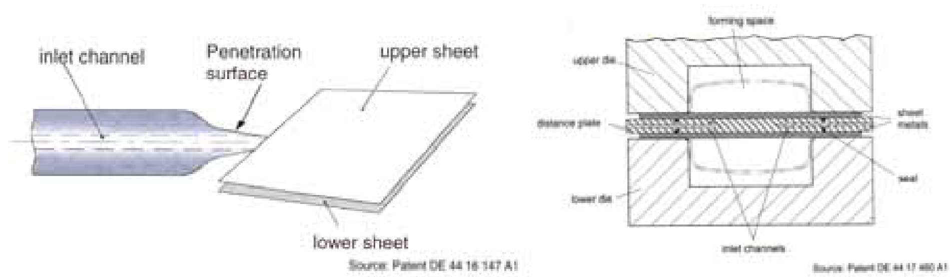


Figure 30 Schematic of the docking system from Krupp – Hoesch [Krei 1999]



a) Schuler docking system

b) University of Dortmund
docking system

Figure 31 Schematic of the docking system by Schuler and University of Dortmund [Krei 1999]

6. WARM TUBE AND SHEET HYDROFORMING

Aluminum alloys and magnesium alloys offer great potential in reducing weight in body structures and body panels due their its low density and high strength to weight ratio. However their applications are restricted due to their low formability at room temperature compared to mild steels. Aluminum and Magnesium alloys show increased formability when formed at elevated temperature of 200^{o}C-350^{o}C. Development of warm tube hydroforming and sheet hydroforming are at early stage of research at following institutions around the world

- ERC/NSM – The Ohio State University, U.S.A – Warm hydroforming of Mg alloy and Al alloy tube and warm forming of Mg alloy and Al alloy sheet.
- LFT, University of Erlangen – Nuremberg in cooperation with Schuler Hydroforming and Audi, Germany - Warm hydroforming of Mg and Al alloy tube and sheet [Geiger et al 2003].
- University of Darmstadt, Germany – Warm hydromechanical deep drawing and Warm tube hydroforming of Al alloy sheet and tubes [Groche et al 2002].
- IFU, University of Stuttgart – Warm high pressure sheet hydroforming of Mg and Al alloy sheet [Jager 2003].
- Fraunhofer Institute, Chemnitz – Warm hydroforming of sheet and tube

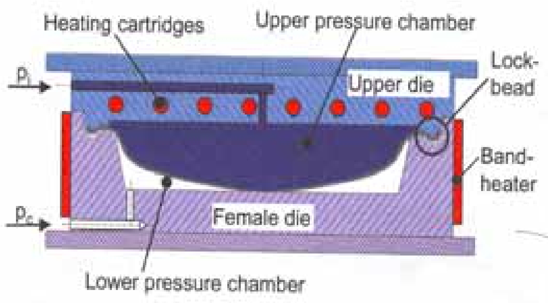


Figure 32 Schematic of warm high pressure sheet hydroforming tooling at IFU [Jager 2003]

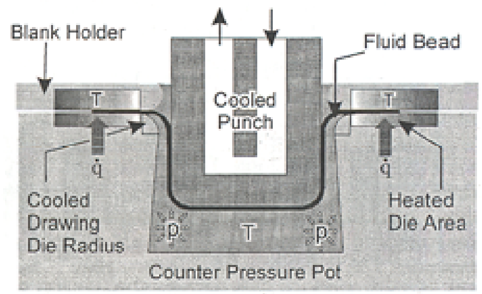


Figure 33 Schematic of warm hydromechanical deep drawing tooling at University of Darmstadt [Groche et al 2002]

In warm high pressure sheet hydroforming, sheet, die and the fluid are heated to the desired temperature. Figure 32 shows the schematic of the experimental heated tooling used for warm high pressure sheet hydroforming at IFU [Jager 2003]. In warm hydromechanical deep drawing, the sheet is initially heated and the flange portion of the die and the blank holder is heated to the required temperature as shown in Figure 33. The punch is cooled while the pressurizing fluid temperature is kept slightly higher than the room temperature. The lower temperature of the punch and the pressurizing medium cools the sheet adjacent to the punch thereby the strength of the sheet is increased to carry the load during drawing and postpone failure due to the excessive thinning. As a result LDR of 3.0 was obtained for drawing aluminum alloy round cup at forming temperature of 250^{o}C [Groche et al 2002]. In tube and sheet hydroforming at elevated temperatures in LFT, University of Erlangen-Nuremberg, sample automotive parts from Aluminum alloy A6061, A5182 sheets and Al-Mg alloy tubes were hydroformed at temperature of 220^{o}C [Geiger et al 2003].

7. Summary

Research and investigation of hydroforming of sheet and tube in industry and universities during the last decade have led to a) Improvement in accurate determination of material properties using tests that emulate the reality in production, b) Development of better test methods to screen the lubricants, c) Advances in press design that resulted in less expensive and compact presses with reduced cycle time. d) Continuous improvement in tool design to increase the scope of applications of hydroforming and e) Development of virtual manufacturing tool through FE simulations to design the process and estimate the optimum process parameters. These developments lead to reduced process development time and enable sheet and tube hydroforming processes to compete with traditional stamping. Currently warm hydroforming of tube and sheet is being investigated to increase the application of lightweight Mg and Al alloys that are less formable at room temperature.

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