FE - Simulation of the Thermal Hydroforming Process

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Abstract:

The metal working industry is always searching for new production technologies to produce more complex parts associated with cost reductions. This paper introduces such a new forming technology. Through global or local heating of aluminium alloy the formability of the metal is enhanced. This forming process has some further advantages. It allows to produce difficult and complex part geometries with only a few steps. Thereby, the production of the components will be more economic, the cycle time will be decreased and the part cost will be reduced. In the course of increasing environmental awareness energy saving becomes more and more relevant through the reduction of the cycle time minimizing the energy consumption. The paper indicates the immense potential of thermal metal forming. It is shown that the complexity of the process and the range of parameters found during thermal metal forming is considerable and is a fertile area for further investigation. Due to the complex connections of the process influence parameters the non-linear finite elements (LS-DYNA) offers the condition to investigate the process. Therefore a FEA- Model has to be developed in order to reach a accuracy known from the hydroforming at room temperature

Keywords:
Hydroforming, Thermal Hydroforming, FE- Simulation, Experimental Setup, Experimental Results, Friction Investigation

1 Introduction

In the history of metal forming technology the automotive industry has proven that they have been the driving force in the last century. Thereby the continuous development of manufacturing processes was the basis for continuous improvement of the products. Simultaneously, new procedures were developed which facilitated more complex component geometries and guaranteed an increased efficiency and availability of the parts.
In order to be able to realize the demands, new deformation processes and manufacturing machines were developed which corresponded to the requirements. Over the years the forming procedures which have arisen can be subdivided. One possibility for the classification is the subdivision in procedures of sheet metal forming or in procedures of massive forming. The most frequently used, and also standardized possibility of the subdivision, is defined in the DIN 8582. In this case the procedures are subdivided according to the mainly effective stresses (Figure 1).

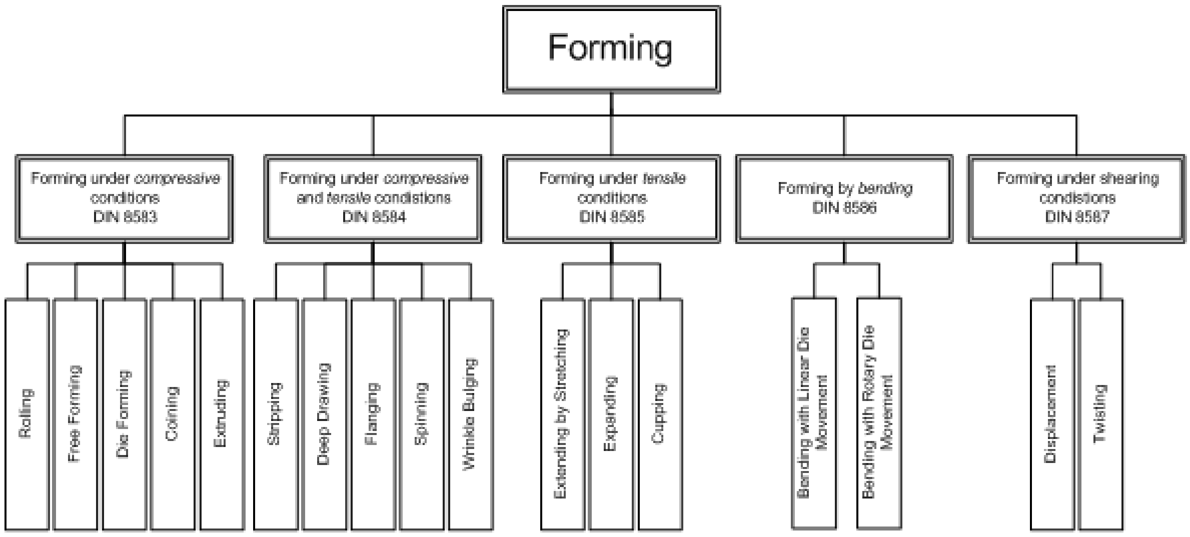

Figure 1: Subdivision of manufacturing processes according to DIN 8582

Due to the fact that resources are becoming scarcer and as a consequence of increasing environmental pollution, lightweight construction is of specific importance in product design. As a result of these requirements, a new forming process could be established among the classical forming processes - the hydroforming of tubes (Birkert et.al 2002). Because of the increasing complexity of components further forming steps are necessary before the actual hydroforming process is commenced. Normally, these are the tube bending and/or the preforming. The following pages are showing the forming-steps of a complete manufacturing chain of the hydroforming process.

2 The Process-Chain of the Hydroforming

Through the increasing complexity of the components further forming-steps have to be prefixed to the hydroforming process. These are in most cases the tube bending and/or the pre-forming (Figure 2). Subsequently the individual forming steps of a complete manufacturing chain of the hydroforming process are described, beginning with the tube bending.

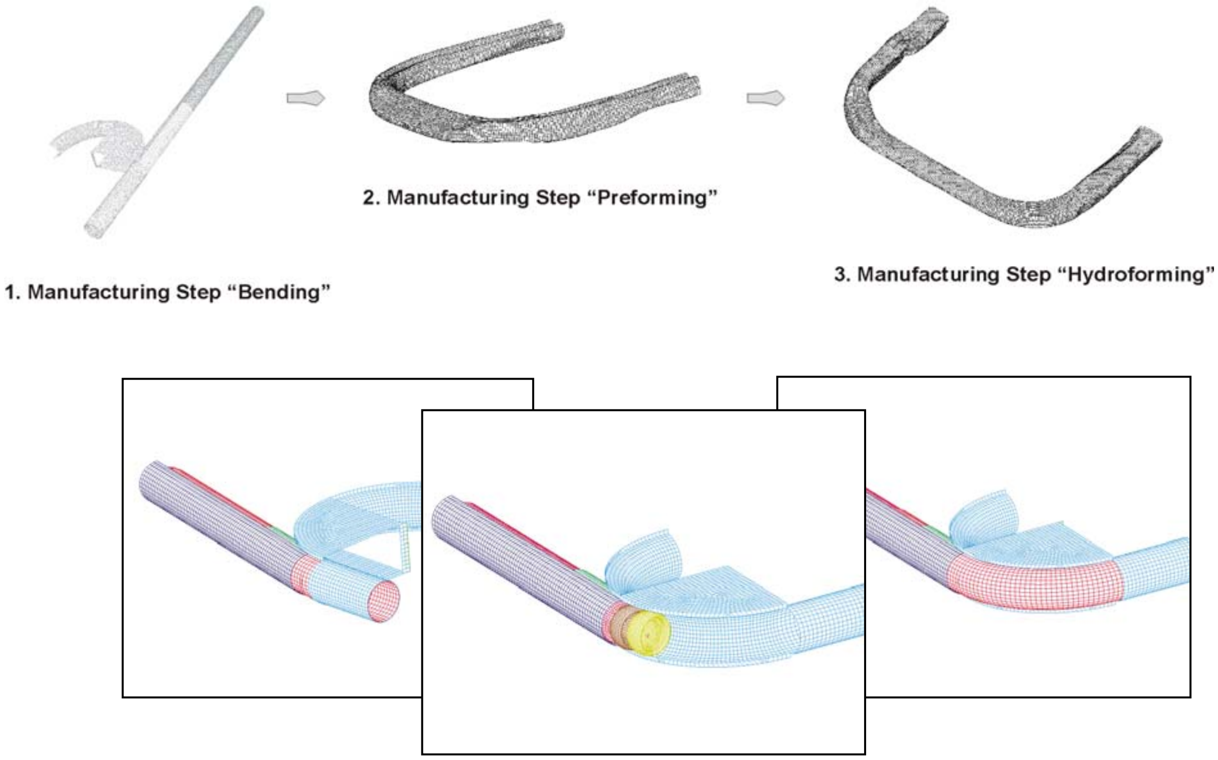

Figure 2: Process-Chain of the hydroforming showing bending, preforming and hydroforming

2.1 The Bending

Since 1999, over 75% of all hydroformed components in the automotive industry had curved component axis. Two different procedures are state of the art of bending processes as pre-forming for the hydroforming process: the conventional rotary draw bending and the die bending. The decision of which procedure will be used depends on economical aspects, mechanical qualities of the material, tube dimension and bending radius.

The increased number of applications of the hydroforming process influenced the desire for new, better and more efficient bending-procedures. Thereby different requirements are demanded. The automotive suppliers for exhaust and cooling systems aspire to smaller bend ratios (D/R). The car manufacturers intend to realize more flexible bend procedures including different bending radii in a short time frame. Two procedures are very promising concerning these requirements: the rotary draw bending with axial load and the free-form-bending.

2.2 The Preforming

The continuously complex component geometries make it frequently more necessary to preform after the bending and before the actual hydroforming process. This process has to be defined considering different economic aspects. Not only the increasing tool and manufacturing costs have to be considered but also the improvement of the component quality, the increase of the manufacturing safety and the reduction of the tool wear. Whether a preforming process is necessary, in order to guarantee a safe manufacturing of the component, mainly depends on the cross section distribution of the initial component in relation to the final geometry. In general it is distinguished in two main groups which make the preforming necessary:

1. The cross sections of the component geometry allow a secure forming of the initial tube, however, there are fields with high local expansion. In this case the preforming is used to reach a pre-distribution of the tube material. During the preforming a material accumulation is created by purposeful modification of the cross sections at places of local expansion or the shape of the cross sections is adjusted as near as possible to the final contour. Thereby the serial production becomes safe in process and the quality of the final product is improved.
2. The diameter of the initial tube is larger than the opening of the gravure in the closing-plane. This would lead to a so called „pinch" during the closing of the tools. Thus a flat pressing is necessary.

In some cases the flat pressing can be done also in the hydroforming dies. For this purpose stamp units have to be integrated into the hydroforming dies. This possibility has to be examined exactly. The stability of the entire tool is influenced by the integration of a stamp unit, and the fatigue resistance can decrease.

To reach the optimal shape of the component after the preforming, different concepts are used. In order to achieve an optimal material accumulation, tools with geometries between the initial and final contour are designed. The tools are often near the final component contour but they can also contain slide units which will press the material in a defined position. At problems during the closing of the hydroforming dies often very simple preforming tools are designed which flatten the initial tube at some places or over the complete length. A third variant is the combination of flattening and material accumulation. This variant is necessary if a high local expansion exists in areas where the tube diameter is larger than the opening of the gravure.

2.3 The Hydroforming

Today, hydroforming processes tend to belong to active fluid medium procedures for the forming of tubes and profiles but also procedures for the forming of welded sheets by means of internal pressure (Fritz et.la 2001). Up to now the main focus of the application lies in the hydroforming of tubes.

First industrial applications of this procedure e.g. for the production of tube bifurcation elements were presented in publications in the 1960s. The use of the hydroforming process increased very quickly as the automotive industry became attentive onto this procedure in the 1980s. They recognized the possible use for the lightweight construction.

The principle of the process for the hydroforming of tubes follows from Figure 3. A tube is loaded into a die which inside geometry corresponds to the exterior geometry of the part to be manufactured. The normally longitudinal divided tools are closed by means of the ram movement of a hydraulic press. The tube end faces are loaded by two in tube longitudinal direction moveable stamps. Each of the forces effecting the tube end faces have to be sufficient to seal the tube interior. Therefore forces are necessary which at least correspond to the force calculated by tube cross section surface and internal pressure. The axial loads can be increased over this value if the forming-task requires this. Compressive stresses are produced inside the tube whereby the formability can be increased.

In the further progression of the process the internal pressure is increased until surface contact is made between the expanding tube wall and the inside surface of the dies. After the complete surface contact has occurred the internal pressure is lowered to the environment pressure, the axial stamps are relieved and the hydraulic press opens for the unloading of the completed component (Birkert et al 2002).

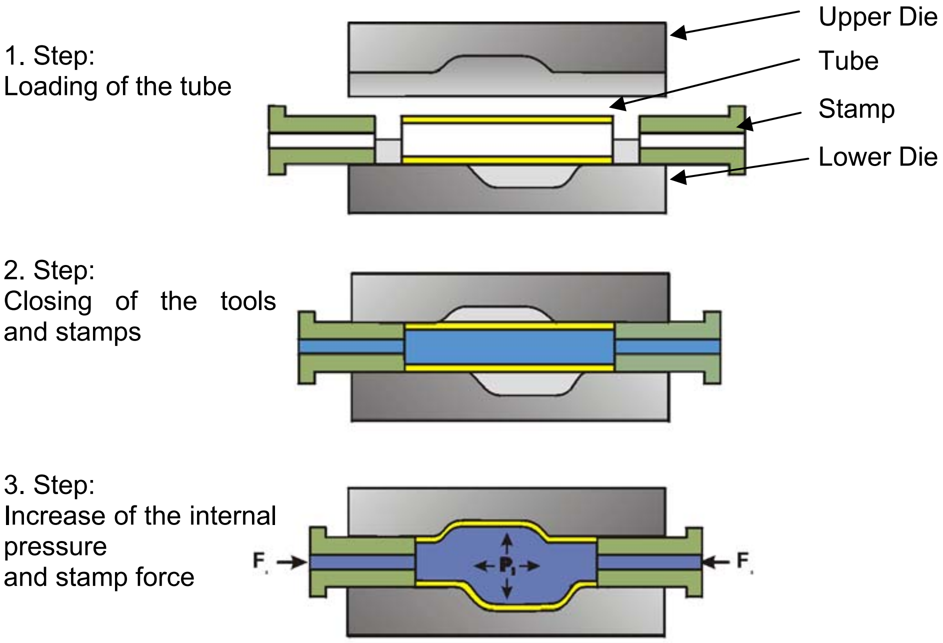

Figure 3: Operation sequence of the hydroforming process of a tube

The increasing number of applications of the hydroforming process shows the potential of this production method. The most important arguments are the flexibility in the cross section design, the

integration of secondary form elements and the high stiffness of the final part in comparison with sheet metal constructions. Particularly in lightweight construction the hydroforming process is used. In this case aluminium is very important (Wieser et al 2002). During the effort to use the maximally possible expansion of the aluminium (approx. 20 %) the boundaries of the formability are very often reached. To this end, new forming methods are being developed. One such methods is “Thermal Hydroforming” – essentially a hydroforming process that uses global or local heating of aluminium sheets or tubes to enhance the formability.
Research work carried out since about the 1920s on the improved formability of materials with increased temperature has lead to the development of superplastic forming today. Superplastic forming is mainly used for limit-lot productions in the aircraft and spacecraft industry as it requires high temperatures (0.5 x melting point), low strain-rates (10^{-5} - 10^{-1} 1/s) and the use of specific materials (Grain size < 10µm). Thermal hydroforming differs from superplastic forming as it can be used for materials which do not posses superplasticity. These are mainly aluminium alloys from the groups 5xxx (AlMgSi) and 6xxx (AlMg), which have the ability to be formed at lower temperatures (<450°C) and higher strain-rates. Therefore thermal hydroforming is suitable for large scale series production.
Since thermal hydroforming is relatively a new technology very few publications can be found on it. Preliminary experiments were performed in order to obtain data for formulating the FEA model. The produced components were measured (strains and wall-thicknesses) and with the findings a FEA-Model was developed. This FEA- Model is important in order to be able to give statements about the accuracy of the calculation and to carry out further investigations theoretically. From hydroforming at room temperature it is known that the FEA- simulation is an important and helpful tool during the feasibility investigation of components (Haas et al 2001). Similarly, FEA- simulation can be used for thermal hydroforming to optimise the process before the tool production.

3 The Experimental Tool

A circular metal with a diameter of 200mm and a wall thickness of 4mm was chosen as the initial geometry. Out of this a cup is formed which has a diameter of 150 mm. The principle concept is shown in Figure 4.

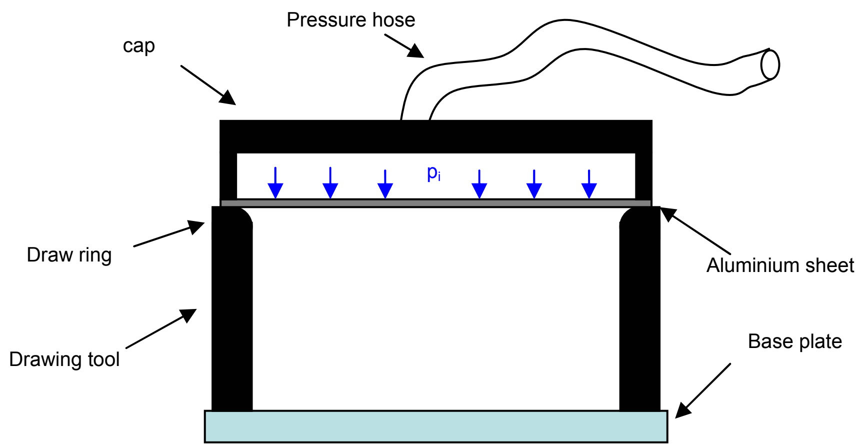

Figure 4: The concept of the experimental tool for the warm metal forming process

Through the increase of the pressure the aluminium sheet begins to deform. Since the flow-in of the sheet is prevented by the cap, the deformation results in a strain of the material. The height of the drawing tool determines the maximum strain. The optimal forming ratios can be produced by the reduction or enlargement of the drawing ring. The complete construction is warmed up in a curing furnace. During the complete experiment the tools and the aluminium sheet are in this furnace. The temperature is controlled with the available furnace control. For the verification of the temperature several measurement points are within the tool, at which the temperature is controlled continuously.
As temperature sensors coated-thermo-elements of the class K were selected. The usable temperature range of these sensors lies between -100°C to 1000°C. The coat consists out of high-temperature-strength Inconel. The measurement connection consisted of a compound of NiCr-Ni and had a reaction time of 0.9ms (T90).

4 Experimental Result

The best results could be achieved at an internal pressure of 40bar and a forming depth of 55mm. In this case the radii formed were good, the forming depth was reached and the cup wall fits to the tool wall (Figure 5)

Figure 5: Experimental Result of a warm formed sheet metal aluminium alloy

The actual forming time of these experiments was 1 minute and 30 seconds. The component could be unloaded only very difficultly from the tool after the forming process only with difficulty, which leads to the assumption that a high friction arose during the forming. The wall thickness distribution of the finished component is shown in Figure 6.

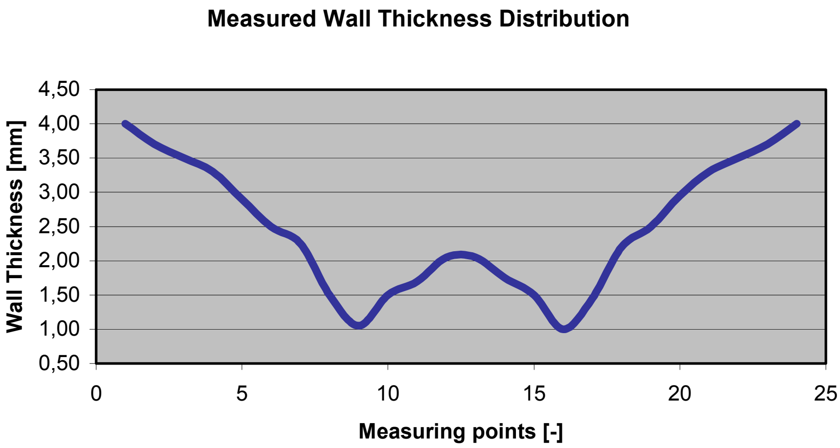

Figure 6: Diagram showing the absolute values of the measured wall thickness distribution of a formed part

In the fixed fields (Measurement point 1 and 24) no thinning of the wall thickness occurs. In connection with the fact that the sheet metal diameter is unchanged after the forming it can be proved that no material flows in from the border. This is important in order to guarantee that the complete deformation of the component arises from the strain of the material. From outside to inside the wall-thickness reduces up to a minimum at the measurement points 9 and 16. Afterwards the wall-thickness increases again to more than 2 mm. This is to be explained, that during the forming the sheet metal gets in the first contact with the tool ground in the centre of the sheet. A further thinning of the wall thickness in this area is prevented by the high friction. Therefore no material can flow from this area to form the radii. Therefore a minimum of the wall-thickness arises at the vertex of the radius.

5 FEA- Simulation of the Thermal Hydroforming

Deformation processes are time-dependent, that means at every point of time another stress and deformation state occurs. For the simulation of the thermal hydroforming process the explicit FEA-Calculation program LS-DYNA from Livermore Software Technology Corporation (LSTC) was used. LS-DYNA is a FEA- Program for high-grade non-linear, dynamic problems. The thermal hydroforming experiment of a cup described previously was simulated with the aid of axes-symmetry. The necessary material parameters (flow-curve) were determined from crush tests. Other necessary material attributes are the density and the Young's modulus. On of the unknown parameters during the simulation and during the experiments was friction. In order to account for the friction the Coulomb - or Kinematic model can be used. Thus for the simulation of the thermal hydroforming the Coulomb friction model of LS-DYNA was used:
The tangential-contact-stress τ is calculated with the material parameter μ (friction coefficient) and the contact pressure σ_n, which is the strength component acting orthographically to the friction surface. The variable μ is largely unknown and was investigated with the aid of the FEA model. Using the FEA simulation model the best analogy with the reality is shown in Figure 7. The maximum difference between simulation and experiment of the wall thickness was in this case 0.15 mm. However, on average the difference is less than 0.1mm.

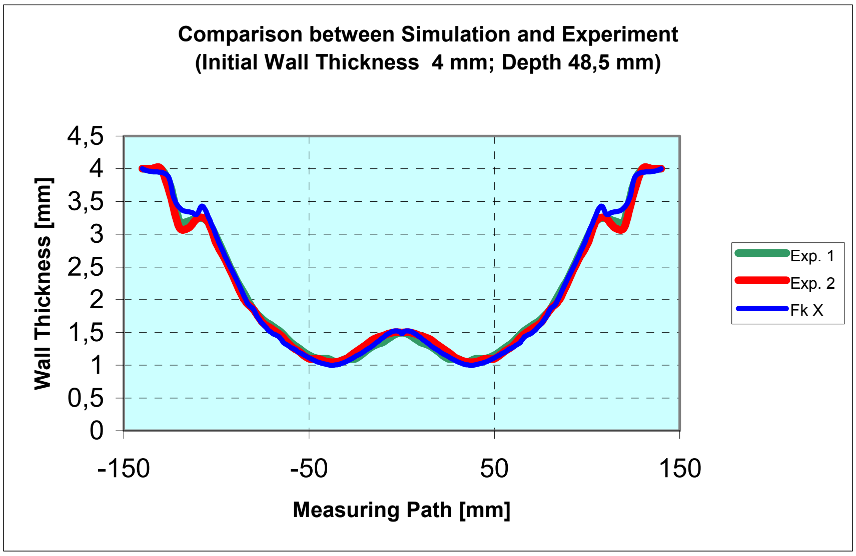

Figure 7: Comparison between the FEA simulation and the experimental wall thickness

Further experiments with different sheet thicknesses and aluminium alloys were carried out. These tests confirmed the close correlation between the FEA simulation model the experimental results.
From these results it can be concluded that:
- The friction is greater for thermal hydroforming than for hydroforming at room temperature
- The thermal hydroforming process is computable with the created FEA-Model and thus feasibility investigations can be carried out.

6 Summary

From the preliminary experiments performed the potential of the thermal hydroforming process was established. In the case of aluminum strains of 130 % were able to be reached during the experiments, which corresponds to four- to five times higher strains than that present in AlMg alloy at room temperature. The simulation model created showed very close correlation to the experimental results. Thus it enables the feasibility study of new components. The necessary material parameters can be obtained by the crush test or the cup testing method.
Further investigations are being performed to ascertain techniques for reducing friction during thermal hydroforming. This is important in order to improve the flow of material and to obtain a homogeneous wall-thickness distribution. In order to improve the efficiency of the thermal hydroforming it is necessary to work on possibilities for the reduction of the cycle time.

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