Investigation of the Process Chain Bending-Electromagnetic compression-Hydroforming on the Basis of an Industrial Demonstrator Part*

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Abstract

The increasing significance of lightweight construction concepts requires innovative and adapted production technologies and process chains for the manufacturing of complex parts made of typical lightweight materials. The feasibility and potential of such a process chain consisting of the steps Bending - Electromagnetic compression (EMC) – Hydroforming is shown in the present paper on the basis of a demonstrator part similar to a structural component from the automotive industry. Here, special focus is put on the requirements on the production steps and the workpiece properties. Furthermore, the development and testing of EMC-equipment that is optimally adapted to the special forming task is described.

Keywords:

Process chain, Electromagnetic forming, Hydroforming, Extension of forming limits

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1 Introduction

Given the general trend of a growing sense of responsibility for environmental protection, research and development in the automotive industry show an increasing interest in reducing fuel consumption and, thus, diminishing exhaust emissions. An important approach for the realization of this aim is the use of lightweight construction concepts including, among other techniques, the application of typical lightweight materials, as e.g. aluminum alloys and an optimized component design, which usually involves a more complex shape of the part (integral construction concept). This requires innovative and adapted production technologies and process chains suitable for the manufacturing of these parts. An example of such a sequence of processes, consisting of the steps Bending - Electromagnetic compression (EMC) – Hydroforming (compare Figure 1), is investigated within a European project (G3RD-CT-2002-00798).

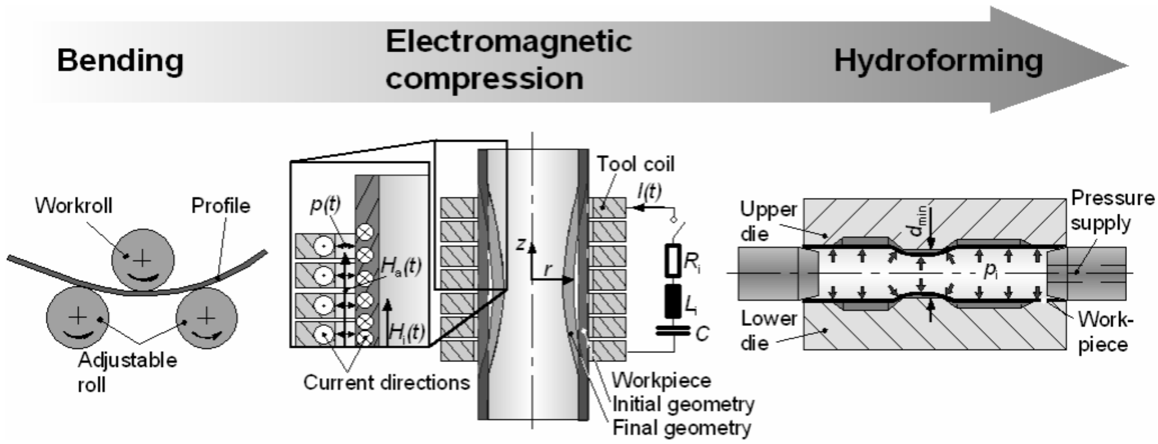

***Figure 1**: Investigated process chain and industrial demonstrator*

The standard tube hydroforming technology offers comprehensive possibilities for the production of complex component shapes [1]-[3], which can be further extended by using appropriately contoured preforms. In the conventional hydroforming process the forming limits are set, on the one hand, by the initial tube diameter, which is usually determined by the smallest local circumference of the finished workpiece geometry, and, on the other hand, by the maximum tangential strain, restricting the maximum achievable circumference of the produced part. The use of contoured semi-finished parts offers the possibility to apply tubes of longer initial diameters, which are locally compressed in those areas where the circumference of the finished part is relatively small so that a wider spectrum of circumferences can be realized within one and the same part.

One possible technology for the production of such contoured preforms is the electromagnetic compression, a high speed forming process using the energy density of pulsed magnetic fields to apply a radial pressure to tubular workpieces with high electrical conductivity, causing a commonly, but not necessarily, symmetric reduction of the diameter. In practical applications a hydroforming process is frequently preceded by a bending step. One important advantage of EMC in comparison to alternative preforming operations, as e.g. spinning, is that it is applicable not only to straight, but even to curved profiles.

2 Influences on the feasibility of the process chain

In a sequence of processes the product of each manufacturing step is the semi-finished material of the subsequent steps. Therefore, each production step defines the requirements on the results of the previous processes. With regard to the investigated forming strategy, this means that especially the two interfaces between the subsequent manufacturing steps are significant for feasibility investigations. From the point of view of EMC, on the one hand, there are requirements made on the result of the workpiece properties after the bending operation and, on the other hand, the achievable workpiece characteristics after the EMC have to fulfill the demands of the hydroforming process.

2.1 Feasibility of the combined electromagnetic compression and hydroforming process

The general feasibility of the combined EMC and hydroforming process could be proved on the basis of different laboratory geometries in [4]. Thereby, the most important requirements of the hydroforming process on the previous steps have been identified as

- sufficient remaining forming capability allowing the calibration of the previously compressed workpiece areas without material failure in the form of cracking, and
- sufficient geometric accuracy of the cross section geometry in order to avoid material failure in the form of wrinkling.

The remaining forming capability of the material strongly depends on the heat treatment and it is reduced by all previous forming operations due to strain hardening effects. According to [5], the strain hardening caused by the electromagnetic compression merely depends on the tangential strain and can not be influenced by an adaptation of the applied pressure pulse. Thus, the tangential strain realized in the preforming operation limits the potential for the deformation and calibration in the subsequent hydroforming step.

Regarding the geometric accuracy of the cross section geometry, it is shown in [5] that the roundness of a tube which has been electromagnetically compressed without a form defining tool (mandrel) decreases with an increasing tangential strain, but it also depends on the course of the applied magnetic pressure. In order to achieve a defined radial deformation, it is possible to apply either a pressure pulse with a longer pressure rise time and a lower pressure maximum or a pressure pulse with a shorter rise time and a higher pressure maximum, whereby the latter leads to a higher forming velocity, related to a better roundness of the specimen. In [4], it could be shown that even a remarkable wrinkling effect can be completely reversed during the subsequent hydroforming process if the shape of the wrinkles is smooth.

In **Figure 2**, an electromagnetically compressed preform and the according workpiece, calibrated by means of hydroforming, is presented. Starting from an aluminum tube (Ø40 x 2 mm), here, a mean tangential strain of approx. 22% was realized in the compression zone while the tangential strain in the expansion area was approx. 8%, a value that was identified to be critical during hydraulic burst tests. With respect to the strong strain hardening effect caused by the EMC, the special potential of this technology to produce preforms of non-rotationally symmetric cross section geometry was exploited in order to reduce the necessary tangential strain during the hydroforming step in this area. On the basis of this example the potential of the combined electromagnetic compression and hydroforming process could be shown for straight tubes.

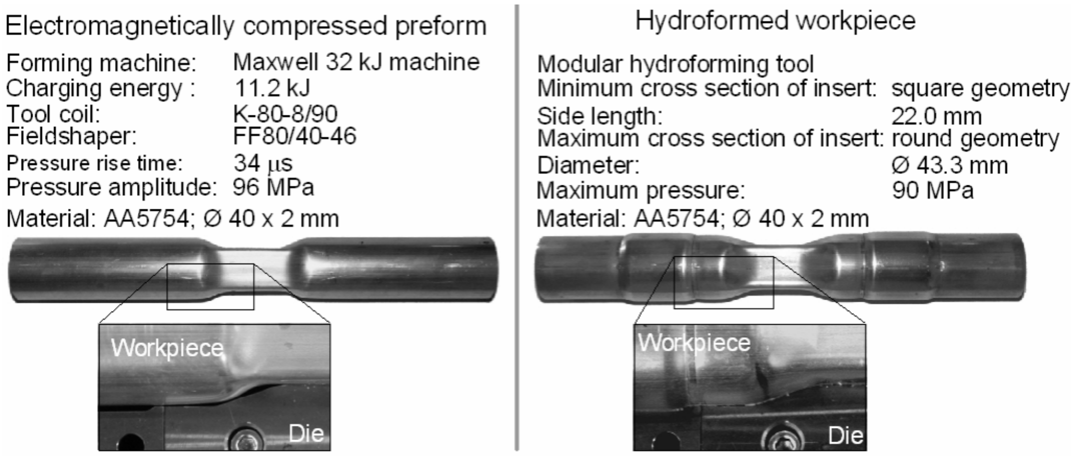

***Figure 2**: Hydroforming tests of workpiece with square cross section geometry [4]*

2.2 Feasibility of the combined bending and electromagnetic compression process

Regarding the feasibility of the combined bending and electromagnetic compression process, investigations using laboratory equipment have shown that, in principle, it is possible to perform an EMC process on curved specimens. Thereby, the influences of the process parameters and the material properties on the roundness of the specimen in the compression area remain the same as in case of straight profiles. Thus, according to [4], the most important requirements on the workpiece characteristics are a good roundness of the tube as well as a homogeneous distribution of the wall thickness and the material properties along the circumference of the tube after the bending process.

Comparative measurements of bent profiles before and after an EMC process have proved a marginal influence of the electromagnetic compression on the contour accuracy. Thereby, a slight tendency to increase the bending radius locally in the compressed area can be detected, while the contour next to the compression area seems to remain unaffected. Nevertheless, depending on the size of the part and the position of the compression zone also, a slight deviation can be problematic with respect to the subsequent hydroforming process so that for processes with high demands on the preform contour an additional adjustment might be necessary.

In order to analyze the reason of this effect, the influence of a non-uniform gap width distribution between tool coil and workpiece was investigated. These tests have shown that, despite of the effect of the gap width on the acting magnetic pressure (compare [10]), even for extremely inhomogeneous gap widths no significant influence on the contour of the workpiece could be detected. This means that a compression process on a curved profile with a curving radius in the dimension of 1000 mm or more can even be performed using a straight tool coil without a remarkable deterioration of the forming result as long as the geometric conditions, as e.g. workpiece diameter, bending radius, and clearance of the compression coil, allow a positioning of the specimen inside the tool coil. On the other hand, a significant increase of the gap width between tool coil and workpiece in order to extend these possibilities causes an increase of the common inductance of tool coil and workpiece. This influences the course of the discharging current to that effect that amplitude as well as frequency are reduced. Thus, the roundness in the compression zone and the efficiency of the process are declined.

Another possible explanation for the influence of the electromagnetic compression on the contour might be given by residual stresses caused by the preceding bending operation that interfere with the additional stresses caused by EMC. A promising solution to reduce or even avoid this could be the substitution of the bending process by curved profile extrusion, an innovative production technique developed at the Institute of Forming Technology and Lightweight Construction (IUL), University of Dortmund (compare [EP 1 169 146 B1]).

3 Production of an industrial demonstrator part using the process chain Bending-EM-compression-Hydroforming

Based on the previously described fundamental investigations, the feasibility of the complete process chain is analyzed, considering an industrial demonstrator part as an example. The chosen geometry is similar to a structural component from the automotive industry, more precisely to a roof rail, and DaimlerChrysler provides the according hydroforming tool. The part could already be realized successfully for different steel materials by using the process chain Spinning – Bending – Hydroforming (compare [6]) and will now be produced in aluminum in order to reduce weight. Therefore, extruded tube material with a diameter of 76.2 mm and a wall thickness of 2.5 mm made of AA5754 and AA6008 has been used. In Figure 3, the final workpiece as well as the target geometries after each production step, which proved to be suitable for the production of the steel parts, are shown.

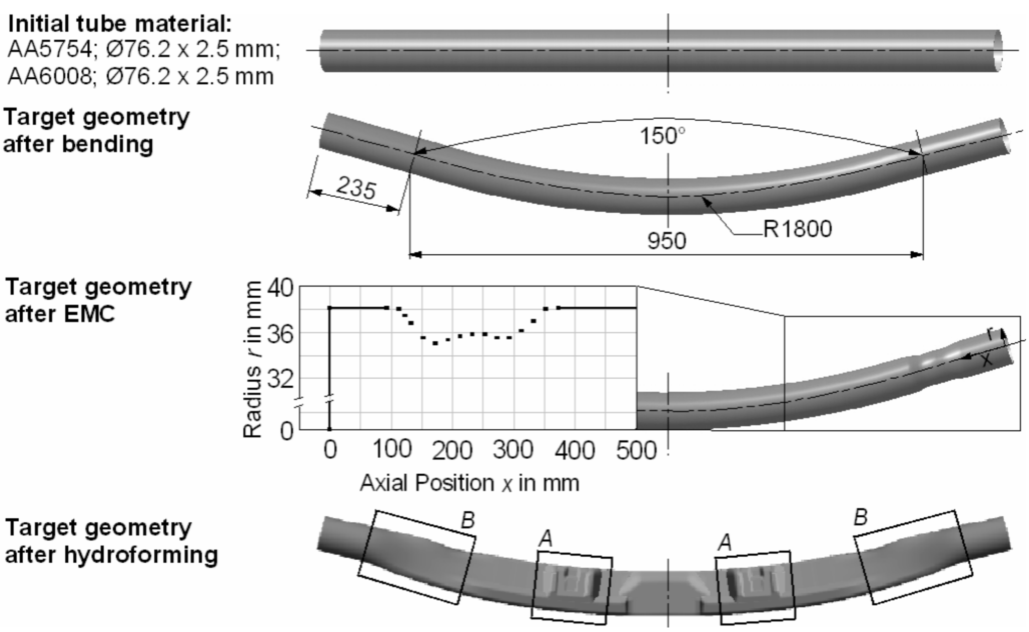

***Figure 3**: Industrial demonstrator part*

The target contour after bending was developed on the basis of the final workpiece geometry and the geometric conditions of the used hydroforming tool. The investigations have shown that, with regard to the subsequent hydroforming process, there are extremely high demands on the contour accuracy in order to avoid any extrusion of the workpiece material into the parting plane during the closing of the hydroforming tool.

The target contour after the electromagnetic compression step was determined on the basis of the local circumferences of the finished part. These have been measured and the corresponding diameters were adapted to the bending line. The maximum strain is located in area *A* where the sunshades are mounted to the roof rail. With regard to the strain at failure of the applied aluminum alloys, an initial tube diameter of at least 76.2 mm and an initial circumference of 239.4 mm respectively is required. In contrast, the local circumferences in the area *B* are shorter than 239.4 mm so that a compression becomes necessary. The length of this compression zone is approx. 250 mm and the distribution of the desired diameters along the bended axis of the tube (as sketched in Figure 3) should not cause any significant tangential strain in the compression area during the subsequent hydroforming step.

3.1 Design of EMF-equipment

Although there are a lot of thinkable preform contours oriented by the circumferences of the final workpiece cross sections, the first proved feasibility should be shown using EMC without any mandrel, the easiest process variant. This results in the already mentioned axis-symmetric preform and requires a tool coil, which has to be optimally adapted in order to realize a suitable pressure distribution. In close cooperation of the IUL and the Poynting, a directly acting compression coil was developed to be used with the 32 kJ Maxwell Magneform machine at the IUL (capacitance $C \approx 960$ µF; inner resistance $R_i \approx 3$ mΩ; inner inductance $L_i \approx 52$ nH; short circuit frequency $f_{SC} \approx 23$ kHz).

To allow an easy handling of the partly curved semi-finished part after bending, a usable diameter of 80 mm has been defined, keeping in mind that the inductance has to be as low as possible to realize a short pressure rise time. As described more detailed in [8], for every forming task and forming machine an optimum number of turns exists to achieve an efficient transfer of charging energy into the acting pressure. In this case the optimum requires 8-10 turns. Typically, the construction is on the safer side if one or two turns more than the optimum are used, but in this case the number of turns should be as low as possible within the efficiently reasonable solution due to the mentioned reasons of a low inductance. This small number of turns and the length of the forming zone of approx. 250 mm lead to the idea of a double-winding coil (see Figure 4): This coil consists of two separate windings, which are connected in parallel to the clamping unit of the pulse generator. As indicated in the equivalent diagram in Figure 4, the discharge current runs through the common middle contact plate over both windings to the contact plates at the right and the left ends of the whole coil system. So the width of the turns could be reduced significantly.

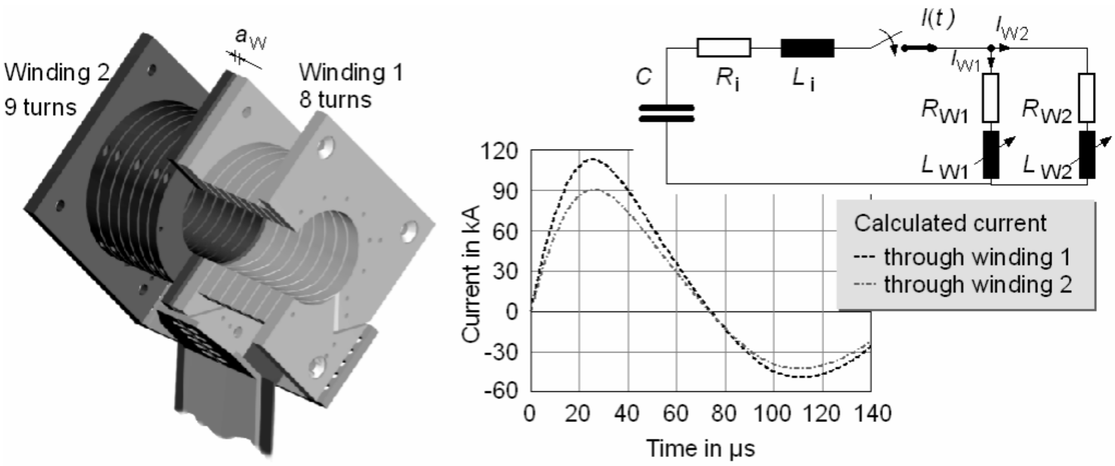

***Figure 4**: Tool coil developed for the electromagnetic compression of the demonstrator part and according coil current*

For a further and more detailed dimensioning, as for example the precise width of every single turn to realize the required pressure distribution, a coupled Finite Element Analysis (FEA) has been used. The numerical modeling is based on the developments of Karch, as described in [7], using the software package ANSYS 8.0. It contains the simultaneous solution of the transient electric circuit (including the pulse generator), the electromagnetic and the structural equations. Since the simulation tool is restricted to 2-dimensional problems the design of the tool coil could only be performed considering straight workpieces and the previous bending step had to be disregarded. Also the used material characteristics are determined by quasistatic tensile tests, neglecting the strain rate terms. Being aware of its inaccuracy, the simulation results are qualitatively good enough to dimension the tool coil especially considering the resulting course of the discharge current as well as the distribution of the magnetic pressure.

As shown in **Figure 5**, the desired workpiece deformation could be approximated best by an asymmetric winding design: one with 8 turns and one with 9 turns and a varying width of 10 to 13 mm. The use of a varying winding density to influence the pressure distribution according to DE 102 07 655 was successfully tested for flat coils (compare [9]) and could now be transferred to compression coils.

According to the different electrical properties of the parallel windings, the current will be distributed, while the measurement detects the sum of both. The simulated current over time curves as well as the resulting pressure distribution at the time of current maximum are shown in Figure 4, too. As an additional feature and with the aim of achieving as much flexibility as possible for slight modifications of the preform contour, both windings can be mounted with different distances a_w between them, adjustable from 0.5 up to 6 mm.

In order to evaluate the numerical coil design and the realized coil as well, compression tests have been carried out using straight workpieces and the resulting contour in the deformation zone was measured. As presented in Figure 5, the comparison of the numerically and experimentally determined contours shows good qualitative agreement.

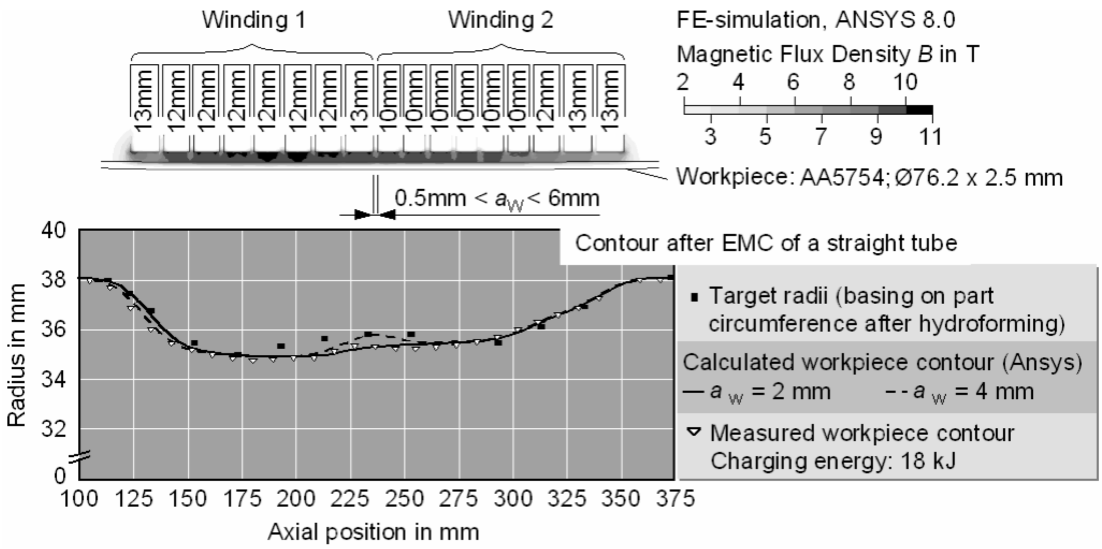

***Figure 5**: Coil winding and resulting contours of the electromagnetically compressed workpiece*

3.2 Electromagnetic compression of bent semi-finished parts

In the next step the compression of previously bent profiles was regarded. The target geometry after the bending step, shown in Figure 3, could be realized with high contour accuracy. The mean deviation from the ideal contour could be reduced to less than 1 mm. Comparative contour measurements after bending and after EMC have proved a small influence of the electromagnetic compression on the contour accuracy (compare **Figure 6**). Thereby, the bending radius in the middle between the two compression areas seems to be largely unaffected, while the angle between the straight end zones of the part is slightly increased.

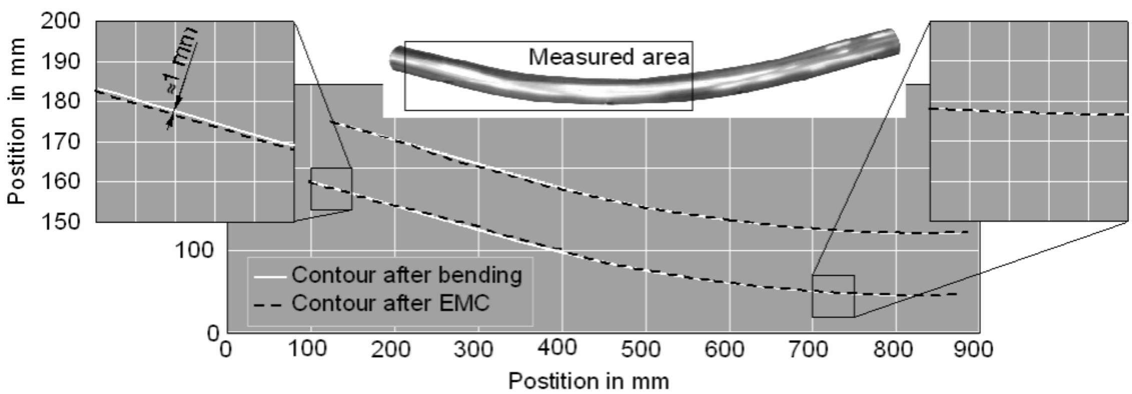

***Figure 6**: Contour accuracy of the bent and compressed preform*

3.3 Testing of the bent and compressed semi-finished parts

In order to evaluate the preforms, hydroforming tests have been carried out in close cooperation between IUL and DaimlerChrysler AG, Hamburg. The parts were formed in a two-stage process consisting of the steps closing of the tool without or with low inner pressure and high pressure calibration of the part. With regard to the motivation of the investigated process chain, especially the first step is of interest because, here, it can already be seen whether the preforming was successful and the complete closing of the hydroforming tool is possible.

As presented in Figure 7, the testing of bent and compressed preforms has shown that extrusions of the material into the parting plane of the hydroforming tool could nearly be avoided (example (b)). Contrary and as expected, the application of bent semi-finished parts of uniform initial diameter led to significant extrusions (example (a)). These obvious extrusions render the closing of the tool and the successful production of the part impossible. This clearly shows the advantage of the combined forming strategy Bending – Electromagnetic compression – Hydroforming in comparison to the standard hydroforming process.

The subsequent testing of the calibration step has shown that after a successful closing of the tool the part could be formed without cracking, whereby a pressure of up to 2500 bar was applied. For this pressure all deviations on the roundness caused by the EMC using the optimized tool coil described in 3.1 could be reversed (example (d)). So the feasibility and the potential of the complete investigated process chain could be proved. On the other hand, comparative experiments applying a tool coil that is less suitable with regard to this special application have affirmed the importance of adapting the coil parameters to the forming task. As shown in example (c), the preform quality achievable by performing multiple subsequent compression sequences, using a tool coil with the same diameter (80 mm), a shorter length (90 mm), and a longer pressure rise time is not sufficient to avoid irreversible wrinkling.

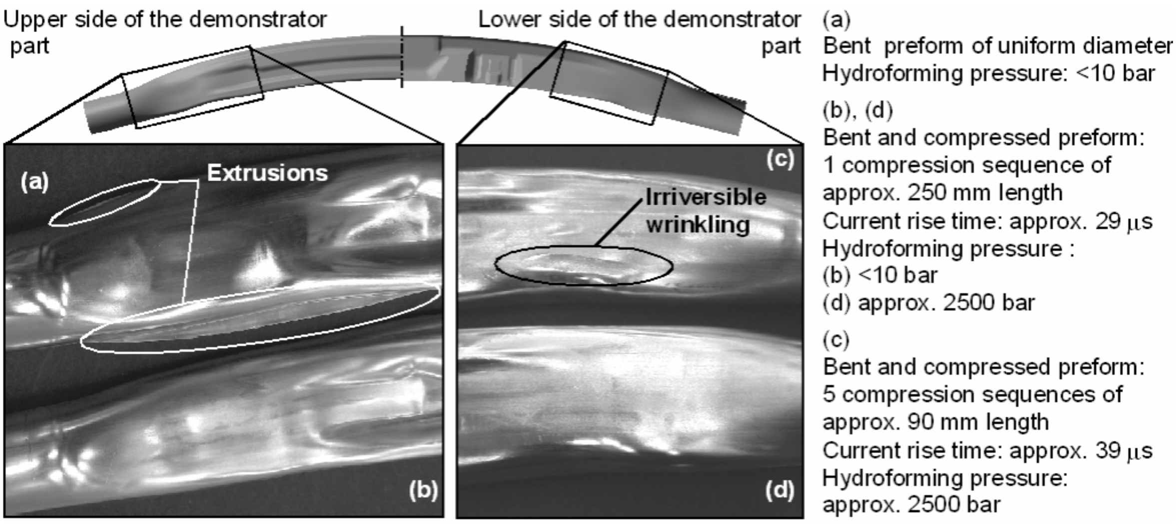

***Figure 7**: Results of hydroforming tests for compressed tubes and tubes of uniform diameter*

4 Summary and Outlook

The increasing significance of lightweight construction concepts requires innovative and adapted production technologies and process chains for the manufacturing of complex parts made of typical lightweight materials. The feasibility of such a process chain consisting of the steps Bending - Electromagnetic compression (EMC) – Hydroforming could be shown on the basis of a demonstrator part from the automotive industry. In order to realize a suitable preform geometry by means of EMC without applying a mandrel, a tool coil optimized for this special forming task was developed using a coupled 2-dimensional Finite Element Analysis. Thereby, the resulting course of the discharging current, on the one hand, and the distribution of the magnetic pressure causing the resulting workpiece contour, on the other hand, has been considered. In order to evaluate the coil design, compression tests were carried out on straight and bent workpieces, validating the numerically determined workpiece contour. The further processing of the bent and compressed semi-finished parts by means of hydroforming could be realized successfully and the potential of the investigated process chain to extend forming limits of the conventional hydroforming process could clearly be proved.

On the other hand, the experiments have shown an extreme sensitivity of the hydroforming process regarding the bending line and the contour in the compressed area for this special part. Already slight contour deviations caused extrusions into the parting plane during the closing of the tool. In order to render the hydroforming process easier and more reliable numerous possibilities to improve the shape of the preform, e.g. by applying mandrels of different cross section geometries are thinkable. As shown in [4], the adaptation of the cross section geometry causes an inhomogeneous distribution of the tangential strain along the circumference of the part related to an according distribution of wall thickness and strain hardening. Selective variations of the workpiece properties in that way might be used in order to purposefully influence the forming stages during the hydroforming process.

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