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Tube Hydroforming in Automotive Applications

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Abstract

Hydroforming enables manufacturing of closed sections with non-uniform cross-sectional areas along the length by using a circular tube as the input material. While conventional stamped and welded closed sections need a flange area to facilitate welding, hydroformed closed sections enables weight saving by avoiding the flange area. The capacity of the Hydroforming process enables a designer to replicate the profile of brackets / child parts directly on the components, thus reducing the number of brackets / child parts.

In the presentation an overview will be given of the hydroforming process, the TSG capabilities for tubular hydroformed components as well as the used CAE and FE tools applied to transfer traditional designs into designs optimised for hydroforming. An explanation will be given on the Advanced Free Expansion Test; a test used to determine the hydroforming performance of tubular materials.

Introduction

The demand for lighter component solutions remains a primary driver in the automotive industry. Hydroforming is considered as one of the potential enabling technologies to deliver lightweight components.

A new generation of hydroforming components; novel applications based on a better understanding of the process and the material application behind the products, designed with manufacture in mind, can deliver cost effective mass reduction in the race for lightweight solutions.

These new generation hydroform components make use of Advanced Steels and the characteristics of an advanced tubular product, in solutions based on materials, and applications based hydroforming know-how.

In the paper an overview will be given of the various hydroforming methods. After that 2 examples will be given of the development of tubular components: a bumper system and an engine cradle.

Hydroforming methods

Basically there are 2 main hydroforming methods: tube hydroforming and sheet hydroforming [1]. The principal of tube hydroforming is given in figure 1. A pre-bended tube is placed in a tool set in a press which applies the closing force. At the ends of the tube 2 cylinders are placed that can apply axial feeding. The tube will be filled with fluid and the tube will be formed under pressure.
In figure 2 a typical sequence is shown for tube hydroforming of a simple T-component. First the tube will be positioned in the die set, the tools will close and the tube will be filled with water. Axial feeding will build up pressure and enable the inflow of material into the T-shape. After releasing the pressure, the dies can be opened and the part be removed.

Apart from various commercial applications a number of studies have been done on the use of hydroformed tubular components in car body. In figure 4, an example is shown of a Hydrofrom Intensive Body, designed by Land Rover in cooperation with Tata Steel and a number of Hydroforming companies. In this body an number of traditional sheet metal components have been replaced by hydroformed tubes, leading to lesser components, weight saving and an excellent crash performance.
Although tube hydroforming is a long known technology, the applications of hydroformed tubular components has increased in recent times, because of the more advanced pressing control technology, but also because of the availability of reliable Finite Element Models (FEM), that eliminate the expensive trial and error process in the development of the tools an components. In figure 5 and 6 an example is shown of a state of the art FEM analyses of the complete production process, starting with tube making on a roll forming line (figure 5) followed by pre- bending of the tubes, closing of the tools also pre forming the tube and finally the hydroforming step (figure 6).
Apart from tube hydroforming much research is done in sheet hydroforming, although the number of actual applications is still relatively limited. In figure 7 the classical method for sheet metal forming is shown, where the hydraulic fluid is used as a flexible die in a traditional deep drawing process of cylindrical components. In this way the deep drawability can be increased significantly, leading to much larger deep drawing ratios compared to traditional deep drawn components.

**Figure 7. Sheet hydroforming**

Apart from analyzing this process with FEM, Tata Steel uses automated strain measurement systems to measure the severity of the forming process and optimize the component and process. In figure 8, an example is shown of a conical component, on which a grid mark has been applied prior to hydroforming. After the forming process the grid mark has been measured with an optical automated strain analyses system and the minor and major strain are plotted in a Forming Limit Diagram, showing that the forming of this component with a high deep drawing ratio of this material is feasible.

**Figure 8. Strain analyses of a conical hydroformed component.**

Apart from sheet hydroforming as an enhancement of the classical deep drawing process, a special process has been developed especially for automotive outer components called the Hydromec process. In figure 9 the principle of this method is shown where a sheet is pre-formed in one direction generating a uniform strain in the sheet. After that a mechanical punch will press the sheet in the other direction giving the component its final shape, supported by the hydraulic fluid. In this way a component with a lot of pre-strain will be pressed, which will give the component excellent dent resistance, especially when so called...
bake hardening steels are used that raise the Yield strength of a pre-formed component considerably during the paint cycle.

Figure 8a. The Hydromec process.

Figure 8b. A Hydromec bonnet

In figure 9 another special form of sheet hydroforming is shown, the so called pillow hydroforming, where 2 stacked sheets are presses together in one toolset into a an outer and inner panel of in this case a bonnet, reducing cycle time, tool costs and increasing dent resistance.

Figure 9. Pillow sheet hydroforming.
Example: Bumper system
The first industrial component which will be shown is a bumper system, where the aim was to replace a classical sheet metal bumper system constructed of a number of stamped sheet metal components (figure 10) by a single hydroformed tubular component (figure 11) [2].

![Original sheet metal bumper system](figure10)

![Redesigned hydroformed component](figure11)

Figure 10. Original sheet metal bumper system

Figure 11. Redesigned hydroformed component

A number of material requirements for the performance of this crash component were determined:
- Energy absorption
- Strength
- Ductility

All requirements were evaluated and optimized using FEM.

One important aspect for this component was the so called corner filling at the relative sharp radii of the component. At the end pieces of the component, the corner filling can be controlled by the axial feed to the tube. However in the middle of the component the full corner filling has to be obtained from the tube circumference in plane strain condition (figure 12).

![Corner filling areas](figure12)

Figure 12 Corner filling areas

The corner filling behaviour of various advanced steel tubes has extensively been researched using a research part as shown in figure 13. These experiments were also simulated using FEM enabling to determine the reliability of this method. Figure 13 shows that the primary strain peaks at the contact edge found in the experiment are well predicted by the FE method. The secondary strain peak at the centre of the corner is less well predicted, however the failure position is at the contact edge, so this is the most relevant one.
Figure 13a Corner filling test specimen

Figure 13b Cross section of the tube

Figure 13. Comparison of experimental and numerical of the corner filling test.

In figure 14, simulations are shown for various advanced steel types. It is clear that materials like DP and TRIP with a high n-value show low strain peaks.
At higher strains (figure 15) we see the HSLA grade fail and the DP800 grade be very close to the failure limit. DP600 and TRIP show favourable behaviour for this component.

The behaviour of a tube during hydroforming can be tested using the so called free expansion test (FET) as shown in figure 16. With this tester a tube can be freely expanded until bursting. By applying axial feed, a Forming Limit Curve can be constructed for a tube.

In figure 17, it is explained that it is important to test the tube in a FET test and not only the original sheet material as because of the tube making process, the mechanical behaviour of the final tube is not the same as of the original sheet material. The FET test enables to test very high elongation levels comparable to tube hydroforming and normally no weld failure will occur, giving the actual mechanical material behaviour.

Apart from the mechanical properties of the final tube, also the friction during the hydroforming process plays an important role. In figure 18, the influence of friction is shown for the corner filling test. It is clear that a lower friction lowers the strain peaks. This improves the formability and enables the use of materials with lower formability to produce a complicated component.
In figure 19 and 20 the FEM calculations were shown of the actual bumper component. The corner fill test, the FET test and the FEM calculations were used to optimize the shape of the component as well as the pre-bending, pre-forming and axial feed at hydroforming. This has led to optimal corner filling and a component that met crash requirements.

**Example: engine cradle**

The use of Advanced Steels in hydroforming need careful considerations; a good example is the Engine cradle shown Figure 21 [3].

*Figure 18. The influence of friction on hydroforming*

*Figure 19 FEM calculations of the bumper system*

*Figure 20. Final component showing successful corner filling and rest ductility for crash performance*
At first glance this component is a typical example of the use of hydroforming to replace several conventional stamped parts by one hydroforming component, but it also uses the benefits of a High Strength steel grade resulting in a lighter solution.

However, successfully hydroforming this engine cradle in particular and Dual Phase materials in general, is not an easy task. The hydroforming process of this engine cradle was already the subject of a paper at the 2001 [4] Hydroforming Conference in Pamplona. In principle the limits of hydroforming High Strength Steels should be taken into account at the very early stage of the design process in order to avoid any problems in a later stage, in this case Advanced High Strength Steels were new to the market and a limited amount of data was available to support the development process.

After extensive studies at the later stages of development, the engine cradle has been produced from a Tata Steel Tube, which is a press formed and laser welded tube designed to increase the potential options for hydroforming applications.

The engine cradle was initially produced from a conventional roll formed and resistance welded tube (ERW). However, the combination of material and process for this application results in two problems.

- Excessive strain hardening introduced by the roll forming process
- A negative influence on the local mechanical properties due to the heat input of the resistance welding process

The strain hardening introduced by the roll forming process is a result of the developments of strains in both the longitudinal direction and the circumferential direction of the tube. The longitudinal strains are mainly geometry based and can be estimated by analytical software packages such as Copra™.

The circumferential strains are mainly a result of the calibration stands in the tube mill and can be estimated by modelling the tube making process in a Finite Element model. Although we were unable to measure a specific example of this particular Dual Phase tube in its unformed state, previous measurements and calculations performed by Tata Steel showed that this can be as much as 6% and higher [5].

Annealing can be used for mild steel tubes to recover formability after strain hardening, but is not possible for Dual Phase steels, since this would destroy the martensitic phase in the material. Therefore, the
strains introduced by the roll forming process are unrecoverable resulting in a relatively poorly hydroformable tube.

The resistance welding process introduces a relatively large amount of heat into a local area in the circumference of the tube. This heat input results in various changes in the microstructure. The melted region turns into a martensitic and bainitic structure after cooling down.

Figure 22a shows the microstructure of a resistance-welded Dual Phase tube. The melted region becomes relatively hard (430 Hv, see Figure 23) and therefore has a high yield stress, resulting in a poorly formable but strong region. However, the heat input also influences the heat-affected zone (HAZ), which concerns the material immediately adjacent to the weld. Figure 22a shows the microstructure of this HAZ. The heat input results in a slightly softer region, this softer region can also be recognized in the hardness curve of Figure 23. It is exactly this softened region, which results in problems during hydroforming.

Figure 22. Micro structure of Dual Phase 600 welds seams

It is assumed that the softened region has a slightly lower yield stress than the neighbouring material (mother material and weld seam). The hydroforming process encourages deformation at this weak region in the tube circumference. This deformation results in local thinning and in strain hardening (yield stress increase).
Dual Phase materials have a very high n-value at the beginning of the stress strain curve (see Figure 24 and Table 1) resulting in a rapid increase of the yield stress for small deformations (strain hardening). However the n-value at higher strain levels is much lower (see Figure 24 and Table 1) such that it becomes more sensitive to strain localization around pre-existing defects or geometry constraints, in this case a pre-existing material defect like a softened HAZ.

![Figure 24. Typical Dual Phase 600 tensile test curve (specimen taken in the rolling direction)](image)

<table>
<thead>
<tr>
<th>Rp (MPa)</th>
<th>Rm (MPa)</th>
<th>n-value (6%-8%)</th>
<th>n-value (10%-Ag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>417</td>
<td>647</td>
<td>0.181</td>
<td>0.157</td>
</tr>
</tbody>
</table>

*Table 1. Typical mechanical properties of a Dual Phase 600 material (specimen taken under 90° to the rolling direction)*

During a free-expansion test the tube is expanded under internal pressure over a free length of at least three times the tube diameter. The radial expansion is measured during the test. The radial expansion at failure is then used to quantify the formability of the tube.

Free-expansion test results also support the two observations above, failure takes place in the HAZ at low expansion levels (less than 10% radial expansion under plane strain conditions).

Figure 25a shows an example of a freely expanded roll formed and resistance welded Dual Phase 600 tube. Figure 26 shows the pressure-expansion curve recorded during the free-expansion test of the tube originally destined for the production of the engine cradle.

![a) Roll formed and resistance welded tube](image)
b) The Tubular Blank

Figure 25. Typical failure modes after free-expansion testing of DP600.

![Graph showing measured data with pressure expansion curves for conventional roll formed resistance welded tube and Tubular Blank]

Figure 26. Pressure expansion curves measured during the expansion of a conventional roll formed resistance welded tube and a Tubular Blank

The DP600 Tubular Blank typically is better formable than a conventional roll formed and resistance welded tube. The process uses press forming in combination with laser welding.

Theory suggests that the press forming process should develop less strain hardening. A Finite Element simulation of the press forming process was carried out to verify this. Figure 27 shows the result of the Finite Element simulation and it clearly predicts an even strain distribution and a low maximum strain level of only 2%. A roll formed tube generally shows a non-even strain distribution in combination with a maximum strain level of approximately 6%.

![Calculated equivalent strain distribution in a press formed Dual Phase 600 Tubular Blank]

Figure 27. Calculated equivalent strain distribution in a press formed Dual Phase 600 Tubular Blank

The two disadvantages of the conventional roll forming and resistance-welding process mentioned above also resulted in serious difficulties during the Hydroforming process of the engine cradle.
Tata Steel was therefore asked to investigate using the Tubular Blank (a laser welded and roll formed product) to establish whether the stated benefits:

- Low strain hardening during the forming of the Tubular Blank
- A small HAZ as a result of the laser welding Process

could help solve the problems.

Tata Steel carried out basic Finite Element simulation of the part in order to investigate the expected maximum strain levels. These studies show that a maximum major strain level of 20% is required under plane strain conditions (see Figure 28).

Figure 28 Predicted required strain distribution in the component

Several critical areas are defined; four critical areas are a result of corner filling and two areas are critical as a result of the pre-bending operation. The latter two areas are less critical since these areas are not plane strain.

This strain level is considered very critical for Dual Phase material. It is therefore concluded that using a conventional roll formed tube will indeed result in serious problems in hydroforming. However, it is regarded critical but feasible if a Dual Phase Tubular Blank is used for this application.

When the production of the engine cradle using The Tubular Blank started, a continuous improvement process was initiated. This continued improvement focused on the through process chain characteristics of subsequent analysis of the performance of the Dual Phase Tubular Blank at the different production steps. These steps are:
- Bending
- Pre forming
- Hydroforming

Figure 29a shows a Tubular Blank after bending. The bending of The Tubular Blanks generally does not cause significant problems. However, it was found that the bending set-up needs to be adapted, if Tubular Blanks are used. Dual Phase materials exhibit high springback [6]. The Tubular Blank is inherently softer than the conventional roll formed tubes for a given material grade. Therefore the springback behaviour of a Tubular Blank compared to a Roll Formed tube is also different (the springback of a Tubular Blank is generally less). Experience also shows that the amount of springback can vary between different material batches, this is mainly a result of variations in the yield stress of the material. Dual Phase materials are very sensitive to these changes, recalling the earlier comment regarding the stress/strain characteristics (see Figure 24). Therefore, small variations in strain levels introduced during
the material production process result in large variations in both the yield stress and the springback behaviour. It is therefore advisable to take these variations into account in order to design a robust process, when Dual Phase materials are used.

Figure 29b shows The Tubular Blank after pre-forming. The pre-forming of the product does not pose any significant problems. However, again it should be kept in mind that Dual Phase materials can show variation in springback behaviour. The pre-forming step could well be used to correct the geometry variations after bending.

Figure 29c shows the engine cradle after hydroforming. The use of The Tubular Blanks resulted in a dramatic improvement of the reject level after hydroforming. This proved that hydroforming the engine cradle is indeed feasible using this new tube making technology.
Figure 29. The Tubular Blank after each process step

Dual Phase materials can result in lightweight components with high performance since the yield stress and especially the Ultimate Tensile Stress is attractively high.

In addition the aforementioned characteristics of the Dual Phase stress strain curve also means that yield stress will increase dramatically during the hydroforming process. This combination of material and process characteristics improves the performance possibilities of a Dual Phase component.

Figure 30 shows the tensile test results of a specimen taken from the actual hydroformed engine cradle. Here, the hydroforming process resulted in a yield stress of 548MPa, which is an increase of over 30%. The location where the tensile specimen was taken is indicated in Figure 29c.

Figure 30. Tensile test data of a specimen taken from the engine cradle after hydroforming (location see figure 29c)

Figure 31 shows the yield stress increase measured on freely expanded Tubular Blanks at different expansion levels, confirming that low expansion levels result in high increases in yield stress.
The capability to develop ‘as formed’ material properties in crash performance simulation is a key area of research that will allow the car designer to further optimize the performance of the structure.

Whilst the mechanics of this process are contained within commercially available analysis codes, a practical methodology to execute this with hydroform components, in a routine analysis, within a practical time frame is not.

Following a successful program for metal stamping, a work program for hydroforming has been completed and presented [4].

The ability to predict with increased accuracy the benefits of combining Advanced High Strength Steel with other aspects of the Tubular Blank, for example using tailored and conical blanks to overcome geometrical design aspects, should lead to component and module solutions that offer maximum mass saving benefits through hydroforming.

Conclusions

Hydroformed tubes can be used to develop cost effective lightweight components.

Knowledge of the full process chain from slab to the performance of the actual hydroforming product is vital to the successful use of Advanced Steels in hydroforming components. The material choice significantly influences the component and production process design, the process control throughout the supply chain from slab to tube making process strongly influences the success of the hydroforming process.

Finally, the application of Advanced Steel delivers maximum benefit when combined with appropriate tubular technology and a full understanding of the impact of the material’s behavior in the vehicle.

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