Q. Hydroform Materials and Lubricants Project (ASP 060[i])

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Objective

- Develop mechanical test procedures and forming-limit diagrams for tubes.
- Improve the accuracy and confidence in finite-element modeling of tubular hydroforming.
- Investigate the fabricating and performance characteristics of tailor-welded tubes (TWTs).
- Develop an understanding of steel and lubricant requirements for hydroforming using a combination of experiments and finite-element modeling.
- Support the work of other A/SP project teams when they investigate hydroformed structural components.
- Validate the performance benefits of hydroforming in automotive structures.

Approach

The approach taken on this project is first to gain a basic understanding of the hydroforming process and potential issues, then apply the understanding to support other A/SP project teams in vehicle applications. The investigation encompasses various steel grades and gauges of steel tubing, including TWTs and advanced high strength steel (AHSS) in free-expansion and corner fill processes using several types of lubricants. The work has been divided into several phases.

1. Phase 1 – Investigate free-expansion and corner-fill characteristics.
2. Phase 2 – Investigate effects of pre-bending, lubricants and end feeding on hydroforming limits.
3. Phase 3 – Investigate some of the pre-bending parameters for the hydroforming process.
4. Phase 4 – Investigate some of the bending parameters for AHSS tubing.
5. Phase 5 – Determine the experimental forming limits of steel tubes.
6. Phase 6 – Develop methods for empirical prediction of tube forming-limit diagrams and analysis of hydroforming data.

7. Phase 7 – Investigate tubes made from tailor-welded blanks of varying grades and thicknesses.
8. Phase 8 – Demonstrate the benefits of tube hydroforming through projects focused on real-world applications.

Delays in obtaining sheet stock and tubes caused Phases 3 and 4 to follow Phases 5 and 6.

Accomplishments

During the report period (October 1, 2005 – September 30, 2006) the following were accomplished:

- Conducted additional inside and outside corner-fill experiments with 90° bent IF and DP600 tubes with welded end caps to study the effect of elimination of tube end feed.
- Fabricated tubes from tailor-welded blanks of varying thicknesses and grades.
- Conducted free-expansion tests on the above tubes.
- In March 2005 the team was challenged to demonstrate the manufacturability of an advanced high-strength steel (AHSS) hydroform tailor welded tube (TWT) lightweight automotive front rail. The team has taken on this challenge and accomplished the following to date:
  - Procured steels and tooling to fabricate tubes made from tailor-welded blanks with six different thicknesses/grades of high-strength steel.
  - Procured tooling to fabricate the front frame rail from the above tubes.
- Developed a concept for a burst-testing-criteria fixture and identified a contractor to build it.
- Develop a proposal for a project, "Investigation of Fabricating Dual Phase and TRIP Steel Tube from an ERW Production Line."

Future Direction

During fiscal year 2007, the Hydroforming Materials and Lubricant plans to accomplish the following:

- Fabricate and determine the manufacturing parameters of a hydroformed front frame rail in support of the work performed by Lightweight Front Structures, A/SP 080 (see 2.W).
- Complete laboratory testing of TWTs made from blanks with two grades/thicknesses.
- Conduct free-expansion and straight-tube corner-fill tests on TWTs.
- Complete project on the hydroforming of DP600 and IF Bent Tubes with Welded End Caps.
- Conduct the project, "Investigation of Fabricating Dual Phase and TRIP Steel Tube from an ERW Production Line."
- Initiate a project to verify yield equations for hydroforming through controlled stress path free-expansion tube testing.

Introduction

Hydroformed steel tubes have been used in the automotive industry to form components that meet structural objectives, particularly strength and rigidity, at optimal mass. One of the most significant advantages of tubes is that they are monolithic closed sections and, as such, exhibit significantly greater stiffness in torsion than conventional open sections, such as "C" and "hat" shapes. Eliminating the need for weld flanges, which are required to join two open members into a closed member, offers a potential for reducing vehicle mass. The use of hydroformed tubes is limited largely by lack of knowledge of the capabilities and parameters of hydroforming processes and the effects of those processes on the tubes.

This project was undertaken to investigate and quantify the capabilities and parameters of various hydroforming processes so that automotive designers and engineers can utilize a wider range of tube configurations and predict with reasonable accuracy the performance of hydroformed components. Hydroforming tubes made from high-strength and advanced high-strength steels (AHSS), and particularly tubes made from tailor-welded blanks, are of particular interest because of the potential reduction of mass associated with materials of higher strength and optimal thickness.

Discussion

The Hydroforming Process

Hydroforming is a process in which a tube is placed into a die, shaped to develop the desired configuration of the tube. Water is introduced into the tube under very high pressures, causing the tube to expand into the die. The tube ends can be held stationary or moved inward during the process to end-feed material into the die cavity.

The process has two distinct stages, shown in Figure 1. The first stage is free expansion, (Figure 1a). It continues until the tube contacts the die wall (Figure 1b). In the second stage, corner filling, the tube is in contact with the surface of the die, which constrains subsequent deformation (Figure 1c). During this stage, the tube expands into the corners of the cavity, accomplishing corner fill. A tube that has been hydroformed is shown with the die in Figure 2. Note that the test was continued until the tube failed.

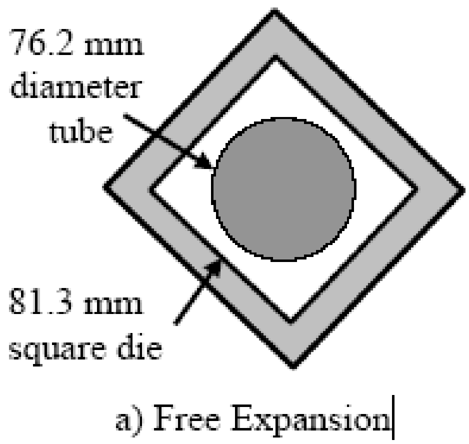

Figure 1a.

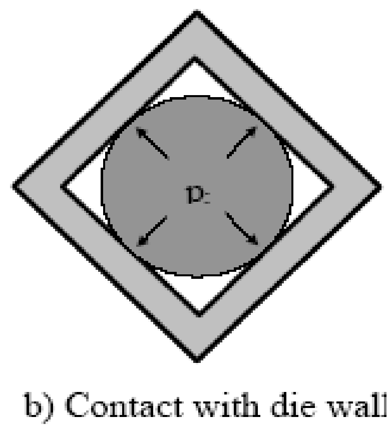

Figure 1b.

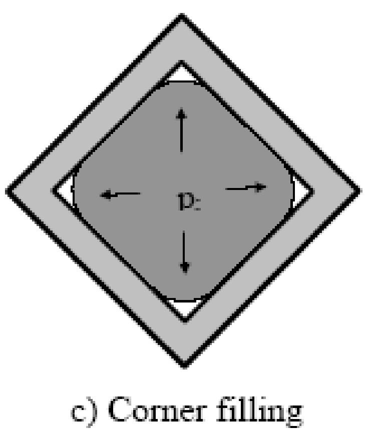

Figure 1c.

The Hydroforming Process.

Figure 2. A hydroformed tube and die.

During corner fill, the tube slides against the die; therefore, friction between the tube and die affects the process, and the lubricant used in the process becomes a significant parameter.

Forming-Limit Diagrams (FLD)

During tube fabrication and during both stages of hydroforming, the tube undergoes plastic strain. The amount of plastic strain that can occur before the material fractures is predicted in stamping processes that utilize flat sheet steel by using a forming-limit diagram (FLD). The FLD is determined by the properties of the material. The hydroforming process is preceded by tube-forming and sometimes pre-bending of the tube, both of which induces strains in the material and alters its properties. Before an FLD can be developed for the hydroforming process, the strain history, that is, the strain induced in the material prior to hydroforming must be known.

An FLD is required for any successful computer simulation of hydroforming. Therefore, in addition to experiments with tube expansion to determine the effects of axial compression and tension in combination with internal pressurization, the effects of pre-bending and pre-forming on subsequent formability were addressed. Collected data were used to develop forming limit diagrams for tubular hydroforming of straight tubes. These data will be used to develop guidelines for optimizing bending operations.

Presently, the formability limits for pre-bent steel in tubular hydroforming are poorly understood. Accuracy needs to be addressed and improved to allow optimum application of tubular hydroforming in the lightweighting of vehicles.

Hydroforming Tailor-Welded Tubes

The project team began work on hydroforming tailor-welded tubes (TWT). The work is being conducted on 76.2-mm (3”)-OD tubes made from two material grades and two thicknesses. The test consists of five TWT configurations:

1) Baseline: 1.5-mm DP600 single-material tube.
2) 1.5-mm DP600 butt-welded to 1.5-mm DP600.
3) 1.2-mm DP600 butt-welded to 1.5-mm DP600
4) 1.5-mm HSLA350 butt-welded to 1.5-mm DP600
5) 1.5-mm HSLA350 butt-welded to 1.2-mm DP600

The blanks were butt-welded before the tubes were formed. In all cases, the tubes are 508 mm (20 inches) long.

The finished tubes were sent to the testing laboratory where they were analyzed. The laboratory found that tube concentricity was not adequate in some cases to allow conventional hydroforming, because it was not possible to maintain an adequate seal between the tube ends and the end caps where water is introduced. At the suggestion of the laboratory, and with the approval of the Hydroforming Team, the laboratory welded the end caps. Free-expansion tests have been completed and the results are being analyzed.

Vehicle Front Structural Rail

In March 2006, the Hydroforming Team began an initiative to fabricate a front structural rail based on a design developed by the Lightweight Front Structures Team (LWFS), ASP080. LWFS had developed designs for a front rail for two vehicles. The first was the target vehicle. The second had 20% less mass than the target vehicle, which is a reasonable assumption based on anticipated secondary effects resulting in lower mass in systems such as suspension, powertrain and roof structure.

Two design concepts were developed for each vehicle and both concepts were optimized by using tailor-welded blanks. The first design concept in each case requires conventional stamping processes to form a "hat-shaped" member with a "top plate" spot welded at the "hat" section flanges. The second concept utilizes a tailor-welded tube consisting of six different grades/gauges of steel. The tailor-welded tube design did not address attachment to contiguous vehicle components.

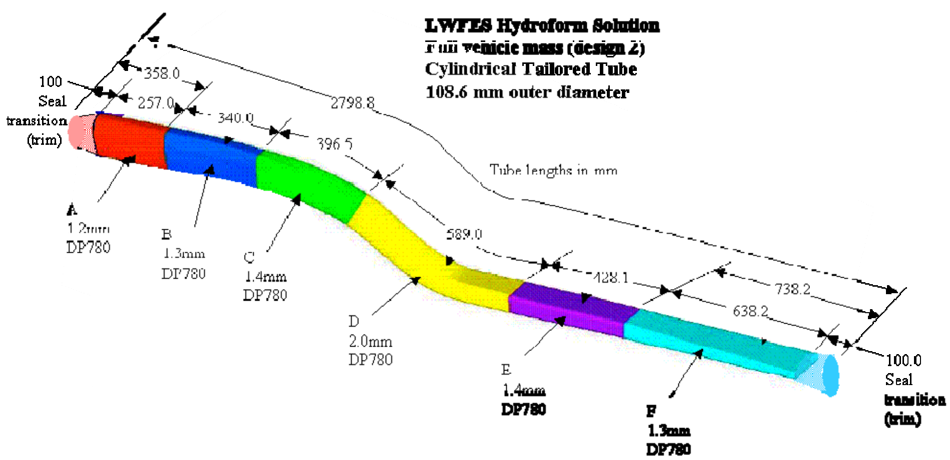

Figure 3. Hydroformed rail for full vehicle mass.

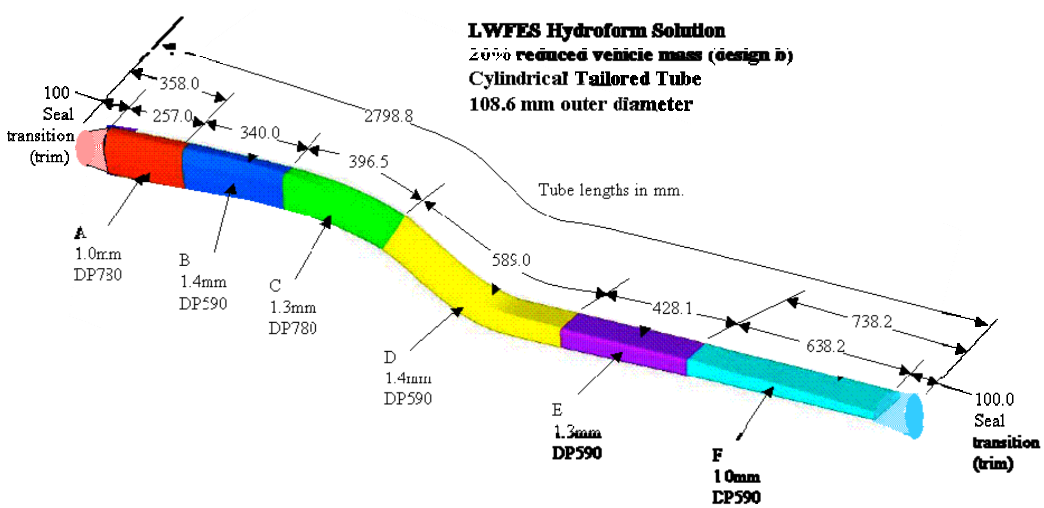

Figure 4. Hydroformed rail for 20% reduced vehicle mass.

The blank lineup for the rail in the target vehicle is shown in Figure 3 and the lineup for the rail in the vehicle with 20% reduced mass rail in Figure 4. It is noteworthy that the rail for the full-mass vehicle utilizes Dual Phase (DP) 780 steel in 1.2-mm to 2.0-mm thickness, while the rail for the 20 % reduced mass vehicle utilizes both DP 780 and DP 590.

The Project Team agreed that the purpose of the front-rail initiative is a manufacturing feasibility study. For this reason, no effort will be made to correct the hydroforming tools to bring the end-product within dimensional tolerance limits. Rather, the hydroforming supplier will be asked to utilize his experience to produce tubes as close as possible to dimensional tolerances, then perform comprehensive dimensional studies on the tubes to learn the effects of the fabrication process, such as springback and die-release.
The Team selected a hydroforming supplier and a tube manufacturer, both of whom have state-of-the-art equipment and expertise, are willing to stretch their current technology and are willing to make significant in-kind contributions to the project.

At the end of this reporting period, the hydroforming tools have been procured, the tube-forming tools have been procured, and fabrication of the tubes is under way.

Burst Criteria

The hydroforming team also recognized the need to develop burst criteria for hydroformed tubes. To date, a test fixture has been prescribed and a vendor has been selected to design and build the fixture. The second phase of this initiative will be the actual tests.

Future Work

During the 2007 fiscal year, the Hydroforming Materials and Lubricants team plans the following work:

1. Continue laboratory analysis and hydroforming tests on TWTs made from two blanks.

2. Manufacture front rails from TWTs to both designs (target vehicle and 20%-reduced-mass vehicle, Figures 3 and 4).

3. Perform analyses on hydroformed rails.

4. Develop burst-test criteria by building a fixture specially designed for the purpose and conducting prescribed tests.

5. Complete project on the hydroforming of DP600 and IF bent tubes with welded end caps.

    - Tube bending speed has only a minor effect on bending strains and subsequent hydroforming; bending radius, however, has a large impact.
    - Lubricant selection is important as it affects bending and hydroforming strains.
    - Tube end feeding is very beneficial for achieving complex geometries.
    - Forming-limit diagrams based on sheet-feeding technology are useful for predicting necking strains in free-expansion hydroforming, but bursting in closed-die hydroforming requires further understanding.

6. Conduct the project, "Investigation of Fabricating Dual Phase and TRIP Steel Tube from an ERW Production Line."

7. Initiate a project to verify yield equations for hydroforming through controlled-stress-path free-expansion tube testing.

Conclusions

Analysis of tests run during this reporting period indicates that:

- Tube bending can significantly limit subsequent tube formability and needs to be accounted for in part design

Presentations and Publications

1. "Hydroforming Group", Auto/Steel Partnership Program Review, Department of Energy, September 21, 2005.

2. "Hydroforming Committee," A-S/P SPARC financial planning review, July 18, 2006.

[i] Denotes project 060 of the Auto/Steel Partnership (A/SP), the automotive-focus arm of the American Iron and Steel Institute. See www.a-sp.org. The A/SP co-funds projects with DOE through a Cooperative Agreement between DOE and the United Sates Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the "Big Three" traditionally USA-based automakers to conduct joint pre-competitive research and development. See www.uscar.org.