PROCESS PARAMETER SENSITIVITY STUDY ON TUBE HYDROFORMING

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ABSTRACT

Finite element analysis (FEA) has proven to be a useful tool for stamping process analyses. FEA has also been used increasingly for hydroforming analysis in the industry. In this paper, some examples for various hydroforming process simulations using LS-DYNA are presented. The effects of material characteristics and process parameters on tubular hydroforming are discussed. A sensitivity study has been conducted on a simple geometry. Three steel grades: DS, HSLA and DP, and process parameters such as internal pressure, end feeding and lubricant are included in this study. Simulation results are also compared with experimental data. It is demonstrated that computer simulation can be used as an aid for optimal selection of those parameters to reduce time and cost in tool tryout. In addition, some of the simulation limitations are discussed in this paper.

INTRODUCTION

Tube hydroforming is a manufacturing process to form a part from a tubular blank using pressurized fluid to force it to the shape of the die cavity. Hydroforming offers a number of advantages over conventional stamping processes, such as increased structural stiffness, part consolidation, reduction in the associated tooling and process costs, improvement of manufacturing repeatability and dimensional stability. As a result, hydroforming technology has drawn great attention in the automotive industry. Various applications have been found including components in chassis system, sub-frame, power train, exhaust system and body structures [1-3].

Computer aided engineering (CAE) tools for automotive design have been improved dramatically in recent years. Computer simulations are used for various aspects of metal forming processes, such as formability assessment, die design, product feasibility evaluation, material selection and process design. CAE is also increasingly used in hydroforming applications [3-9]. Hydroforming operations usually involve complex process set up and multi-stage forming. Using computer tryout to optimize process parameters and select the proper materials will greatly reduce the process development time and cost. In this paper, simulation examples of some typical hydroforming processes have been presented. Process and material effects are evaluated in a corner filling case study of a round tube expanded to a square shape.

Several challenges still exist for accurate CAE predictions in tube hydroforming: 1) Material property changes are difficult to track in multi-forming processes. A flat sheet is roll formed and welded into a circular tube. The tube is then bent, preformed and hydroformed into final shape. To reduce simulation errors, tube mechanical properties are used in the current work. Deformation history is transferred from one stage to the next using DYNAIN files. 2) Conventional sheet forming limit curves may not apply to hydroforming due to the forming path change in multi-processes. 3) A tube may be formed under very high internal pressure. As a result, stress in the thickness direction is not negligible. Simulation accuracy is affected using plane stress shell element. This problem will be discussed in this paper.

MATERIAL MECHANICAL PROPERTIES

In this study, three different strength steel grades were used. aluminum killed drawing steel (DS) grade, high strength low alloy (HSLA) and DUAL-TEN, which is a dual phase steel (DP). Tube properties of the steels were used in the simulations in order to get the closest results. The tube mechanical properties used are listed in Table 1 and their true stress-strain curves are given in Figure 1. DS is mild steel, HSLA and DP are high strength steels. Most hydroforming components are used for structural parts, which require higher strength. Compared to HSLA, DP has significant higher ratio of tensile to yield strength, which results in significantly higher strength after the hydroforming process.

Table 1. Steel (Tube) Mechanical Properties

Steels	Yield Strength (MPa)	Tensile Strength (MPa)	Total Elongation	N Value
DS	224	344	43.5	0.200
DUAL-TEN	400	609	26.7	0.145
HSLA340	362	477	28.4	0.150

SIMULATION EXAMPLES

Various tube-manufacturing processes can be simulated using LS-DYNA. A few examples are shown in this paper.

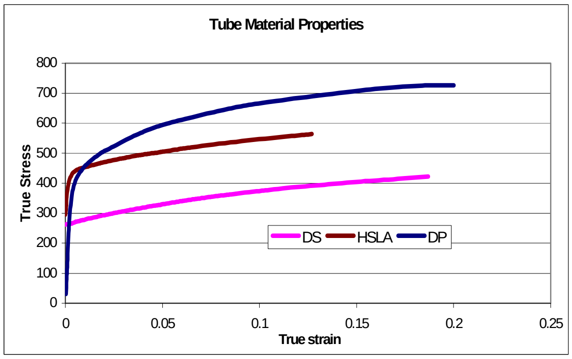


Figure 1. Stress - strain curves

Rotary Bending

Figure 2 shows an example of tube bending, which is from the Auto/Steel Partnership Hydroforming Project [5]. A tube is bent 90 degrees at the center and 45 degrees on the two sides. The original tube wall thickness is 2.23 mm and the material is DS steel.

Figure 3 shows a model of the bending tools. During the bending process, a mandrel is inserted into the tube to prevent buckling. The clamp die secures the tube and forces it to be drawn around the rotating bend die to realize the bending. Simulations are conducted and Figure 4 depicts the contour of thickness distribution of the tube after bending. Thickening occurs on the inner surfaces and thinning on outer surfaces.

Results are also compared with experiments. Thickness is measured at 45 and 90-degree bend sections. The measurement locations and the description of bending surface are shown in Figure 5. Figure 6 shows the result comparison. The simulation slightly underestimates both the thinning and the thickening. The 0 and 360 degree results should be disregarded because the weld line is not considered in the current model.

Figure 2. The bent and hydroformed “S” shape part

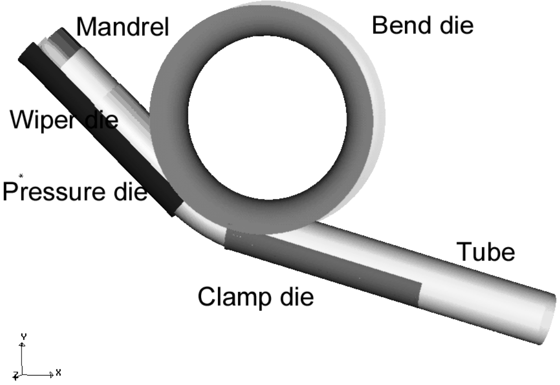


Figure 3. Bending tool models

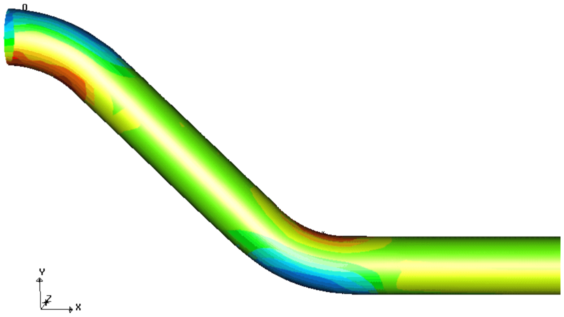


Figure 4. Wall thickness distribution of bent tube

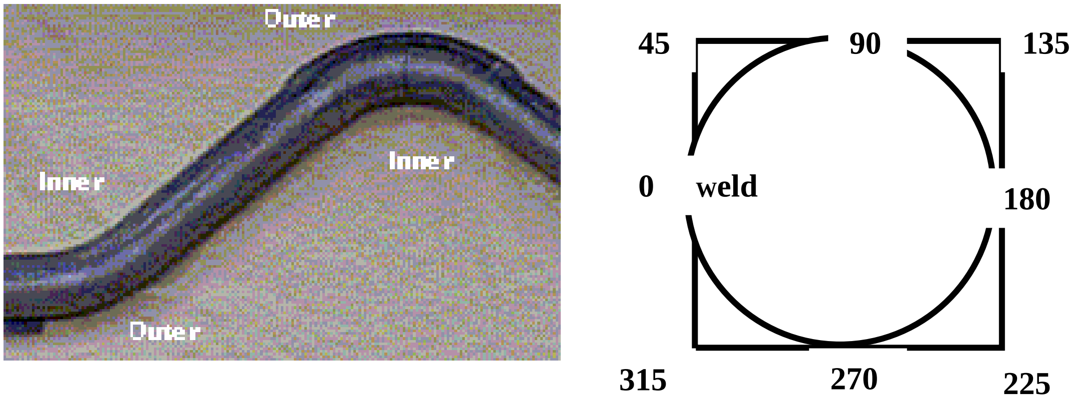


Figure 5. Bending surfaces and the locations of thickness measurement

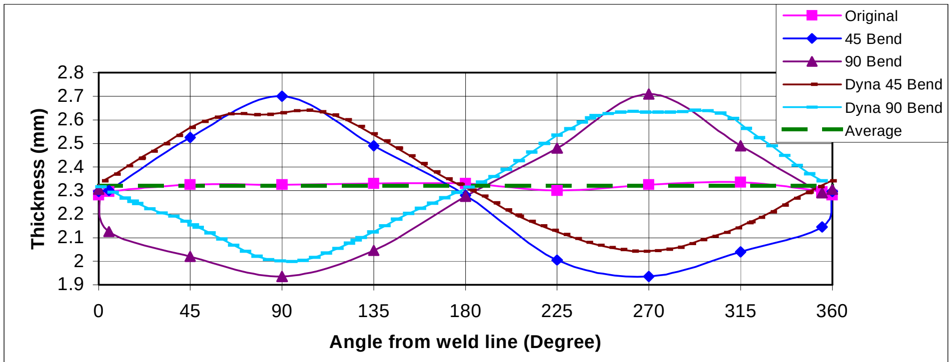


Figure 6. Result comparison of tube bending

Side Rail Hydroforming

Another example is a hydroforming side rail for a pick-up truck frame [4]. The original tube outer diameter is 155 mm and the wall thickness is 2.5 mm. The materials used are HSLA and DP. Simulations were performed on multi-stage hydroforming processes and also in a subsequent crush event. The process includes bending, pre-forming, hydroforming, springback and trimming. The forming results are then transferred to the crush simulation.

The bending in this case is not very severe and a press bend is used. The bending finite element model is depicted in Figure 7. Figure 8 shows the finite element model for the pre-forming and hydroforming operations. As the die closes, the tube is pre-formed and then crushed into the die cavity. Once the die is closed, hydro-fluid is pumped into the tube to pressurize the tube into the die shape. Virtual tryout can be simulated to determine the proper material and optimal setup for end feeding and internal pressure.

Springback was simulated for unloading after hydroforming. Trimming was also simulated to create the final part geometry for the crash simulation. Figure 9 shows all the results of hydroforming process and crash simulations.

The crush simulation was performed on a component base. A 1000 kg mass was attached to the rear end of the side rail, and the rail front end hit a rigid wall at a velocity of 15.6 meters per second (35 miles per hour). Figure10 shows the comparison of energy absorptions. When forming results are included in the simulation, the energy absorption increases by 14% and 35% respectively for HSLA and DP. When comparing the materials, the DP steel absorbs 34% and 14% more energy than HSLA in the cases of including and not including forming results.

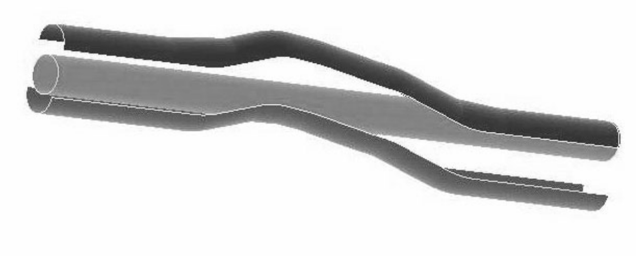


Figure 7. The bending finite element model

Figure 8. Finite element model for the pre-form and hydroforming

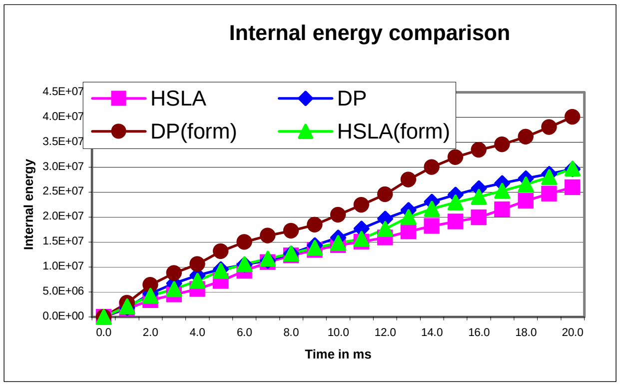


Fig.10 Energy absorption in crash

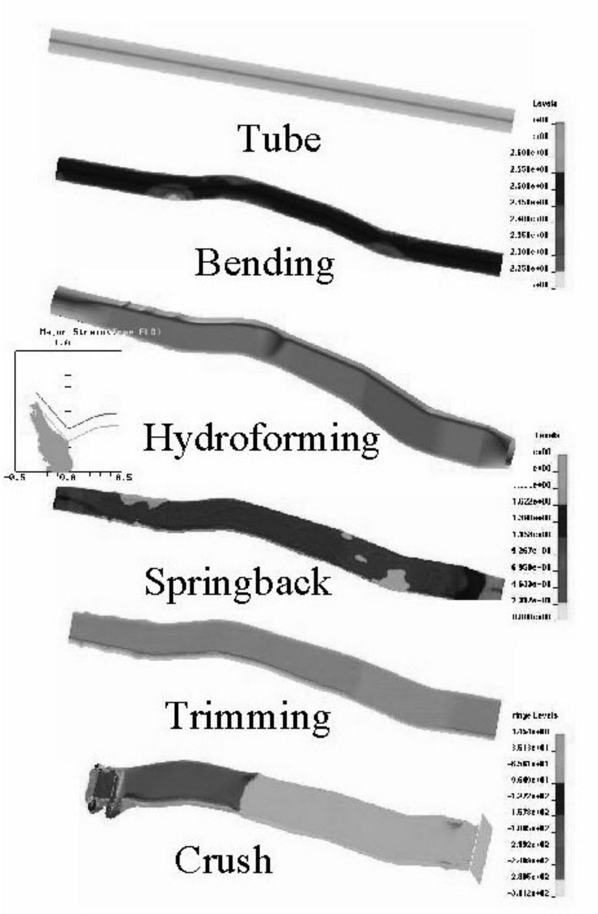


Figure 9. Results for multi-stage simulations

PROCESS AND MATERIAL SENSITIVITY STUDY

Model and Simulation Conditions

Hydroforming is a complicated manufacturing process. To evaluate the influences of various parameters on hydroforming efficiently, a simple example of corner filling is used to demonstrate the benefits of using computers in process designs. As shown in Figure 11, a 76.2 mm tube is expanded to an 81.3 x 81.3 mm square die during hydroforming. When internal pressure is applied, the tube starts to expand evenly until it reaches the die face. As the pressure increases, the tube continues to expand and fill the die corners. The corner radii of the tube decrease until failure occurs. Axial end feeding can be applied to push more material into the die cavity. The simulation conditions are listed below:

- Initial element size is about 5 mm, 2 level adaptive mesh is used

- Thickness is 2.2 mm, 5 through thickness integration points are used
- Material model 37 (Mat_Transversly_Anisotropic_Elastic_Plastic) is used
- In the standard case, the R-value is 1.0 and the Coefficient of Friction is 0.17. In the sensitivity study, only one parameter is varied and the others are kept constant as the standard values.

The corner radius at failure (CRF) is measured and used to assess formability. Better formability will generate a tighter CRF. The conventional forming limit diagram (FLD) is used as the failure criteria, while the n value is measured from tube material instead of a flat sheet. In all the cases, negative minor strains are obtained. The left side of FLD is a constant thickness strain line. Therefore, the failure criteria used represent-thinning criteria, which is usually used in product design practice.

An initial simulation was conducted and the results were compared with the experiments. Results of the thickness along the center section are shown in Figure 12. Except for at the weld line (0 degree), the correlation between test and simulation is good. The thinning trend is very similar and the maximum thinning occurs at the tangential region of the corner radius. The maximum difference is less than 10% compared to the experiment. In the experiments, the weld line is located at the center of the flat side and its effect on the rest of the area is negligible. Taking advantage of the symmetry, only one-eighth of the model is used for improving computational efficiency. The one-eighth model is shown in the Figure 13.

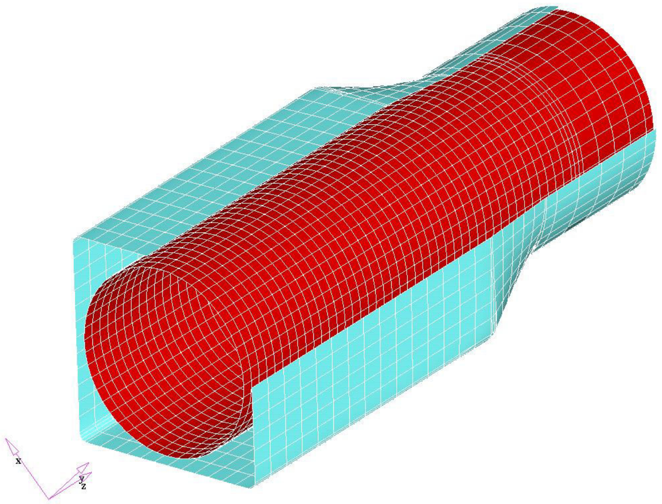


Figure 11 Simulation Model - Half

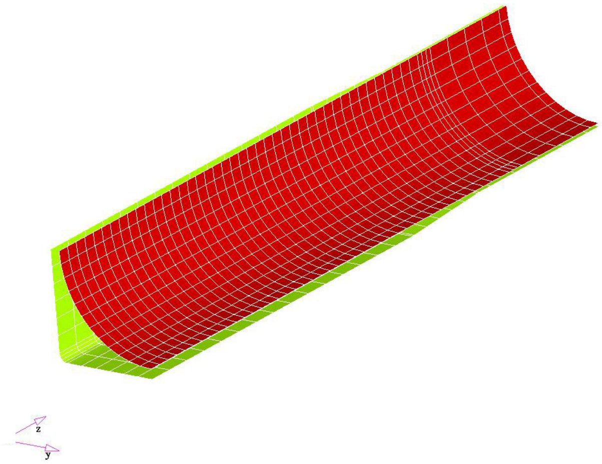


Figure 13 Simulation Model – One-eighth

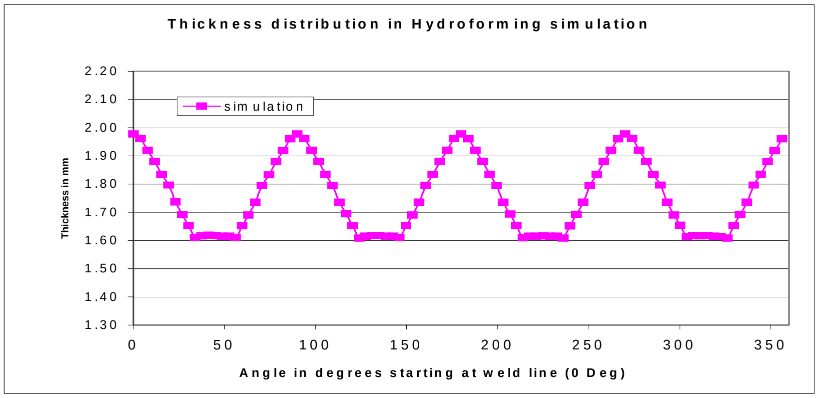


Figure 12. Thickness distribution in the simulation

Friction Effect

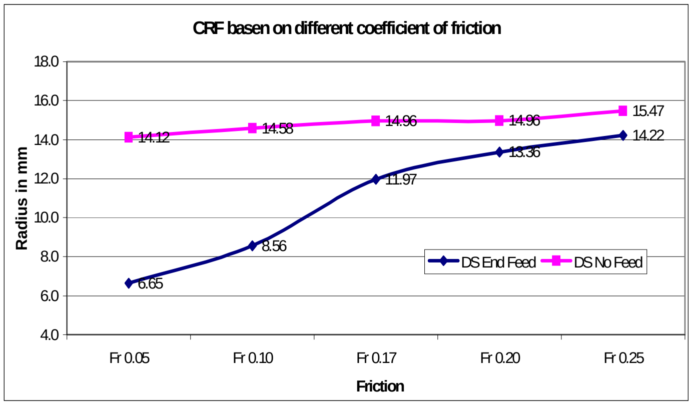


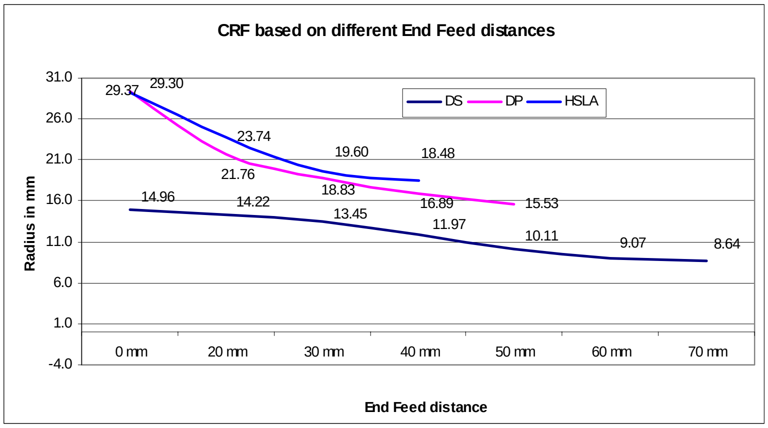
Figure 15 Friction Effect

The contact that develops between the die surface and the tube wall generates friction. The contact area and coefficient of friction have a significant effect on material flow. During hydroforming, material flows both in the circumferential and longitudinal directions. To evaluate the influence of friction, different coefficients of friction were used in the simulations. The results are shown in Figure 15. Without end feeding, material primarily flows in the circumferential direction and the friction effect on CRF is not significant. However, when end feeding is applied, the effect becomes very significant. End feeding with reduced friction can improve forming significantly. The decrease of CRF is more than doubles when the coefficient of friction reduces from 0.25 to 0.05. This result is obtained from analysis of DS, but the results are also similar for other steels.

End Feeding Effect

End feeding helps the material to flow into the die and to increase the formability by changing the deformation mode from near plane strain to draw state. However, excessive feeding may cause wrinkling or buckling. A virtual trial can be conducted by computer simulation to obtain optimal parameter setup. Figure 16 shows the end feeding effects for DP and DS steels. For DS, the results show that better forming or tighter CRF can be achieved with higher end feeding. The optimal feeding distance is about 65 mm for this case. End feeding greater than 65 mm does not improve much on the corner filling and may cause wrinkling as shown Figure 17.

Higher strength steels require higher pushing forces to cause wrinkling, thus they have better resistance to wrinkling. DP steel requires the highest force to cause wrinkling. Therefore, higher end feeding force can be applied to improve formability of high strength steels. As shown in the figure, more end feed and lower CRF can be achieved using DP than using HSLA. Without end feeding, higher strength steel has lower formability. The CRF's are 14.96 29.30 and 29.36 mm for DS, HSLA and DP, respectively. When end feeding increases, the CRF's of high strength steels reduces more rapidly than DS.



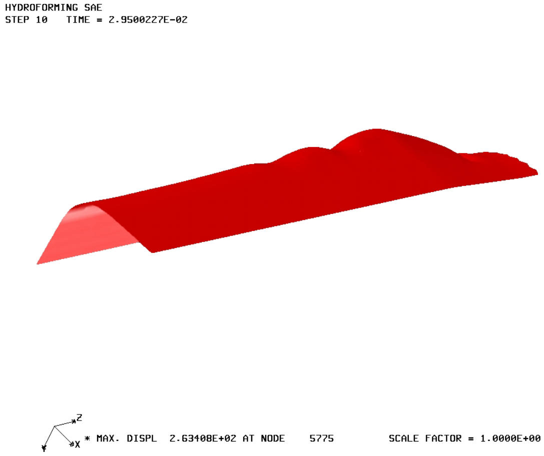


Figure 16 End feeding effect on different materials

Figure 17 Wrinkles due to excessive end feed

Effect of R-value

The R-value (plastic strain ratio) is an important material property. To examine the sensitivity of R-value, forming simulations were carried out by varying the R-value from 0.5 to 2.5 in intervals of 0.5. Figure 18 shows the simulation results of the different R-values for DS steel, with and without end feeding. There is a significant reduction in CRF with end feeding when R-value increases from 0.5 to 1.5, but there is not much difference when it increases above 1.5. However, in the case without end feeding, the effect is not significant. This result agrees with that of deep drawing. R-value is beneficial when strain path is in draw mode (combination of positive major strain and negative minor strains).

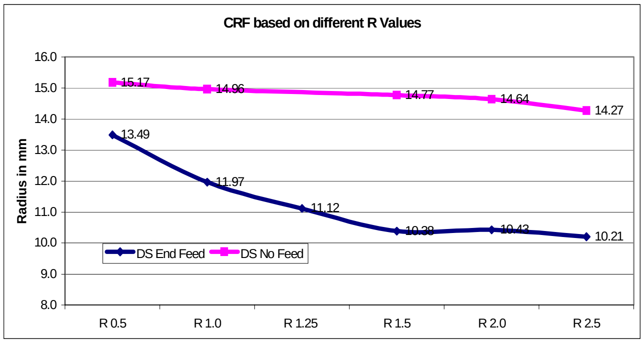


Figure 18 Effect of R-value

Pressure Loading

In hydroforming processes, the internal pressure drives tube deformation. The internal pressure can be controlled by pressure and fluid volume curves. In some processes such as free expansion, the pressure-time curve is not monotonously increasing. It is difficult to pre-set the pressure curve for process control. The volume control method provides a better control. Similarly, simulations can be conducted by using control variable as pressure or volume (input fluid flow rate-time curve) [10]. Figure 19 shows the input and output curves. Linear curve is used as input for pressure control as shown in Figure 19 (curve Pressure in). In volume control, a constant fluid rate-time curve is used. The result of the volume-time curve is almost linear but the pressure path is non-linear as shown in Figure 19 (curve Pressure out). The point of rapid dropping in pressure indicates the burst initiation. The burst pressures for both methods are similar in this case.
Figure 20 shows the results at burst for volume control.

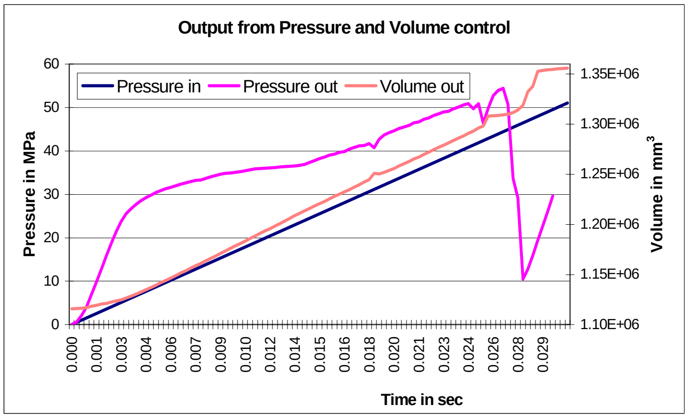


Figure 19 Volume & Pressure -Time curves

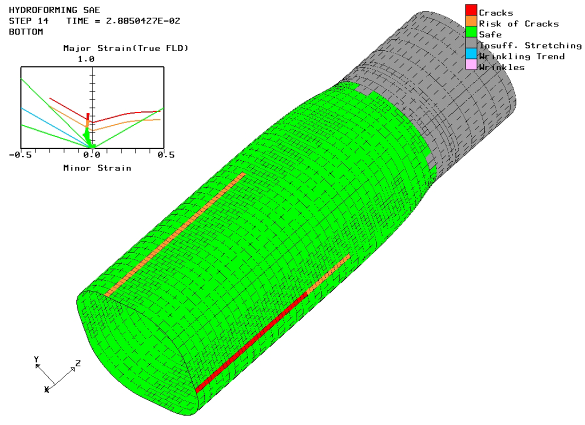


Figure 20. Failure in Volume control

LIMITATION OF SHELL ELEMENT

The internal pressure, p, required for corner fill can be calculated by:

$$p = \frac{\sigma_\theta \times t}{r}$$

Where σ_θ is the hoop stress, r is the corner radius, and t is the tube thickness.

It is shown that the pressure increases very sharply, as the corner radius becomes small. In some cases the pressure can be greater than the material yield strength. Under this condition, normal stress is not negligible and plane stress shell theory is not applicable. Simulation results will generate significant errors using shell element as shown in Figure 21. In experiments, when filling a 76.2 mm (3 inch) square die with a 76.2 mm (3 inch) diameter, 2 mm DS tube, the corner radius can be filled to a smaller radius than the tube thickness. However, simulation using shell element shows that strains exceed the forming limit when the radius is about four times the thickness.

To verify it, plane strain solid elements are used to simulate the same case as shown in Figure 22. The results are more accurate. When r is less than the thickness, the highest strain is still below the FLD as shown in point S in Figure 21, In this case, one layer of solid elements is sufficient to obtain reasonable results.

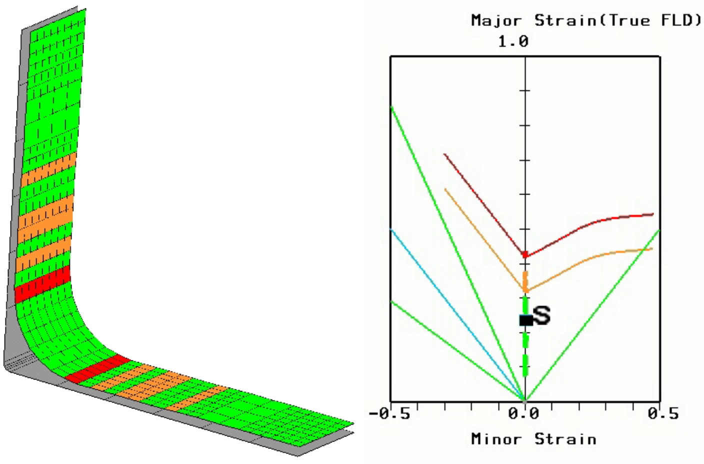


Figure 21 High strain caused by Shell element

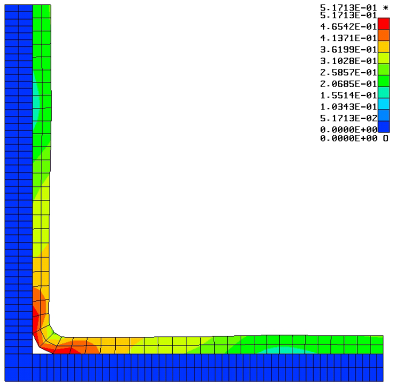


Figure 22 Solid Element

CONCLUSIONS

- LS-DYNA can be used to simulate various bending and hydroforming processes and the performance of hydroformed parts. It can also be used for process parameter optimization and material selection.

In the above corner filling case:

- Friction has a significant effect on hydroforming when the end feeding is applied.
- With proper selection of end feeding, hydroforming of high strength steel can be improved significantly.
- R-value has a significant effect on hydroforming when end feeding is used but has little effect on fixed end cases.
- Both pressure control and volume control methods can be applied using LS-DYNA.
- When internal pressure is high and corner radius is small, shell elements are not adequate to give good results. Solid elements are a better choice.

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REFERENCE

1. Charles Bruggemann, Sanjay Shah, "Hydroforming Process Overview and Applications", The 2nd International Conference on: Innovations in Hydroforming Technology, Columbus, Ohio, 1997
2. Dohmann F., Hartl, Ch., "Hydroforming: Research and Practical Application", The 2nd International Conference on: Innovations in Hydroforming Technology, Columbus, Ohio, 1997
3. Klaus Siegert edited, "Hydroforming of Tubes, Extrusions and Sheet Metals", *Proc. Of International Conference on Hydroforming"*, 1999.
4. X. M. Chen, M. F. Shi and P. M. McKune, S.M. Chen," Applications of High Strength Steels in Hydroforming Dual Phase Vs. HSLA", SAE Technical Paper No.2001-1-1133.
5. X.M. Chen, S.D. Liu, "Experimental and Simulation Study on Tube Bending and Hydroforming", SAE Technical Paper No. 2000-01-1114.
6. S.D. Liu, D. "Tube Hydroforming Process Development with the Aid of Computer Simulation", SAE Technical Paper No.2001-01-1134.
7. Z.C. Xia, "Failure Analysis of Tubular Hydroforming", Proc. of 2000 International Mechanical Engineering Congress and Exposition.
8. Jay Liu, "Experimental and Simulation Study on Tube Bending and Hydroforming", SAE Technical Paper No. 2000-01-1114
9. Chen, Kuo-Kuang, "A simulation for Corner Filling in Tube Hydroforming", To be published
10. LS-DYNA User' Manual, Livermore Software Technology Corporation, 2001

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