Hydroforming Simulation of High-strength Steel Cross-members in an Automotive Rear Subframe

Kee Joo Kim[1,#], Chang Won Sung[2], Young Nam Baik[2], Yong Heon Lee[3], Dae Sung Bae[3], Keun-Hwan Kim[4] and Si-Tae Won[5]

1 CAE Team, Ssang Yong Motor Company, 150-1 Chilgol-dong, Pyungtaek-si, Kyung-gi-do, 459-711, South Korea
2 Department of Mechanical Engineering, Kyung Hee University, 1 Seocheon-dong, Giheung-gu, Kyeonggi-do, 449-701, South Korea
3 Department of Mechatronics Engineering, Hanyang University, 1271 Sa-3dong, Sangnok-ku, Ansan, Kyeonggi-do, 425-791, South Korea
4 Automotive Steel Application Research Group, POPSCO Co., 699 Gumho-dong, Gwangyang-si, Jeonnam, 545-090, South Korea
5 Dept. of Die & Mould Design, Seoul National University of Technology, 172 Gongneung 2-dong, Nowon-gu , Seoul, 139-743, South Korea
Corresponding author / E-mail: kjkimfem@smotor.com, Tel: +82-31-610-3427, Fax: +82-31-610-3770

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Hydroforming is a forming technology in which a steel tube is set in a die and formed to fit a specified shape by applying hydraulic pressure from inside the tube while also applying force in the tube axial direction (axial feed). In present study, the entire design process chain for an automotive cross-member was simulated and developed using hydroforming technology on high-strength steel. The part design stage required a feasibility study. The process was designed using computer-aided design techniques to confirm the actual hydroformability of the part in detail. The possibility of using hydroformable cross-member parts was examined using cross-sectional analyses, which were essential to ensure the formability of the tube material for each forming step, including pre-bending and hydroforming. The die design stage included all the components of a prototyping tool. Press interference was investigated in terms of geometry and thinning.

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1. Introduction

Improving the fuel economy of new automobiles has become an important issue. One of the simplest ways to improve the fuel economy is to decrease the weight of an automobile. Hydroforming technology has become a very competitive manufacturing method with recent advances in high-pressure hydraulic systems, precision control technology, and press capacity. Hydroforming can bring many advantages to automotive applications by providing better structural integrity, reduced production costs, material savings, reduced weight, reduced joining processes, and improved reliability.[1-10]

Hydroforming can be used to economically produce a wide spectrum of automotive parts, including engine cradles, exhaust parts, subframes, radiator supports, side rails, and various body parts. It is a forming technology in which a steel tube is set in a die and formed to fit a specified shape by applying hydraulic pressure from inside the tube while also applying force in the tube axial direction (axial feed). Hydroforming mainly produces parts with hollow sections but varying cross-sectional geometries along their length. A tubular blank is expanded by high-pressure fluid in the die cavity, which is designed to yield the geometry of the final product. The incoming tube, which is cut to the proper length, must be bent so that it is close in shape to the final desired product. Generally, a pre-bent tube requires a preforming process before being placed in the cavity of the hydroforming die. In most cases, the preformed geometry significantly influences the success of the hydroforming process. Once preformed, the tube is delivered into the hydroforming die and pressurized from both ends by an internal fluid.

The strength grade of the tubular material used for hydroforming is increasing, which aids in the production of lightweight automobiles. Recently, 400–500-MPa tensile strength-grade steel material has been adapted especially for structural chassis parts. Some chassis parts are under development using over 590-MPa tensile strength-grade steel. In this study, the development of an automotive cross-member included in the rear subframe is proposed using tube hydroforming of 440-MPa tensile strength-grade steel material. The quality of a simulated and an experimentally measured cross-member is compared in terms of geometry and thinning.

2. Part Design

A rear subframe is placed underneath passenger cars to connect the rear wheels, axle, and body. The rear wheels are connected to the subframe by links or arms to provide suspension. The rear subframe is composed of front and rear cross-members. In the present study, the front cross-member included in the rear subframe, shown in Fig. 1, was developed using tube hydroforming.

At first, the part was thoroughly examined along its length to determine the feasibility of using the hydroforming process. Figures 2 and 3 show an analysis of the cross-sectional perimeter along the cross-member.

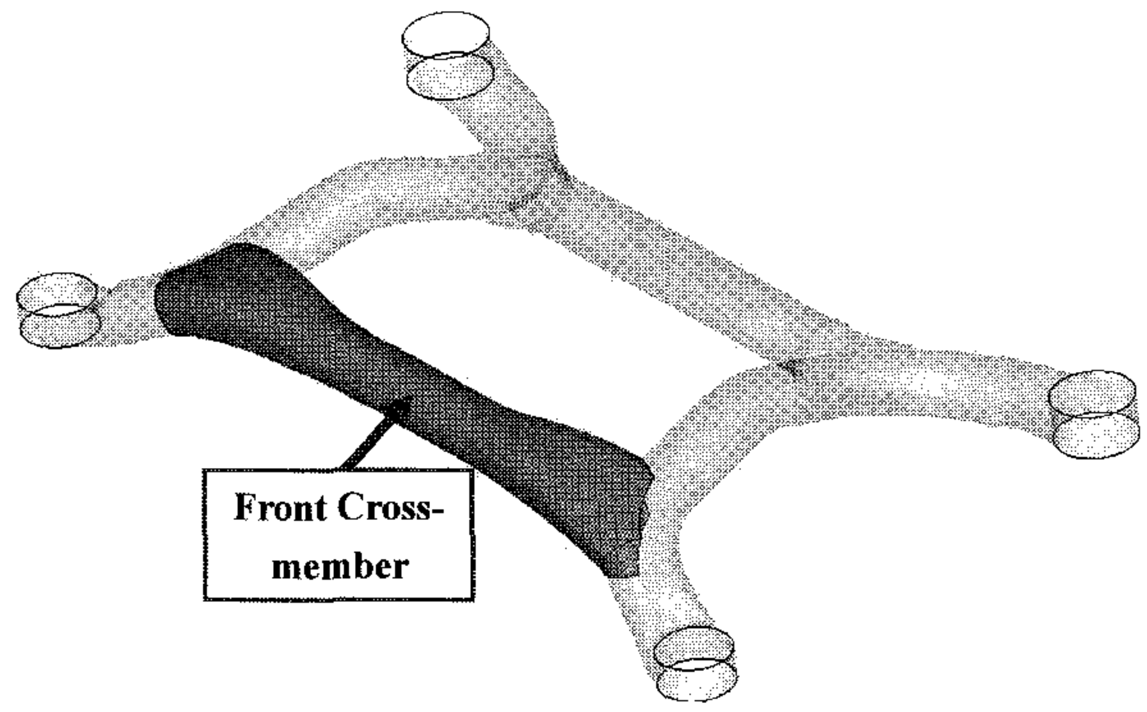
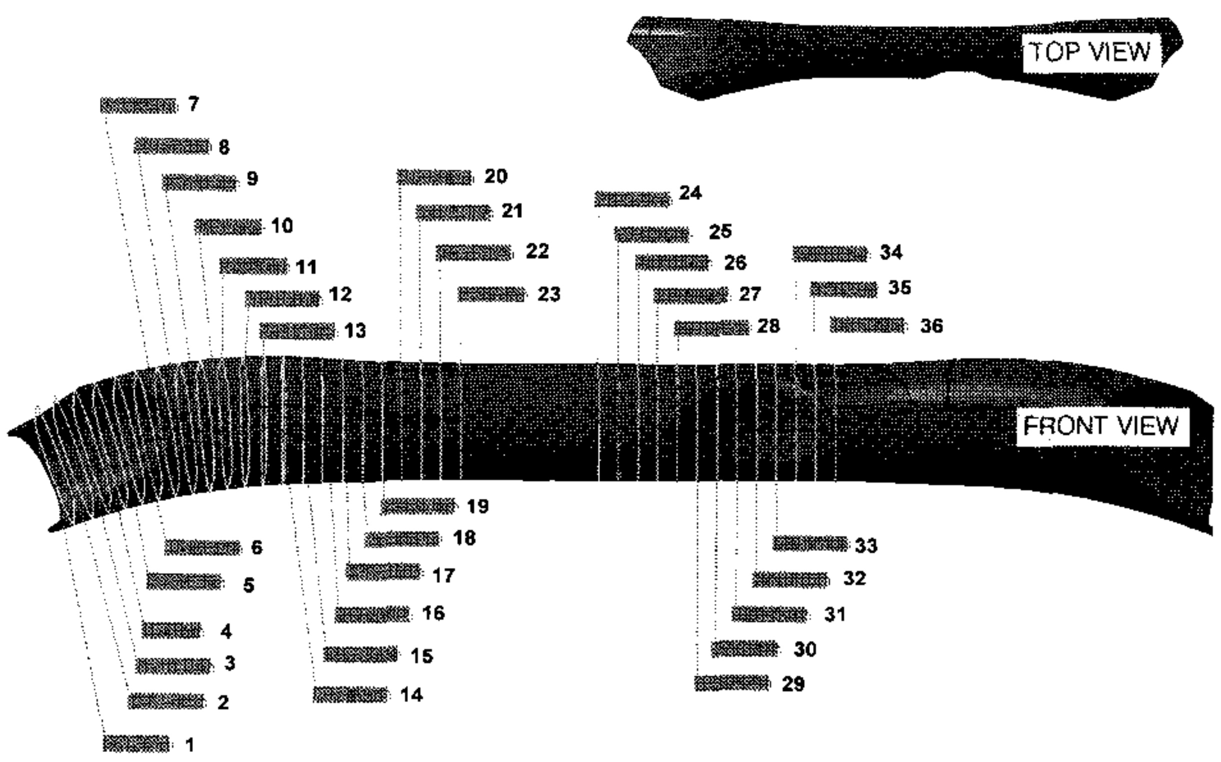


Fig. 1 Front cross-member geometry included in the rear subframe



No	Section Length	Expansion Ratio
1	349.9	46.2
3	349.9	46.2
5	349.9	46.2
7	339.3	41.7
9	327.2	36.7
12	313.7	31
15	290.4	21.3
18	263.4	10
21	242.6	1.3
24	239.7	0.1
27	239.6	0.1
30	229.3	-4.2
33	225.6	-5.8
36	240.5	0.5

Fig. 2 Cross-sectional analysis (length unit: mm, expansion ratio: %)

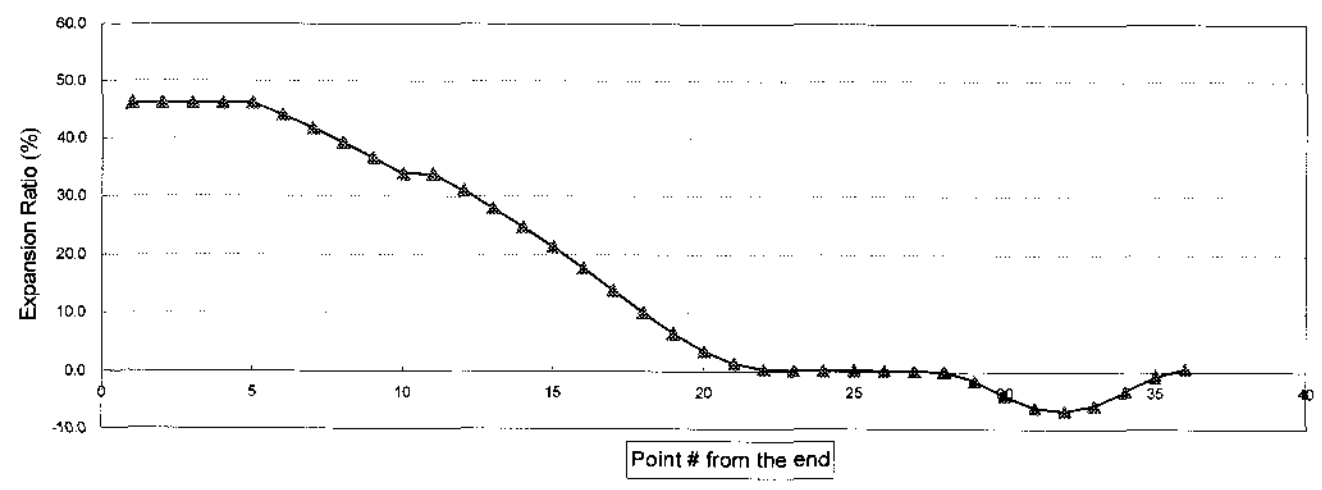


Fig. 3 Cross-sectional analysis: point number from the end versus expansion ratio

This was used to obtain the minimum and maximum circumferential lengths and the minimum corner radius to determine an appropriate tube size and approximate the required closing forces and calibration pressure for the mechanical properties of the tube. The minimum and the maximum perimeters were 225.6 and 349.9 mm, respectively, and corresponding expansion ratios were –5.8% and 46.2%.

The optimum tube for this part has an outer diameter of 76.2 mm (3.0 inches), which gives a circumference of 239.4 mm. Although the maximum expansion ratio, located near the end of the part was high, the tube is suitable because it can be expanded in this region with the aid of axial feeding during the hydroforming process. Since the minimum expansion ratio is smaller than the tube circumferential length, a wrinkle can be expected. Table 1 shows the results of a preliminary analysis used to obtain the axial feed force and to determine the appropriate press capacity.[11,12] The tubular material properties for the hydroforming process simulation were obtained from a tensile test. Sheet tensile specimens with a gauge length of 50 mm were prepared from the tube material. The tensile tests were performed using an Instron machine with an initial strain rate of 5×10^{-4} /s. Tensile elongation was determined with an extensometer. Figure 4 shows the true stress–true strain curve for the tubular material, which was a high-strength steel tube with a tensile strength of 473 MPa. Elastic–plastic work hardening material and the Coulomb friction model were used with a friction coefficient of 0.1. The anisotropy was not considered. The model for hydroforming consisted of an upper die, a lower die, and a tube that was in a geometrically bent shape.

Table 1 Calculated press capacity

Corner radius, minimum	8.0 mm
Tube size (determined)	76.2 mm (outer diameter)
Thickness of tube wall (given)	2.3 mm
Maximum force to seal tube ends	57.1 t
Force to move materials at tube ends	30.3 t
Force due to friction	51.8 t
Calibration pressure, minimum	1,419.4 bar
Axial feed force	139.2 t

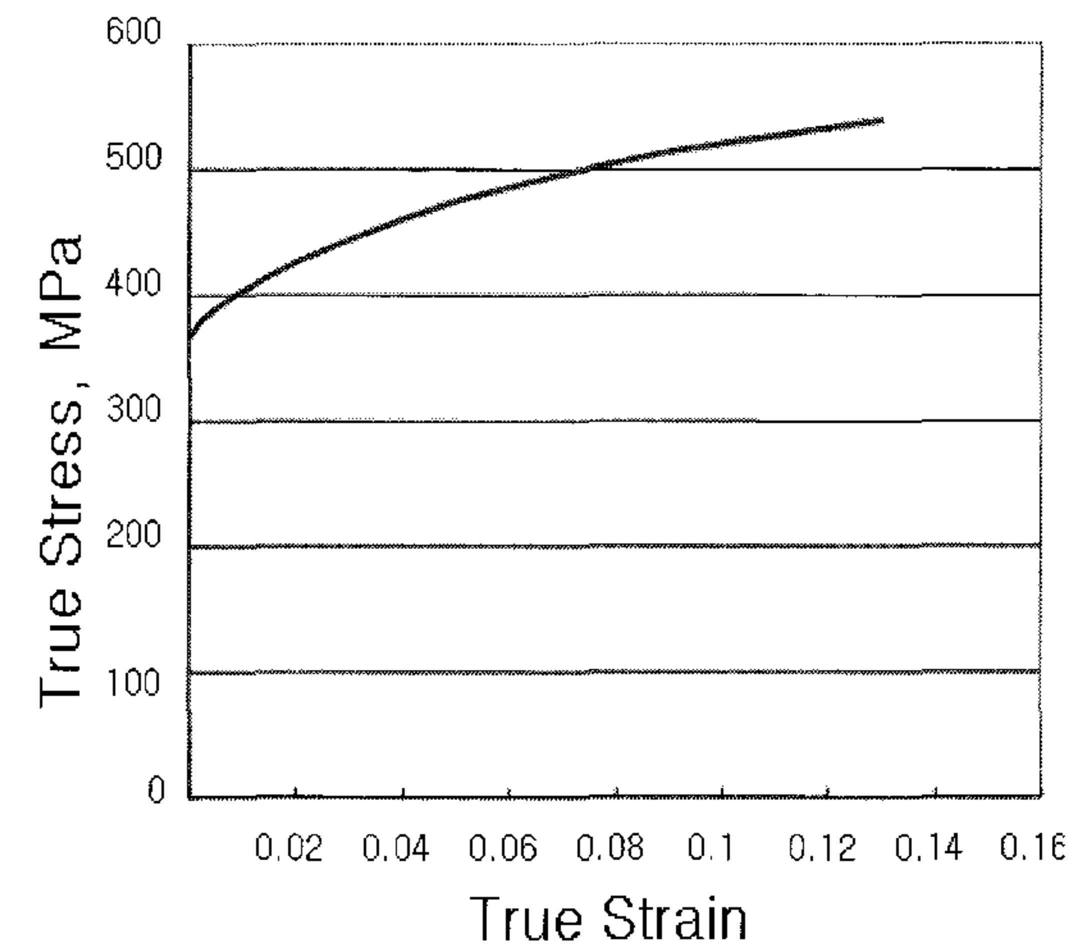


Fig. 4 True stress–strain curve of the tube material

The bending and hydroforming simulation was performed with LS-DYNA3D, an explicit commercially available program. Approximately 50,000 shell elements were used, and the tools (upper and lower dies) were modeled with rigid elements.[12-15] Figure 5 shows the hydroforming lower die cavity and the bent tube model, which was subjected to a two-time bending process before insertion into the die cavity. The interference between the lower die and tubular blank models was carefully examined.

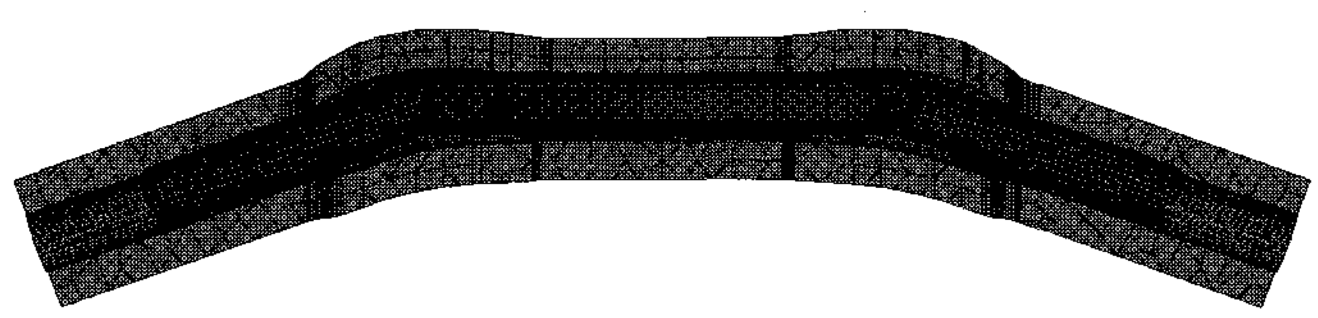


Fig. 5 Initial mesh of the hydroforming die cavity and tube

When the die closed, the incoming tube was crushed between the upper and the lower die cavity. The tube wall can be pinched if the width of the tube is larger than that of the cavity. However, in present study, after substituting the bending simulation tube into the die cavity model, preforming was not required in the die cavity before hydroforming, as shown in Fig. 5.

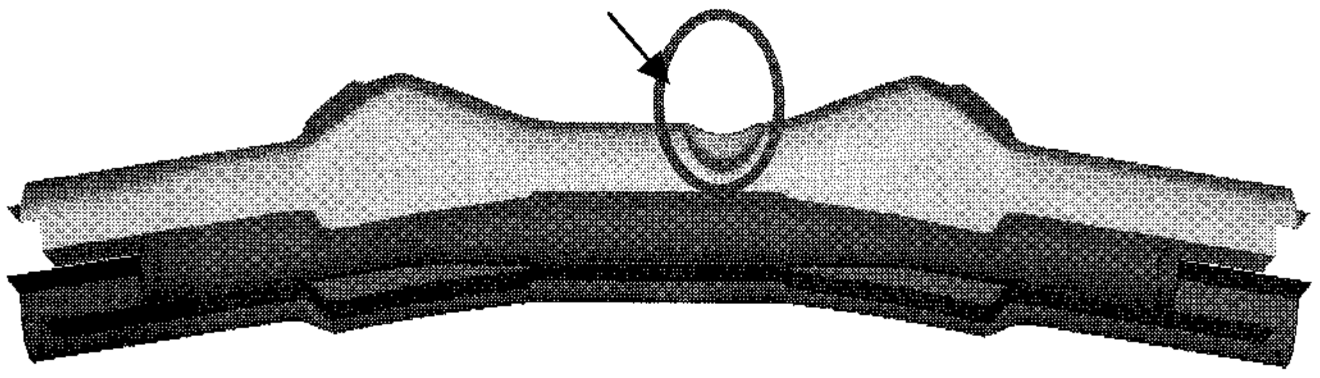


Fig. 6 Hydroforming simulation model including the upper die and tube

Figure 6 shows the model for the hydroforming simulation, including the bent tube and upper and lower dies. A wrinkle was expected at the region indicated by the arrow because of the high concave hollow.

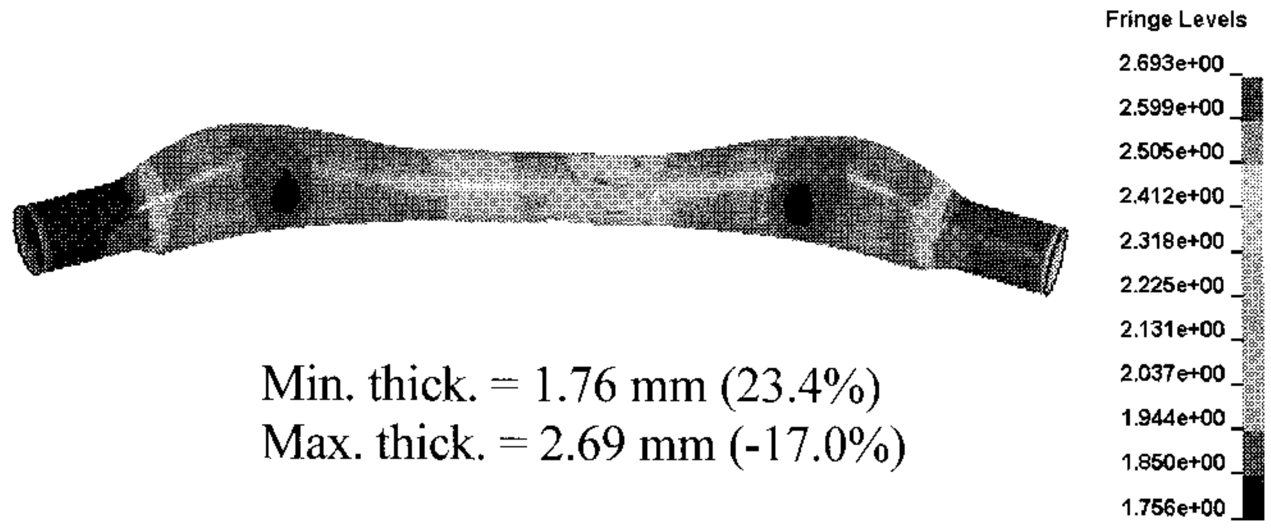
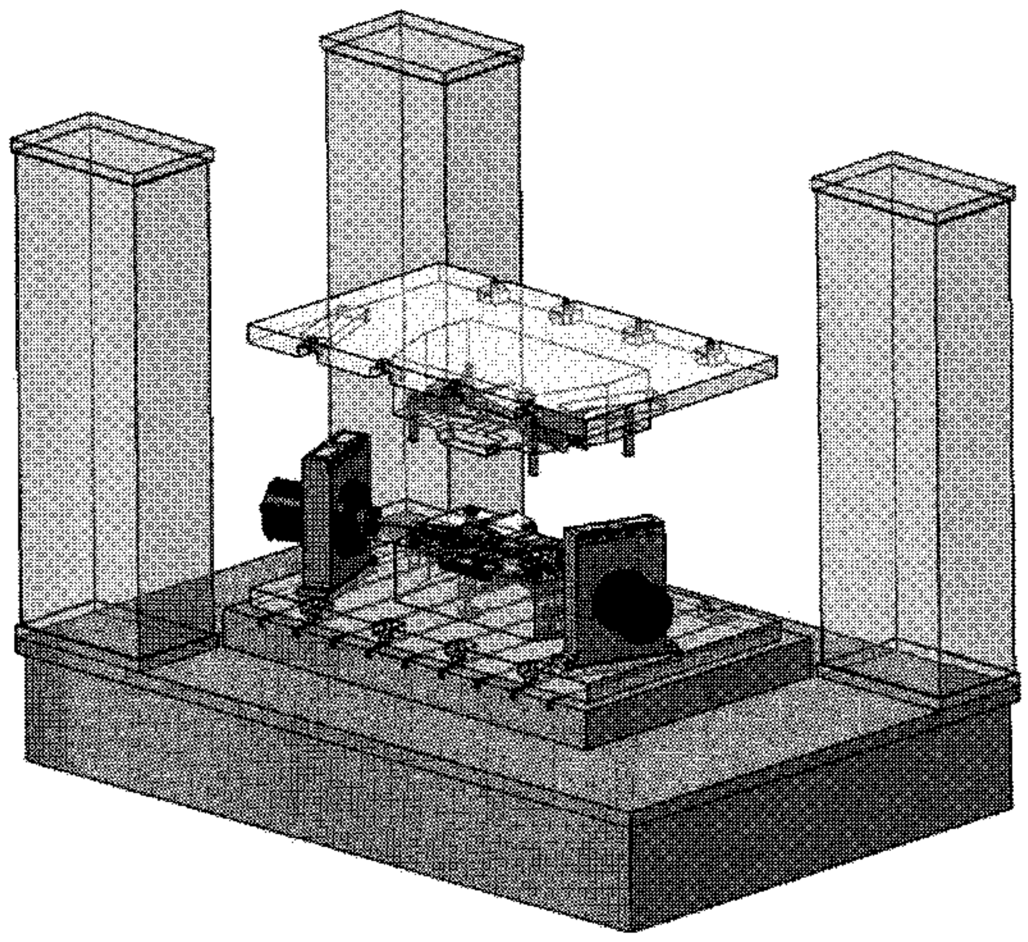


Fig. 7 Predicted geometry and thinning distribution after the hydroforming process

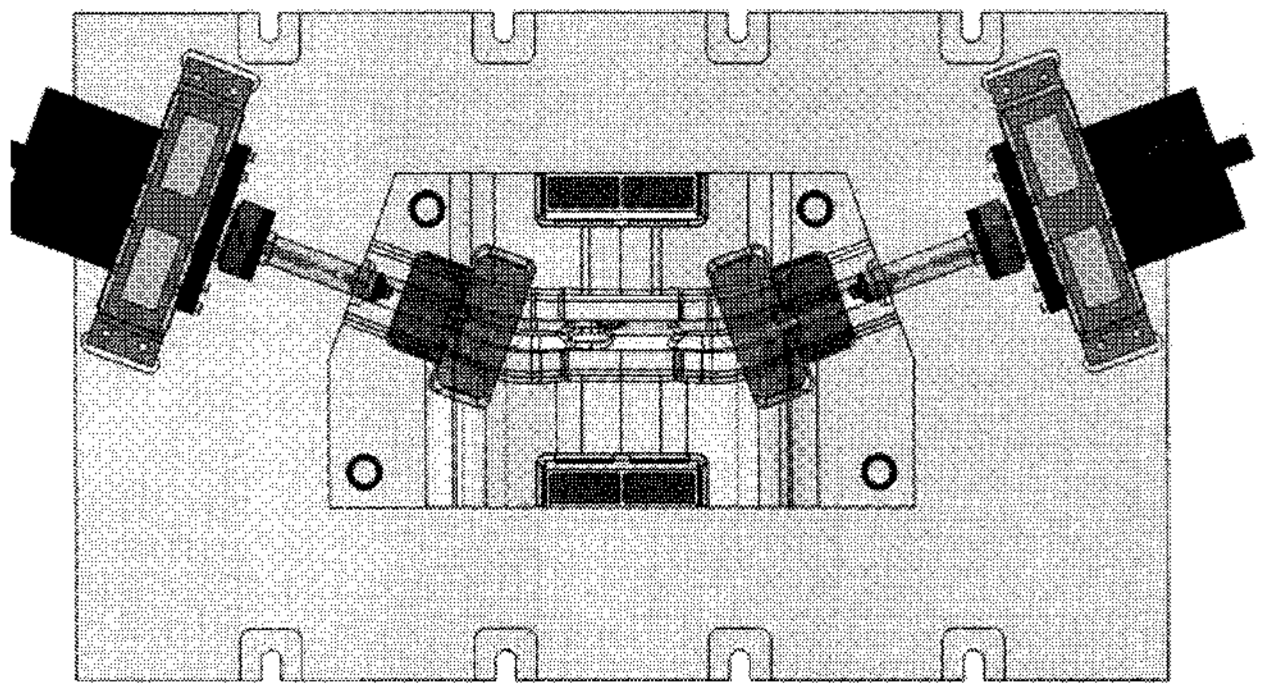
Figure 7 shows the part after completing the hydroforming process. An additional axial feed of 80 mm was applied at both ends of the part to supply material to the zone where thinning occurred to prevent bursting. The maximum thinning was 23.4% at the inner corner of the cross section, as shown in Fig. 7. This is acceptable from a design viewpoint considering it is located in an inner region that can be thickened by the two-time bending process.

3. Die Design

An overview of a hydroforming die design for prototyping is shown in Fig. 8. The detailed die design was performed using CATIA V5. The hydroforming die consisted of several components such as guiding plates, a pressure plate, a guide pin/bush, an ejector, an axial cylinder, and a die monoblock. The interference between the die and the press column must be considered. Figure 8(b) shows a detailed top view of the lower die design with the cavity and axial forming cylinders.



(a) iso-view



(b) top view

Fig. 8 Overall die design including the press column

4. Comparison between Simulated and Experimental Results

Figure 9 shows the experimentally manufactured hydroformed cross-member of the rear subframe.

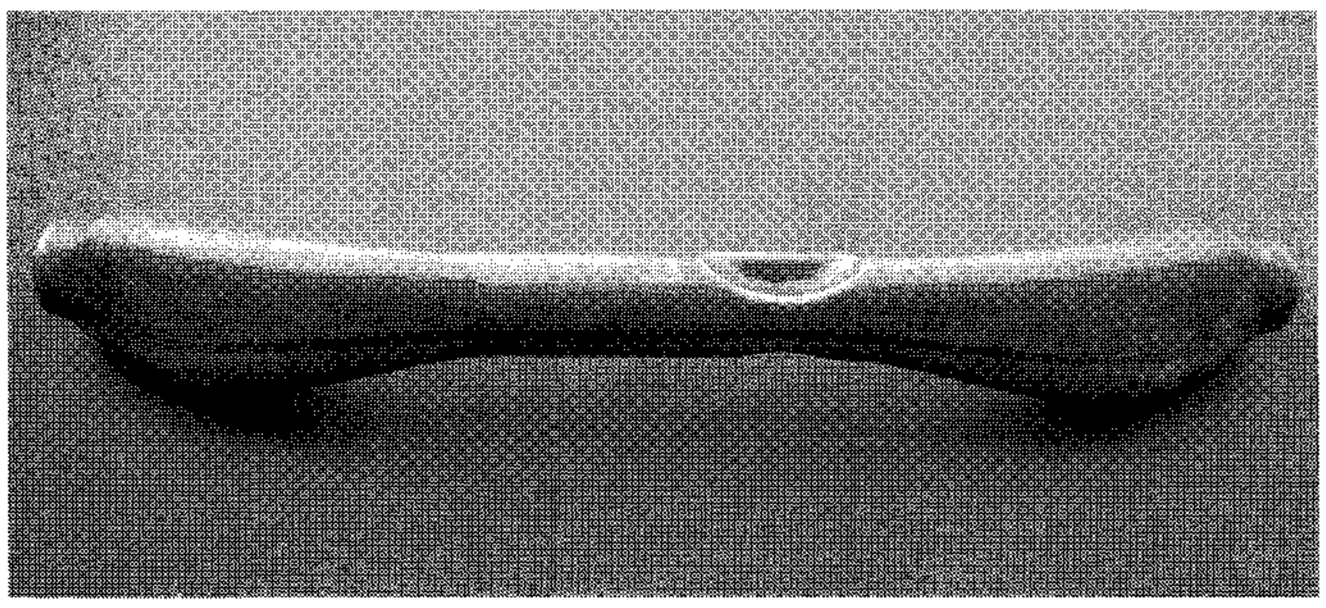


Fig. 9 Hydroformed part

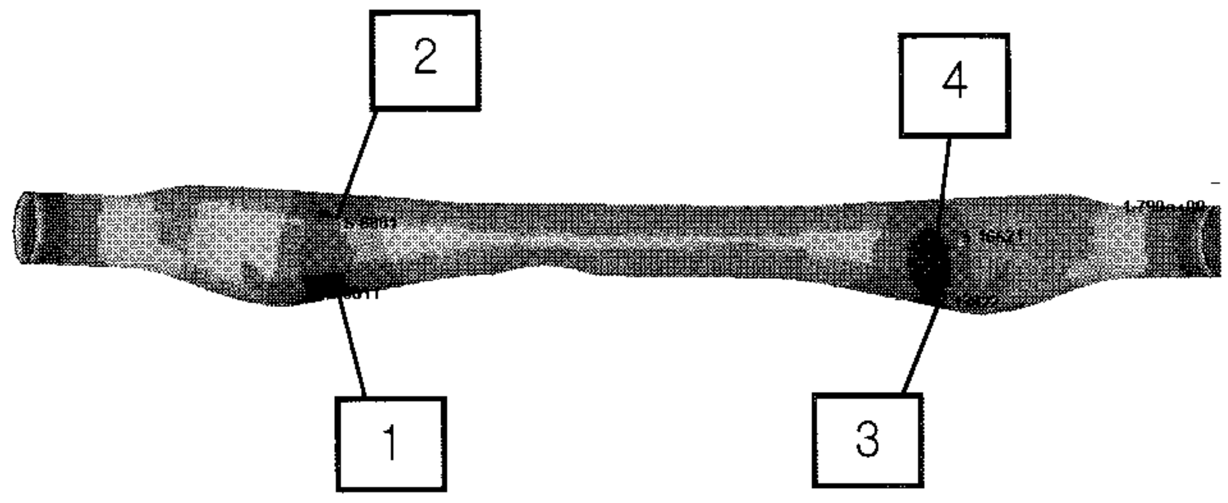


Fig. 10 Positions at which the thickness of the experimentally formed hydroformed part was measured

Several types of defects were found during the hydroforming prototyping, such as bursts and wrinkles, which were caused by various factors. These were corrected by applying a lubricant or controlling the appropriate process condition.

Figure 10 shows the positions at which the experimentally formed hydroformed part thickness was measured using a three-dimensional laser scanner. The results of measured thinning are listed in Table 2. The minimum thickness reduction was 1.84 mm (at position 1 or 3). The position of the maximum thinning corresponded to the simulation results. The maximum deviation was 2.51%, and the geometry of the experimental part was in good agreement with the simulation results.

Table 2 Calculated and measured thickness

Position	Measured	Calculated	Deviation
1	1.87 mm	1.85 mm	1.07%
2	1.99 mm	1.94 mm	2.51%
3	1.84 mm	1.88 mm	-2.17%
4	1.99 mm	1.98 mm	0.50%

5. Conclusion

A hydroformed cross-member of an automobile rear subframe was developed successfully using 440-MPa tensile strength-grade steel tube using the entire process chain for tube hydroforming. For the part design, preliminary analyses along the given part geometry were performed to determine the overall process. The distribution of the expansion ratios was acceptable, and the calculated process parameters, such as die closing force, calibration pressure, and axial feed force, met the capability of the equipment. The part was experimentally fabricated using a prototyping die for hydroforming. After the completing the hydroforming process with an additional axial feed of 80 mm at both ends of the part to supply material to the end zones where thinning occurred, the maximum thinning was reduced to 23.4%. The maximum deviation between the experimental and simulated parts was 2.51%, and the geometry of the experimental part was in good agreement with the simulation results.

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