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# Development of automotive engine cradle by hydroforming process

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## Abstract

The hydroforming technology may bring many advantages to automotive applications in terms of better structural integrity of the parts, lower cost from fewer part count, material saving, weight reduction, lower springback, improved strength and durability and design flexibility. In this study, the whole process of front sub-frame parts development by tube hydroforming using steel material having tensile strength of 440 MPa grade is presented. At the part design stage, it requires feasibility study and process design aided by CAE (Computer Aided Design) to confirm hydroformability in details. Effects of parameters such as internal pressure, axial feeding and geometry shape in automotive engine cradle by the hydroforming process were carefully investigated. Overall possibility of hydroformable engine cradle parts could be examined by cross sectional analyses. Moreover, it is essential to ensure the formability of tube material on every forming step such as pre-bending, preforming and hydroforming. At the die design stage, all the components of prototyping tool are designed and interference with the press is examined from the point of deformed geometry and local thinning.

*Keywords*: Hydroforming; Engine cradle; Axial feeding; Bending; Thinning

## 1. Introduction

The hydroforming has quite a long technological history of over 5 decades. The hydroformed parts at early stage were manifold elements in simple geometry, similar parts for sanitary use and some instruments [1]. Nowadays, the hydroforming technology has become a very competitive method with the advances in high pressure hydraulic systems, technology of precise control by computer and press capacity. It offers many advantages in comparison with conventional manufacturing technologies such as weight reduction through parts consolidation, integrated process of forming lower cost with fewer parts and tools, fewer secondary operations e.g. hole punching and welding, lower springback which reduces dimensional variations after forming, improved strength and durability and design flexibility where geometry of cross section can be varied along the part [2-4].

It can produce a wide spectrum of automotive parts including engine cradle, exhaust parts, front and rear sub-frame, radiator supports, side rails, camshaft and

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various body parts in an economic way. It mainly produces parts with hollow section but varying cross sectional geometry along the length. Tubular blank is expanded by high-pressurized fluid in the die cavity, which is designed to yield the geometry of the final product. The incoming tube, which is cut to proper length, needs to be bent to have near shape of the final product. Generally, the pre-bent tube requires pre-forming process in order to be placed in the cavity of hydroforming die. In most of the cases, the preformed geometry significantly influences on the success of hydroforming process. The preformed tube is then delivered into hydroforming die and pressurized from both ends by the internal fluid. In order to meet the requirements of light-weight of automobile, the strength grade of tubular material for hydroforming is also increasing. 300~400 MPa grade of tensile strength steel has been widely used for hydroforming. However recently 400~500 MPa grade of steel material is being adapted more and more especially for structural chassis parts. Some chassis parts are under development using over 590 MPa grade of tensile strength steel. In this study, the whole process of engine cradle development by tube hydroforming using 440 MPa grade of tensile strength of steel material is presented. In addition, the comparison of the quality is examined between simulated and experimental engine cradle from the point of geometry and thinning.

## 2. Part design

An engine cradle is placed in the front and under space of the passenger car and as connector between front wheel and body. Front wheels are connected to this part by links or arms to ensure the comfort suspension. The engine cradle is composed of a main member and a cross member. In present study, main member is developed by tube hydroforming. Fig. 1 shows the shape of the engine cradle including a main member and a cross member.

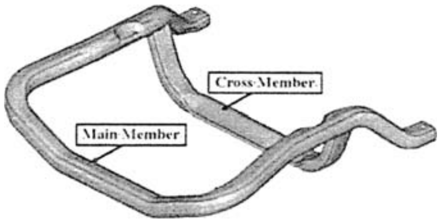


Fig. 1. Geometry of main member and cross member of engine cradle.

At first, the part is thoroughly examined closely along the direction of length to check out the feasibility for hydroforming process. Fig. 2 shows the analysis results of the cross section perimeter along the main member. This is to get the minimum and maximum circumferential length and the minimum corner radius of the part. From these results the proper size of the incoming tube is determined and approximate closing forces and calibration pressure required can be calculated considering mechanical properties of the tube. The minimum and the maximum perimeters are 201.2 mm and 219.8 mm and corresponding expansion ratios are 0.8 % and 10.3 %, respectively. The optimum tube size for this part is 63.5 mm (2.5 inch) of outer diameter which has 199.5 mm of circumferential length. The maximum expansion ratio is acceptable and it is located near the end of the part, which can be expanded with the aid of axial feeding during the hydroforming process. Since the maximum and minimum expansion ratios were larger than tube circumferential length, no wrinkle is expected.

The tubular material properties for hydroforming process simulation (bending, preforming and hydroforming) are obtained from the tensile test and are listed in Table 1. The high strength steel tube with tensile strength of 473 MPa is used. Elastic-plastic work hardening material and the Coulomb friction model are used. The anisotropy is not considered. The model for hydroforming is composed of an upper die, a lower die and a tube which is in geometrically bent shape.

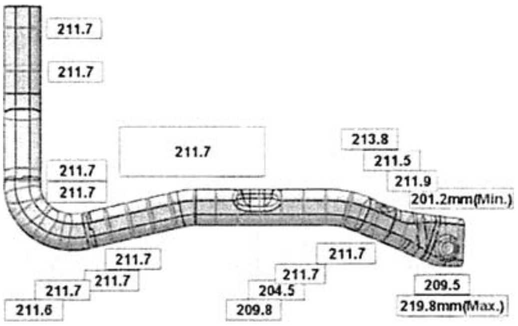


Fig. 2. Analyses of cross sections along the half symmetry part (unit: mm).

Table 1. Mechanical properties of tube material.

| E, GPa | YS, MPa | TS, MPa | U.El, % | T.El, % | n |
|---|---|---|---|---|---|
| 210 | 365 | 473 | 16.3 | 31.4 | 0.15 |

The bending simulation was carried out with LS-Dyna commercially available program. Fig. 3 shows the bent tube after bending simulation with the thickness contour. From the simulation results, the initial tube thickness of 2.3 mm was changed with variation of 1.9~2.7 mm. Fig. 4 shows the model for lower die and tubular blank. The simulation of the hydroforming process is also carried out with LS-Dyna. The interference of the models between the lower die and tubular blank was carefully examined. At a die closing stage, the incoming tube is subjected to be crushed between the upper and the lower die cavity. Tube wall may be pinched where the width of the tube is larger than that of the cavity. Even though the incoming tube is smaller than the cavity, it is still risky that tube wall may be pinched while it was crushed and flattened. In present study, after substituting from the bending simulation tube into the die cavity model, the precrushing (instead of preforming) of the main member was needed to set down at die cavity before hydroforming as shown in Fig. 4.

Fig. 5 shows the final part after the completion of hydroforming process with addition of axial feeding of 20 mm at both ends of the part for supplying materials to the zone where thinning occurs and prevents burst. The crushed tube is completely calibrated to have the geometry of cavity with the maximum internal pressure of 1500 bar. The maximum thinning is 25.0 % (at B-zone) at the corner of cross section near the end of the part and the maximum thickening is 19.1 %. In case of C-zone, the initial thinning was reduced from 26.5 % to 22.6 % after add of axial feeding of 20 mm. As shown in Fig. 5 after hydroforming simulation, the thinning of A, B and C-zone was all over 20 %. For improving these thinning, the examples of some cross sectional correction would be recommended as shown in Fig. 6. In case of A-zone, the section height should be reduced by flattening. In addition, in case of B and C-zone, if the corner part was cut by a slant line then a projecting part was released and expansion ratio was decreased, the thinning could be reduced.

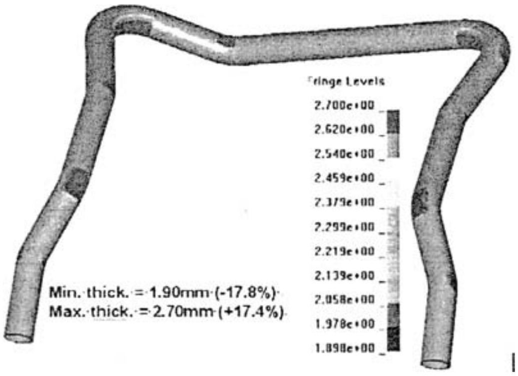


Fig 3. Thickness after simple bending simulation.

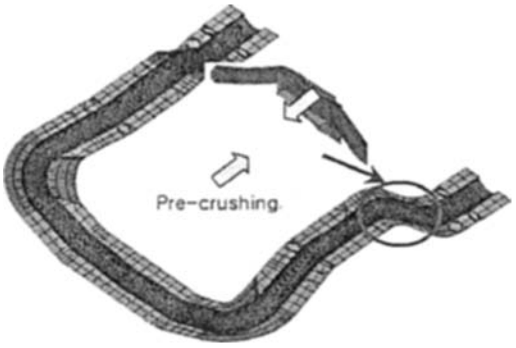


Fig. 4. Initial mesh of hydroforming die cavity and tube.

## 3. Die design

Overview of hydroforming die design for prototyping is shown in Fig. 7. The detailed die design is done with CATIA V5. The interference between die

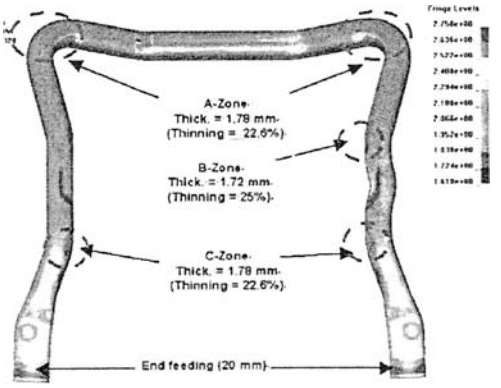


Fig. 5. Predicted geometry and distribution of thinning after hydroforming process.

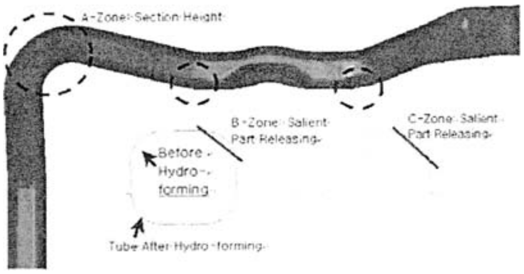
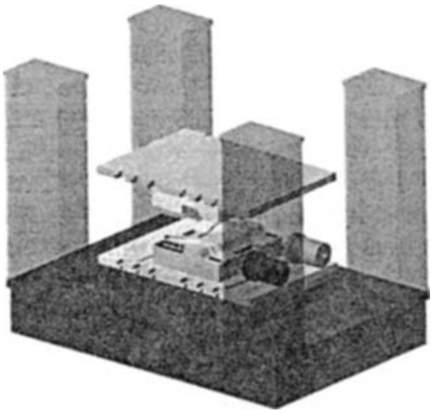
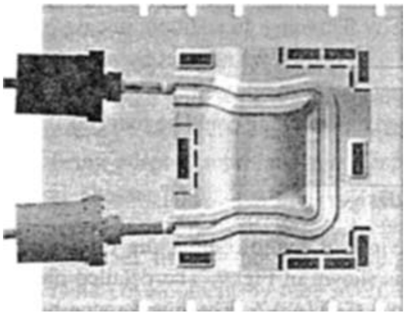


Fig. 6. Example of part geometry modification.



(a) iso-view



(b) top view

Fig. 7. Overall die design including press column.

and press column has to be considered. Fig. 7(b) shows the detailed top view of the lower die design with cavity and axial forming cylinders in the present study.

Meanwhile, for the confirmation of forming possibility, the exact hydroforming pressure and press capacity should be calculated. Fig. 8 shows the thin walled pipe which is pressurized by internal force and the yield strength of the pipe can be described in Eq. 1 [5].

$$\sigma_y = P_i R_i / t \tag{1}$$

Here, $P_i$, $\sigma_y$, $R_i$ and $t$ are internal hydroforming pressure, material yield strength, effective internal radius of the tube wall and tube wall thickness, respectively. The press capacity can be determined by the part total area. The press capacity (hydroforming die closing force), $F_{clamp}$ is proportion to the internal hydroforming pressure and tube size.

$$F_{clamp} = P_i \cdot d_i \cdot l \tag{2}$$

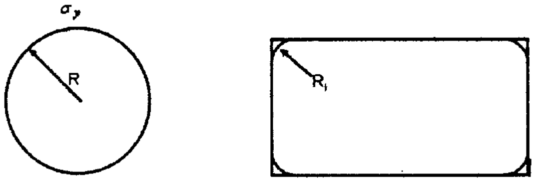


Fig. 8. Relationship between internal pressure and wall thickness.

Table 2. Calculation results of press capacity security.

| | |
|---|---|
| Corner radius, min. | 10 mm |
| Tube size (determined) | 63.5 mm (outer diameter) |
| Thickness of tube wall (given) | 2.3 mm |
| Max.force to seal tube ends | 38.7 ton |
| Force to move materials at tube ends | 25.1 ton |
| Force by the friction | 35.9 ton |
| Calibration pressure, min. | 1,419.4 bar |
| Axial force for feeding | 99.7 ton |

Here, $d_i$ and $l$ are the tube outer diameter and tube length, respectively. In case of being necessity of the axial feeding process, the axial force as a function of intensifier pressure transfer of the internal pipe, sealing and formability insurance, can be calculated as following,

$$F = F_s + F_a + F_f \tag{3}$$

Here, $F_s$ is the maximum force to seal tube ends and $F_a$ is the force to move material at tube ends by plastic deformation. In Eq. 3, $F_f$ is the force by the friction. Table 2 shows the calculation results of press capacity security for knowing the axial force for feeding and calibration pressure using above equations.

## 4. Comparison between simulated and experimental results

Fig. 9 shows the hydroformed part (experimentally manufactured main member of the engine cradle). During the hydroforming prototyping, several types of defect can be found such as burst and wrinkle which are caused by various factors.

Fig. 10 shows the positions of the hydroformed part (experimental) where the thickness is measured by 3-dimensional laser scanner and the results of measured thinning is listed in Table 3. The minimum thickness

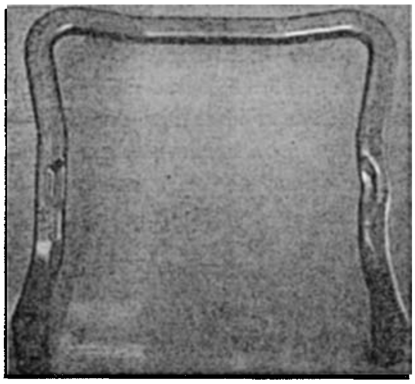


Fig. 9. Hydroformed part.

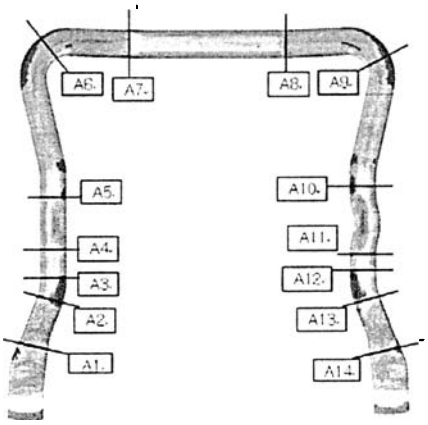


Fig. 10. Positions where the thickness is measured on the hydroformed part.

Table 3. Comparison of the thickness variation between calculated and measured values.

| Position | Measured | Calculated | Deviation |
|---|---|---|---|
| A1 | 2.05 mm | 2.03 mm | 1.0% |
| A2 | 1.81mm | 1.81 mm | 0.0% |
| A3 | 1.83 mm | 1.83 mm | 0.0% |
| A4 | 1.89 mm | 1.93 mm | -2.1% |
| A5 | 1.83 mm | 1.85 mm | -1.1% |
| A6 | 1.84 mm | 1.76 mm | 4.4% |
| A7 | 1.60 mm | 1.72 mm | -7.5% |
| A8 | 1.96 mm | 1.87 mm | 4.6% |
| A9 | 1.82 mm | 1.80 mm | 1.1% |
| A10 | 1.79 mm | 1.75 mm | 2.2% |
| A11 | 1.79 mm | 1.75 mm | 2.2% |
| A12 | 1.74 mm | 1.79 mm | -2.9% |
| A13 | 1.78 mm | 1.79 mm | -0.6% |
| A14 | 2.17 mm | 1.95 mm | 10.1% |

of the part is 1.60 mm (at A7 position). The position of the maximum thinning corresponds to the result of the simulation. As shown in Table 3, the maximum deviation is 10.1 % and the geometry of the experimental part is in good agreement with the simulation results.

## 5. Conclusion

The hydroformed main member of the engine cradle was developed successfully using 440 MPa tensile strength grade of steel tube through whole process chain of tube hydroforming. For the part design, preliminary analyses along the given part geometry were carried out and overall processes were designed. It was found that the distribution of expansion ratios was in acceptable level and calculated process parameters such as die closing force, calibration pressure and axial force for feeding met the capability of the equipment. According to the simulation, thinning of the tube wall was predicted to have acceptable value. The experimental part was fabricated using prototyping die for hydroforming and was inspected. The minimum thickness took place where it was predicted in simulation and the value was 1.60 mm, which meets the requirement of the part development. The hydroformed part was in very good dimensional accuracy.

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