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Development of Hydroforming Technology

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Abstract

Recently hydroforming has been applied for auto parts however it has problem that forming condition is difficult. In this report, hydroforming tests and FEM analysis with simple shape were carried out and deforming behavior during hydroforming were observed. It was found that the loading path of internal pressure and axial feeding has effect on hydroforming deformation. Next hydroforming allowance evaluation method was developed. By this method, the effect of material properties was proved. The conventional hydroforming machine is large and expensive, but a compact machine was developed. By these results, hydroforming market becomes larger.

1. Introduction

Hydroforming (hereinafter abbreviated as HF) has been known as bulging, and has been employed in the manufacturing of bicycle components[1)], piping joints[2)] and the like from long ago. Additionally, the reduction of automobile weight has been pursued over the last several years, as seen typically with the ultra-light steel auto body (ULSAB) project[3,4)], and HF has come to be widely employed in the manufacture of automobile components. Its application in this field began in Europe and North America[5,6)], and has been showing rapid expansion in those countries. In Japan, on the other hand, the application of HF to the manufacture of car components began in 1999[7,8)]. The authors studied the forming method in parallel to the above historical trend and developed a wide variety of technologies related to HF such as fundamental forming methods, material evaluation methods, actual auto parts and forming machine. This paper presents some results of those research and development activities.

2. Characteristics of Hydroforming

HF is a method for forming tubes by placing a tube between a pair of metal dies and applying hydraulic pressure to the inside of the tube. In order to prevent wall thinning of the tube, it is forced toward and into the dies from both its ends (hereinafter referred to as axial feeding) during the forming process to realize a large deformation.

In the application of HF to the manufacture of automobile components, it is often the case that the shape of the dies are so complicated that a tube in its original straight shape does not fit into the dies, and it undergoes pre-forming work for bending and/or partially flattening before the HF process. It is also possible to pierce a hole in a work while the hydraulic pressure is applied to it. Thus, in discussions relating to HF, recently, all of these steps are well understood as parts of the HF process (see **Fig. 1**).

The reasons why HF is rapidly expanding its application in the

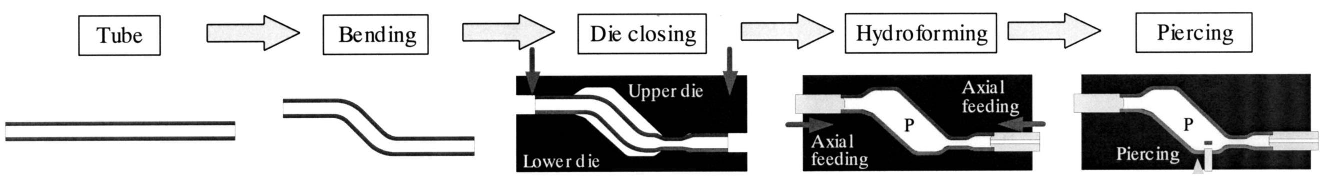

Fig. 1 General hydroforming process

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field of automobile component manufacture, namely its advantages over conventional press forming, include the following:

(1) Cost reduction by integration of some components
(2) Weight reduction by reducing of welded flanges for joining parts
(3) Improvement of fatigue properties by reduction of welded joints
(4) Improvement of component strength by forming in closed sectional shape and work hardening
(5) Simplification of work processes by hole piercing in dies and reduction of welded joints
(6) Improvement of yield by reduction of trimming margins
(7) Reduction of spring back by plastic forming of an entire piece
(8) Capability of large deformation by realizing as much shear deformation as possible

Despite these advantages, the application of HF is still limited compared to that of press forming, and its use is not expanding to a wider variety of automobile components. The reasons for this, or the shortcomings of HF, are the following:

(1) The forming conditions are complicated, and require particular skill.
(2) The forming machine is very large and expensive.
(3) Work cycle time is long and productivity is low.
(4) Spot welding of a product with other parts or components is difficult.

Item (1) above, especially, is due not only to the fact that HF is a new technology but also to the fact that there are many parameters for the forming work and they are interrelated with each other in a complicated manner. To be more specific, the combination of the internal hydraulic pressure and axial feeding and their loading path (their application pattern) determine the viability of the forming work[9,10] and what is more, the optimum conditions of these factors are different with different materials. In view of the above, this paper explains which forming condition of HF is effective in adequately forming which material. This paper also presents development of a compact and economical HF machine as an example of studies related to item (2) above.

3. Influences of Loading Path over Hydroforming Process

3.1 Methods of tests and FEM analysis

In consideration of the fact that the loading path of the internal pressure and axial feeding determines the viability of forming work by HF, the authors conducted forming tests using simple shape dies for the purpose of examining the general influences of the loading path. The materials used were steel tubes 63.5 mm in outer diameter, 2.3 mm in wall thickness and 490 mm in length having a yield stress (YS) of 340 MPa, a tensile strength (TS) of 400 MPa and a total elongation (El) of 38.1%. Anti-corrosion oil having good lubricity was applied to the outer surface of the tubes. The dies were those for forming a work having a rectangular section 95 × 63 mm, as shown in **Fig. 2**.

A simple loading path was used for the tests: as seen in **Fig. 3**, internal pressure was raised to p_H under a slight axial feeding stroke at each of tube ends for sealing purposes, then the axial stroke was increased to δ_F at each end while the internal pressure was kept at p_H (holding pressure), and finally the internal pressure was raised from the holding pressure to a burst pressure p_B while the axial stroke was kept at δ_F. Although it is common HF practice to apply an axial stroke and raise internal pressure at the same time, internal pressure was kept constant during axial feeding at the tests for the purpose of decreasing the number of parameters. Another fact to be taken into consideration was that, under a fixed final pressure, the final shape of a work such as corner shape changed depending on the strength of its material. For this reason, the internal pressure was raised at the final forming stage until the work burst.

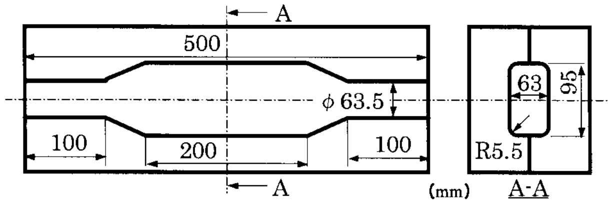


Fig. 2 Die shape for HF tests

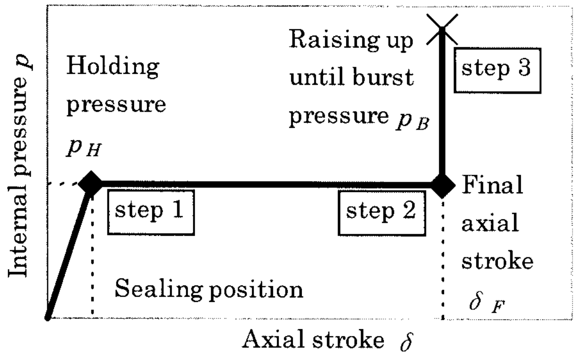


Fig. 3 Loading path in HF tests

In parallel to the tests, FEM analyses to examine the phenomena observed at the tests in detail were conducted. The solver employed was a dynamic explicit method (PAM-STAMP), and the shell element used was about 2.5 mm square. Work hardening was approximated using the n-power's hardening law, and the friction coefficient μ was set at 0.07. The die conditions and the loading path were the same as those of the tests.

3.2 Deformation during hydroforming process

The deformation of a work during the HF processes was observed in the first place. **Fig. 4** shows the results of the forming tests and FEM analyses of deformation at different forming steps under the conditions of p_H = 36 MPa and δ_F = 40 mm. The work little ex-

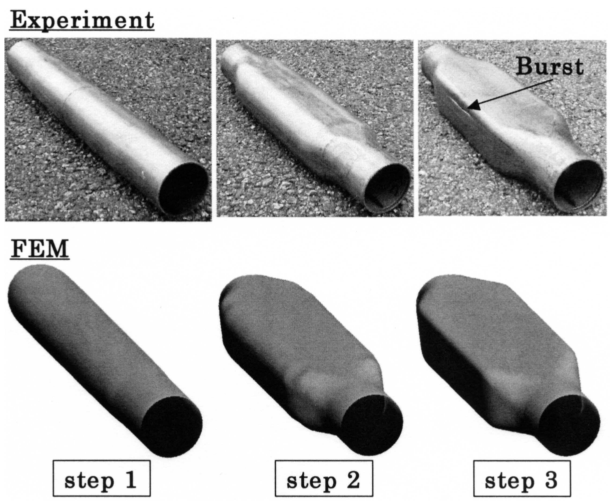


Fig. 4 Deforming shape during HF process

panded at step 1, the first stage, then at step 2 it expanded in the circumferential direction as axial feeding proceeded. That is, whereas at step 1 the axial stroke was small, and as a consequence, the deformation was presumed to be a plain strain deformation and yield condition was not reached yet, at step 2 the yield condition was reached as a result of application of the axial compression, and the expansion of the steel tube proceeded. Under the internal pressure increase at step 3, the final stage, only the corner portions were formed, and the work finally burst in most cases at an end of a corner radius where a flat portion began to curve at a corner.

It is seen with the photos in the figure that the FEM analysis simulates well the deformation processes of the tests. It was also confirmed that the results of the FEM analysis well agree with test results quantitatively with respect to aspects such as the shape of wrinkles occurring during the HF processes. For further details, see reference literature 11.

Then, the influences of the loading path were examined using the FEM. **Fig. 5** shows the deformation behavior during HF work under different holding pressures at a final axial stroke δ_F of 40 mm. Part (a) shows the behavior of minimum wall thickness strain. Since the plotting is that at the position showing the smallest wall thickness strain during the course of the forming work, the position changes from time to time as deformation proceeds. The portion of a curve

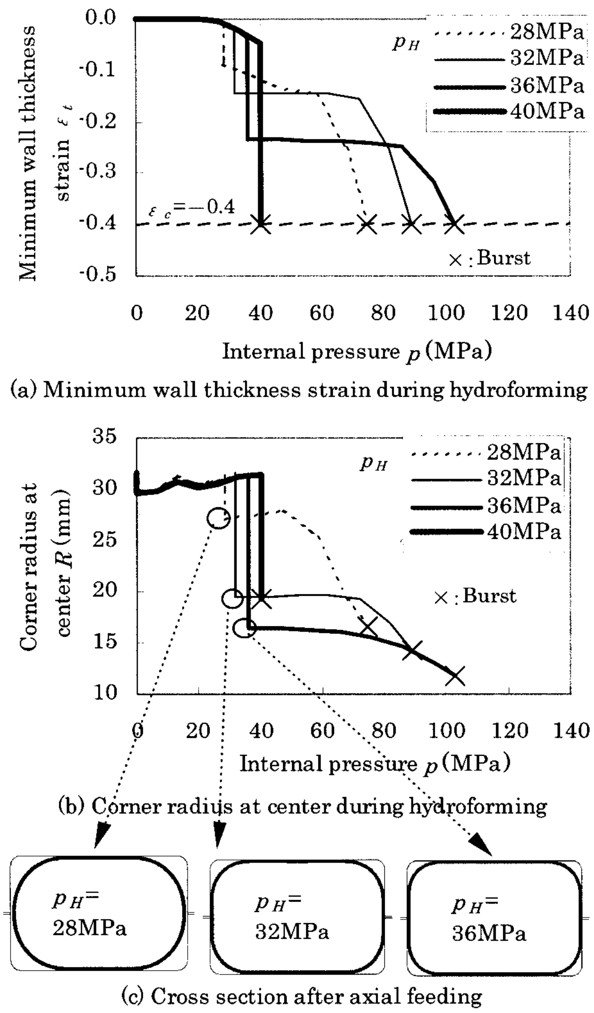


Fig. 5 Behavior of wall thickness strain and corner radius during HF

showing a vertical fall of strain corresponds to the process of step 2 where axial feeding was conducted (axial stroke was increased) under a constant internal pressure, and the mark × indicates the point where the work burst. Here, it was assumed based on actual measurement that a work would burst when critical strain ε_C fell to −0.4. Part (b), on the other hand, shows the outer corner radius at the center section of a work. The sectional shapes at the end of axial feeding, which is marked with a circle, are shown in part (c).

It is understood from the FEM results that the expansion of a work during axial feeding becomes larger as the holding pressure p_H becomes high: in the case of p_H = 36 MPa, the corner radius at the end of axial feeding (step 2) is considerably small and the work has a sectional shape closely fitting to the dies. As the expansion proceeds, the wall thickness naturally decreases, and as a result, in the case of p_H = 40 MPa, which is too high a holding pressure, a critical wall thickness is reached during axial feeding, and the work bursts.

However, as far as the holding pressure is within the range not to cause burst during axial feeding, the lower the holding pressure, the quicker a critical strain is attained during the final pressure increase (step 3) and the work bursts at the lower pressure. This is because, as is understood from the sectional shapes shown in part (c) of Fig. 5, the higher the holding pressure p_H, the more closely a work fits to the dies at the end of axial feeding (step 2) making the gaps at the corners the smaller, and the better the work withstands the pressure rise thereafter. In other words, the material of a work flows during axial feeding, and it flows also in the circumferential direction more or less evenly, but during the pressure rise after the end of axial feeding, the work is arrested at the portions where it is in contact with the dies and strain concentrates at the ends of a curved portion, and as a consequence, a work bursts more easily with a larger gap at a corner.

As shown above, the loading path has significant influence over the formability of HF, and it is essential to choose the most suitable loading path. For example, one can conclude from the above results that it is better to set the holding pressure during axial feeding as high as possible but not to cause bursting; by so doing the final pressure can be made higher and a better sectional shape can be obtained.

4. Influences of Tube Material over Hydroforming Process

4.1 Development of forming allowance evaluation method for hydroforming

The preceding section has made clear what kind of loading path is suitable for the forming work by HF, though with one example. A study was conducted into what kind of steel tube material was suitable for HF.

There has been no widely established method for evaluating the formability of a material tube by HF, except for the evaluation through free bulging tests[12,13]. By this method, however, evaluation has been done only within a range of strain ratio β (= strain in the axial direction / strain in the circumferential direction) of $-0.5 \leqq \beta \leqq 1$. In the actual forming work by HF, on the other hand, the dies constrain a work from outside, and the range of strain often extends to a shear zone ($\beta < -0.5$)[14]. Another problem with HF is that the most suitable loading path is different depending on the material of a work; as a consequence, evaluation of different material tubes based on a specific loading path does not bring about fair results.

In view of the above, the authors attempted relative evaluation of material tubes in terms of the range of successful forming by HF. Such a concept of forming allowance, so to speak, has been used in the field of press forming: the relative evaluation of forming allow-

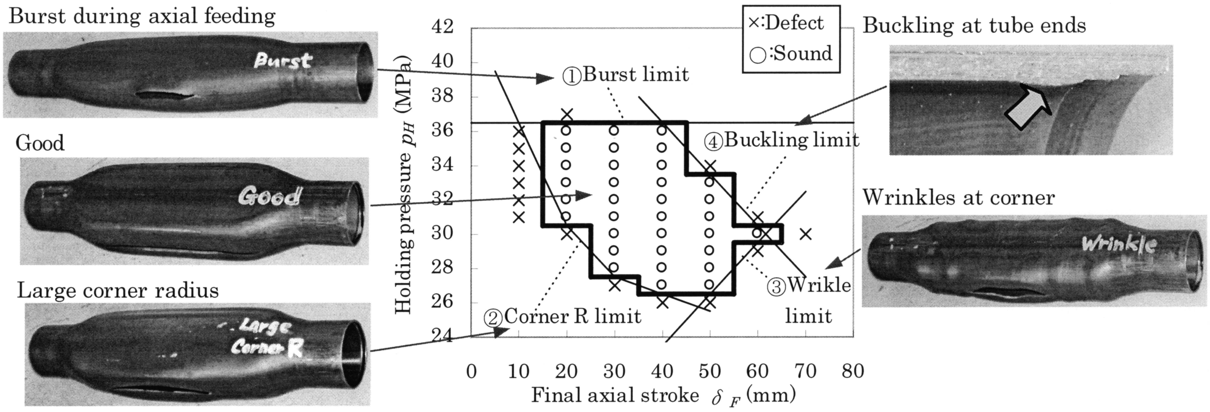


Fig. 6 Forming allowance evaluation for HF

ance has been done by changing the blank holder force and thus determining a range of the force to realize forming work without cracking or wrinkling. In contrast, as described earlier, in HF there are many parameters having influences over the forming work, and similar evaluation has been difficult. However, a loading path such as the one shown in Fig. 3 used for the tests described in section 3 allows simplification of the complicated forming conditions of HF using only two parameters, namely the holding pressure p_H and axial stroke δ_F. **Fig. 6** shows an example of forming allowance evaluation using the same dies and material tubes as those of the tests described in section 3. Here, the area of sound forming is surrounded by four limiting curves, which are:

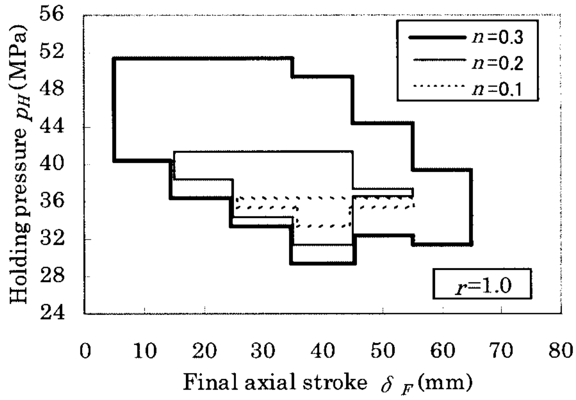
(1) Bursting limit: the holding pressure not to cause bursting during axial feeding
(2) Corner radius limit: corner radius ≦ 20 mm
(3) Wrinkle limit: curvature of wrinkle in rectangular section portion ≦ 0.007 mm^{-1}
(4) Tube end buckling limit: curvature of wrinkle near tube end ≦ 0.07 mm^{-1}

Comparison of the forming allowances obtained by this method for different material tubes enables relative evaluation of their formability by HF.

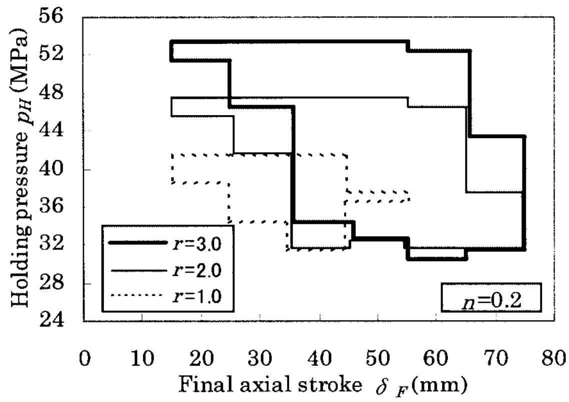
4.2 Influences of Material Properties over Forming Allowance in Hydroforming

While the above method of forming allowance evaluation is very useful in that it allows comprehensive evaluation of the properties of material tubes, it is difficult by the method to specify which of the factors contributes to successful forming work. In consideration of the above and for the purpose of evaluating the formability in HF using more common property figures, we investigated the influences of n-value and r-value over the forming allowance.

FEM analysis is effective in studying influences of individual material properties, and therefore, the influences of n-value and r-value were examined using the same FEM as described in section 3. **Fig. 7** shows the results. It is understood from the graphs that the area of sound forming becomes generally larger as n-value increases, and in contrast, the area becomes larger and shifts to high-pressure and large-axial stroke sides as r-value increases. This means that when a material tube is changed to another having a higher n-value, sound forming of the new tube is possible under the same HF conditions. However, when the new tube has a higher r-value, poor forming may result unless forming condition is changed adequately. It follows, therefore, that an increase in either n-value or r-value improves the formability by HF, but it has to be noted that, in the case



(a) Effect of n-value



(b) Effect of r-value

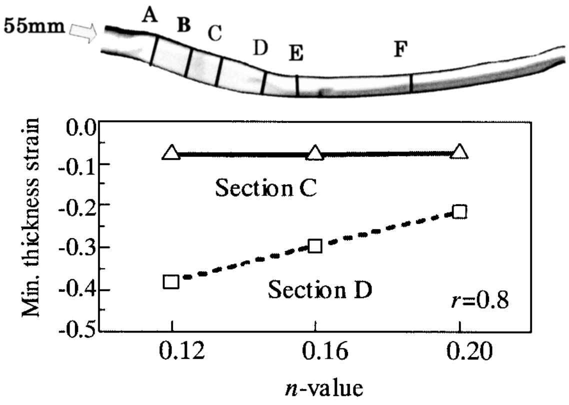
Fig. 7 Effect of n-value and r-value on HF allowance

of an increase in r-value, the improvement effect cannot be fully enjoyed unless forming condition is adequately changed.

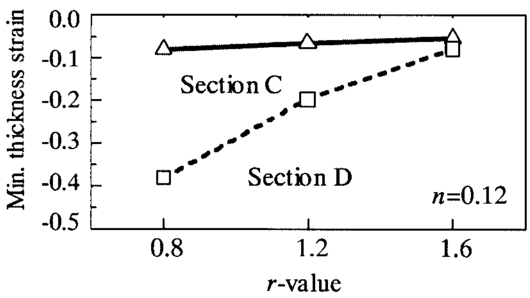
4.3 Influences of material properties over forming of real product

The above results show that both n-value and r-value have influences over the formability by HF at least when the shape of a final product is as simple as the above. Then, a study of the influences of n-value and r-value was conducted in the case of a real automobile component having a complicated shape.

Fig. 8 shows an example of FEM analysis of a center pillar reinforce[8]. Here, one sees that while both n-value and r-value are effective in inhibiting wall thinning at section D, they are little effective at section C, which is nearer to an end. This is presumably because,



(a) Effect of n-value



(b) Effect of r-value

Fig. 8 Effect of n-value and r-value on HF of actual parts

at section C, the tube expanded under the forced material flow as a consequence to the axial feeding, and as a result, the effects of material properties little showed. The effects of material properties are different depending on the shape of a final product and the position therein, as seen above. It follows, therefore, that a high n-value or r-value is not necessarily required in forming a real product by HF.

5. Development of Compact Hydroforming Machine

5.1 Compact design and cost reduction of hydroforming machine

Some knowledge was accumulated about the loading path and material selection regarding HF through the tests and studies described in the preceding sections. It is also thought that it is possible, on basis of these, to draw a guideline for measures to overcome item (1) of the shortcomings of HF listed in section 2. Next, their forming machine development to solve the problem of item (2), very large and expensive machine, is explained. The development, which was carried out as a joint project with Toyota Motor Corporation[15], resulted in a compact HF machine having one-tenth the volume of a conventional HF machine as shown in **Fig. 9**. As a result, the cost of the machine became less than a half that of a conventional machine, and its energy consumption one-tenth. The main points in the development of the machine are explained below.

(1) Simplified process functions

A conventional HF machine had one mechanism for both opening/closing of dies and die clamping during the forming process, and this mechanism required a long-stroke, high-power cylinder. As a consequence, the machine size was large and a large hydraulic system was required. In the developed machine, these functions were allocated to two separate systems, and the whole machine was simplified and made more compact (see **Fig. 10**).

(2) Multi-layer C-shaped frame structure

A multi-layer C-shaped frame structure was adopted for die clamping to support and hold down strong reaction force of forming work in the shortest possible distance. C-shaped high-tensile strength steel plates of a 780 MPa class were laid in the longitudinal direction to form the frame (see **Fig. 11**). This structure made a compact frame viable.

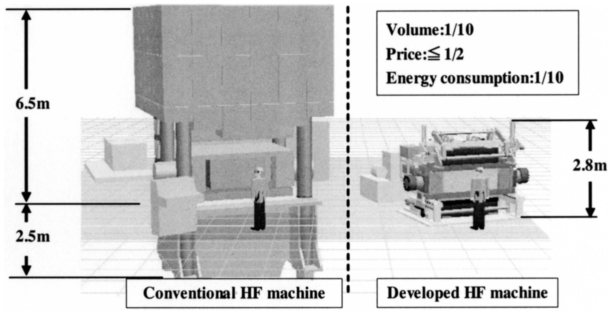


Fig. 9 Comparison of HF machine size (die closing force:35,000 kN)

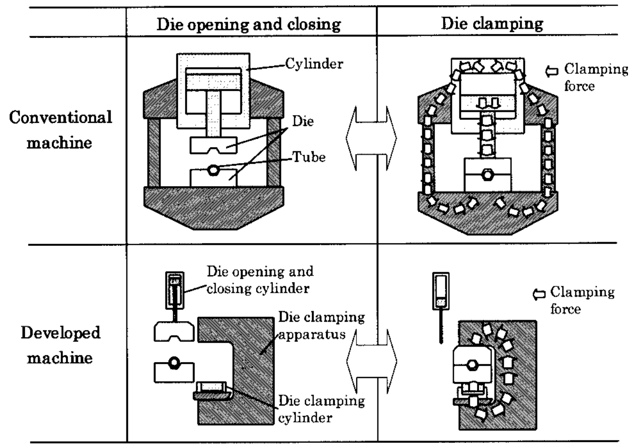


Fig. 10 Comparison of die closing mechanism of HF machine

(3) Die clamping cylinders

As a result of the above two measures, it became possible to use a short-stroke cylinder for the die clamping, and thus it became easy to design it to work at high pressures. Further, providing several cylinders to shear the load made the die clamping mechanism more compact and strong.

(4) Other new technologies introduced

A self-locking mechanism was worked out, whereby ultra-high-pressure water for the forming work produced by a pressure intensifier was supplied to the die clamping cylinders in parallel to the material tube to be formed, in order that a die clamping force proportionate to the forming reaction force was always applied. Other new technologies introduced include an axial stroke control system using

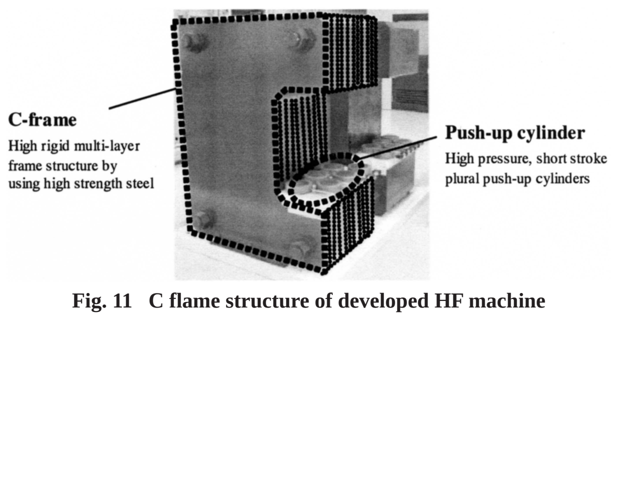


Fig. 11 C flame structure of developed HF machine

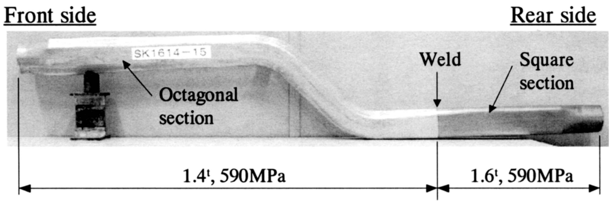


Fig. 12 Forming example by developed HF machine (front side member)

a hydraulic pump driven by an AC servomotor.

5.2 Example of hydroforming work on compact hydroforming machine

Forming work of a front side member is explained here as an example of actual application of the developed HF machine. The front section of the side member, which was designed by Nippon Steel, has an octagonal sectional shape in consideration of crash performance, and forming of this portion requires an expansion ratio of 25%. Steel tubes used were 94 mm in outer diameter and 2,180 mm in length, and their wall thickness and strength ranged from 1.2 to 1.6 mm and from 290 to 590 MPa, respectively. The same front side members were formed using tailored tubes having differentiated wall thickness; the piece shown in **Fig. 12** was formed using a 590-MPa tailored tube having a wall thickness of 1.4 mm at the front end and 1.6 mm at the rear end as the material.

6. Conclusion

Hydroforming has come to be applied to manufacturing of automobile components over the last years, but its problem was that forming conditions were complicated and difficult to understand. Through test forming of specimens of a simple shape by HF and FEM analysis of the test procedures, the influences of the loading path of internal pressure and axial feeding and the properties of material tubes over the forming process by HF were clarified. In addition, a compact design of the HF machine was developed. In the past they were very large and expensive. While these studies and development have expanded the application of HF, there still remain various problems to be solved, such as the technique for joining a work formed by HF with another component. Solution of these problems is essential for further expansion of the application of HF.

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