

Development of New Hydroforming Methods

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Abstract

Hydroforming has applied for many kinds of auto parts in Japan since 1999. In order to expand hydroforming market, increasing of hydroforming limit and joining technology between hydroforming component and other component are important. Therefore authors developed following five new hydroforming technologies, (1) high branch forming technology with moving dies, (2) forming technology of two branches with right angle each other, (3) large expanding technology by means of expanding method with restricted expanding direction and crossing moving dies and counter punches each other, (4) hydro-burring and nut-inlaying technology and (5) full length flange forming technology.

1. Introduction

Hydroforming is a method of forming steel tubes into desired shapes by setting them inside a set of forming dies and applying internal pressure and axial feeding. The method was once called bulging, and has been used since a long period for dividing work into pieces of comparatively simple shapes such as bicycle parts¹⁾ and piping joints.²⁾ After the start of the ultra-light steel auto body project³⁾ in 1994, the method began to be applied to manufacture automobile parts of complicated shapes, and it came to be known as hydroforming. It became applicable to manufacture parts of more complicated shapes than before by, for instance, bending or flattening material tubes before setting them inside dies as schematically illustrated in Fig. 1. It is also possible to pierce holes while applying internal pressure⁴⁾ (called hydro-piercing). The application of hydroforming to manufacture auto parts first spread in U.S.A. and Europe;^{5, 6)} then, it was introduced to Japan in 1999,^{7, 8)} and its application expanded to cover a wide variety of parts.

Of many advantages of the application of hydroforming, unification of parts and weight reduction can be cited as the most typical.⁹⁾ More specifically, unification of parts is advantageous because when a part that was fabricated by welding two pieces or more can be

formed in one piece, total manufacturing cost is reduced and fatigue resistance and dimensional accuracy are improved through elimination of weld joints. Weight reduction, on the other hand, results from elimination of flanges or excessive sheet thickness required for welding, and the use of thinner sheets made possible by increased strength and stiffness resulting from elimination of spot-welded or similar intermittent joints.

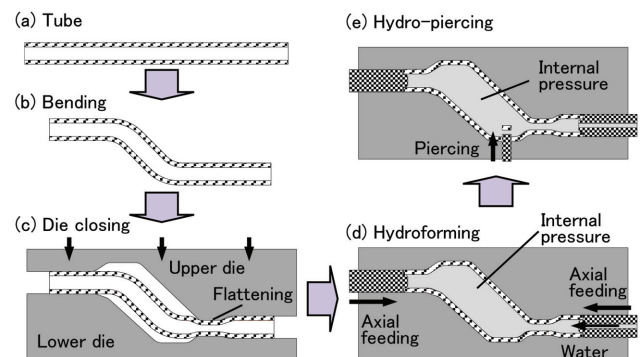


Fig. 1 Hydroforming processes

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Because of the above advantages, the application of hydroforming expanded rapidly at the beginning, but currently the auto parts formed by this method are limited to the cross and side members of chassis,¹⁰⁾ exhaust manifolds,¹¹⁾ etc. To further expand its application, it is necessary to enhance the above-mentioned advantages, namely to pursue further unification of parts and weight reduction, and to this end, the authors have studied measures to advance forming limits, and this paper reports the technologies the authors developed.

Decreasing or removing shortcomings of hydroforming is also effective at widening its application. One of such shortcomings is difficulty in joining hydro-formed parts to others;⁹⁾ the authors studied measures to solve this problem, which are reported in this paper.

2. Advancing Forming Limits of Hydroforming

The principal modes of work by hydroforming are branching and sectional expansion. It is possible to expand the application of the method to parts that has been manufactured by other forming methods and decrease the number of pieces if the forming limit of each of these modes is reduced. With respect to branching, the Nippon Steel Corporation developed a technique to form a high branch using movable dies, and a two-way branching technique to enable forming of two branches at right angles to each other. With respect to sectional expansion, on the other hand, the company developed cross-movable dies for expansion in restricted directions. The developed techniques are explained in the following subsections. It should be noted that the said developments were performed under joint work with customer companies.

2.1 High branch forming with movable dies

In general, a steel tube deforms little under internal pressure alone, but it deforms significantly when axial feeding is applied together with internal pressure;¹²⁾ in other words, feeding material to deforming portions is essential for causing large deformation. However, by conventional practice, axial feeding was applied only from the ends, and the friction in the straight portions hindered the material flow into the branch to form. As a countermeasure, the authors developed movable dies as a means to facilitate the material flow.

As illustrated in Fig. 2,¹³⁾ by the developed method, the dies holding the tube ends toward the center to facilitate material flow into the deforming portion (see Step 2). In addition, to make it easier for the material to flow around the die shoulders, the tube is bent slightly before the die is moved (see Step 1). Fig. 3 shows an example of a high branch formed by the developed method;¹³⁾ the initial material is a JIS STKM11A tube with an outer diameter of 31.8 mm and wall thickness of 1.0 mm. Whereas the maximum branch height obtainable by conventional practice was approximately equal to the diameter of the initial material ($1D$) and a branch height that is 2.2 times the initial tube diameter ($2.2D$) is achievable by the developed method.

The material flow into the branch facilitated by the movable dies according to the developed method is shown in Fig. 4 in terms of the state of strain.¹³⁾ Although by the conventional hydroforming method shown in part (a), the strain state near the end of the branch is plane strain or equibiaxial tension, it is close to pure shear in most part of the branch by the developed method. This indicates that the developed method is suitable for intensive deformation work.

2.2 Orthogonal two-way branching

As stated in the previous subsection, pure shear strain is desirable for large deformation. In forming a T-shape part, the material fed in the axial direction from the ends flows in the circumferential

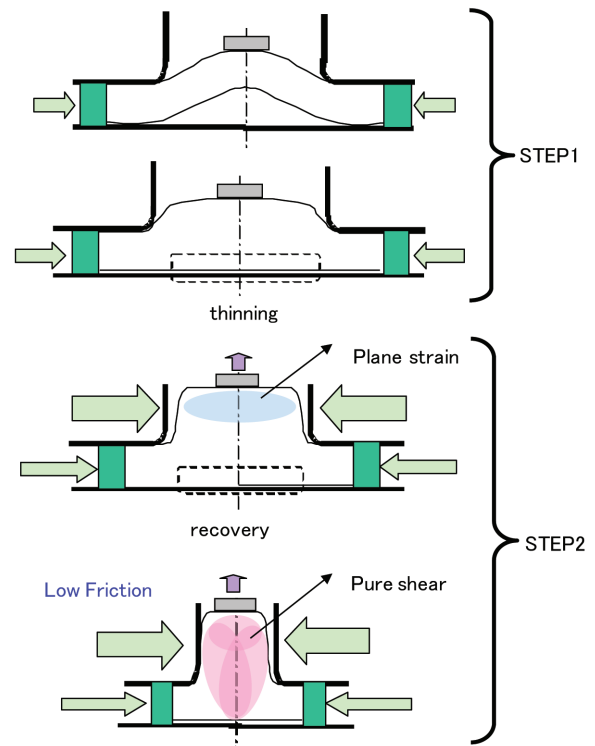


Fig. 2 High branch forming using movable dies¹³⁾

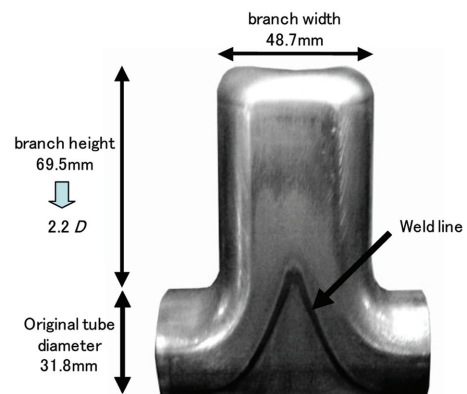


Fig. 3 Example of high branch formed with movable dies¹³⁾

direction at the sides of the branching node.¹⁴⁾ Forming two branches at right angles to each other, on the other hand, means forming a second branch protruding from the same position; this was very difficult by hydroforming.

Nevertheless, the authors developed a hydroforming method that enabled forming of two branches at right angles to each other as shown in Fig. 5.¹⁵⁾ In this case, two branches with a width W_L of 140 mm in the axial direction were formed from a material tube with an outer diameter of 114.3 mm, wall thickness of 2.9 mm, and tensile strength of 440 MPa. This was made possible by intentionally staggering the centerlines of the two branches.

Fig. 6¹⁵⁾ shows FEM analysis results of the states of strain in the cases where the ratio of the stagger K to the axial width of the branches W_L is changed. The most critical portion where the material is likely to break under this type of forming work is the position

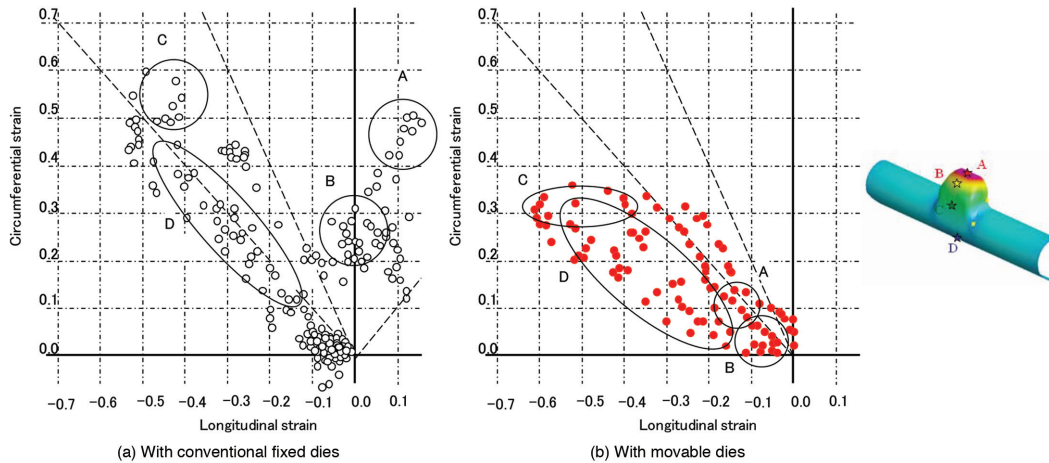


Fig. 4 FEM results of strain states after forming branch by hydroforming¹³⁾



Fig. 5 Forming of two branches in right angles to each other¹⁵⁾

between the branches marked with “a”. The smaller the ratio K/W_L or the smaller the stagger, the more the strain at the portion “a” changes from pure shear to uniaxial tension in the circumferential direction and the larger the absolute value of the strain becomes. When $K/W_L = 100\%$ or the branches are completely staggered, on the other hand, the strain at the critical portion is substantially the same as that at other positions. This indicates that it is possible to form two branches from one tube by hydroforming and minimize the strain at the critical portion by adequately selecting the amount of stagger of the branches. In other words, it is difficult to form two branches from the same position of a material tube at right angles to each other, but this becomes viable when the positions of the branches are adequately staggered.

2.3 Cross-movable dies for sectional expansion in limited directions

As stated in Subsection 2.1, pure shear deformation is desirable for large deformation, but when a steel tube is subjected to free

bulging work under axial feeding, buckling occurs and pure shear deformation is prevented from taking place, and the uniaxial tension in the circumferential direction would be best achievable.¹⁶⁾ Restriction by dies is effective at preventing buckling, and it is desirable that the material to be in contact with the dies from the beginning. Therefore, it follows that pure shear deformation is likely to result from restricting a material tube in one direction by dies and allowing it to expand in another at right angles.¹⁷⁾

According to this understanding, the authors worked out the following method. First, sectional expansion in the vertical direction is applied while restricting horizontal deformation; then, horizontal expansion is applied while restricting vertical deformation. This enables large sectional expansion finally in all directions. Fig. 7¹⁸⁾ shows an example formed by the developed method; here, the circumference of a JIS STKM11A steel tube with an outer diameter of 60.5 mm and wall thickness of 2.5 mm was stretched to approximately three times the initial size. The rate of expansion (%), which is defined by convention as $[\text{circumference after forming} - \text{initial circumference}] / [\text{initial circumference}] \times 100$, of this example is 200%. In consideration of the fact that the expansion rate of parts formed by hydroforming is mostly approximately 10%, and at the largest 40%,⁷⁾ the expansion rate that the developed method achieves is revolutionarily large.

Furthermore, in the above multi-step forming method, the authors developed cross-movable dies as a new forming technology.

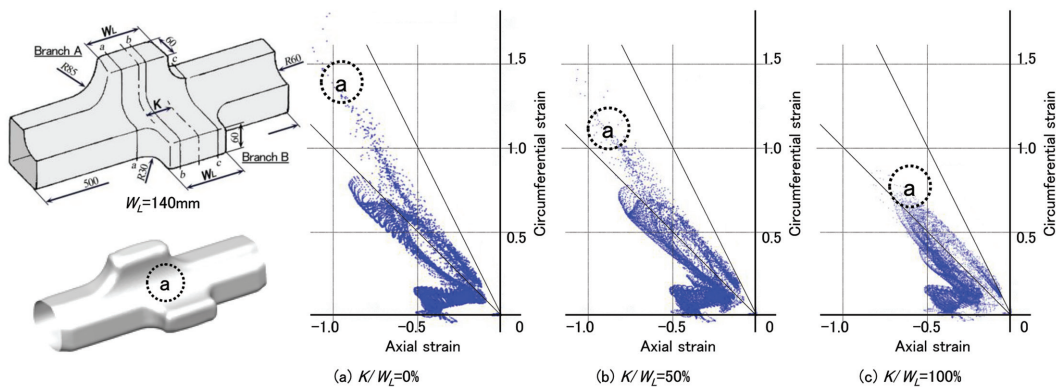


Fig. 6 FEM results of strain states after forming two branches in right angles to each other¹⁵⁾

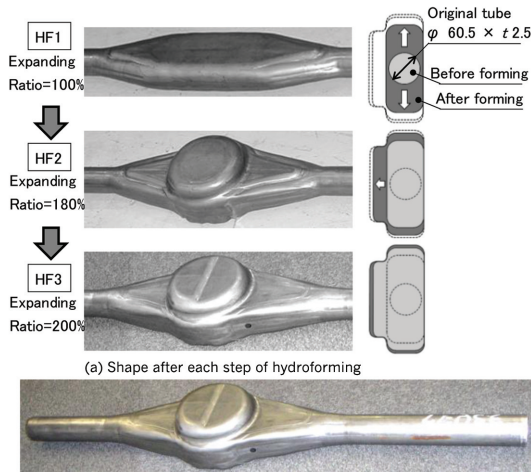


Fig. 7 Large-expansion-rate, multi-step hydroforming under restriction of expanding direction¹⁸⁾

When sectional expansion of a portion away from the ends is intended, as stated in Subsection 2.1, it is generally difficult to supply an amount of material sufficient for the deformation by axial feeding because of the friction in the straight portions in between. To solve this problem, the authors studied the use of movable dies. However, when the initial distance between two movable dies is large, axial buckling and fracture are more likely to occur in the center portion than by the conventional hydroforming as illustrated in part (b) of Fig. 8.¹⁸⁾ Even, counter punches as shown in part (c) cannot prevent the buckling or fracture because of the gaps between them and the movable dies. The mechanism of cross-movable dies was worked out to solve all these problems; as shown in part (d) of Fig. 8, counter punches are provided so as to slide vertically in slits cut in the movable dies. This configuration ensures that most surface of the steel tube is restricted from an early stage of the forming process by the movable dies and/or counter punches, making it difficult for buckling or fracture to occur.

Taking advantage of the developed method using the cross-movable dies, the authors developed single piece axle housings, which had once been manufactured by welding of seven components, from a single steel tube.¹⁹⁾ Fig. 9¹⁸⁾ shows an example of the axle housings manufactured using a JIS STKM11A tube with an outer diameter of 60.5 and wall thickness of 2.5 mm. The overall expansion rate is 180%. In consideration of fatigue endurance, this part was designed in smooth spherical contours to minimize stress concentration.

3. Development of Joining Methods of Hydroformed Parts

In the case where chassis parts, which are mostly joined to other parts by arc welding, are formed by hydroforming, arc welding can be employed. However, in the case of body parts, which are joined mainly by spot welding or with bolts, since pieces formed by hydroforming do not have flanges, it is difficult to join them to other parts. To solve this problem, the authors developed the following seed techniques: hydro-burring, nut inlaying, and full-length flange forming, which are presented in the following subsections.

3.1 Hydro-burring and nut inlaying

As mentioned in Section 1, making holes during hydroforming while maintaining the internal pressure, or hydro-piercing, has been

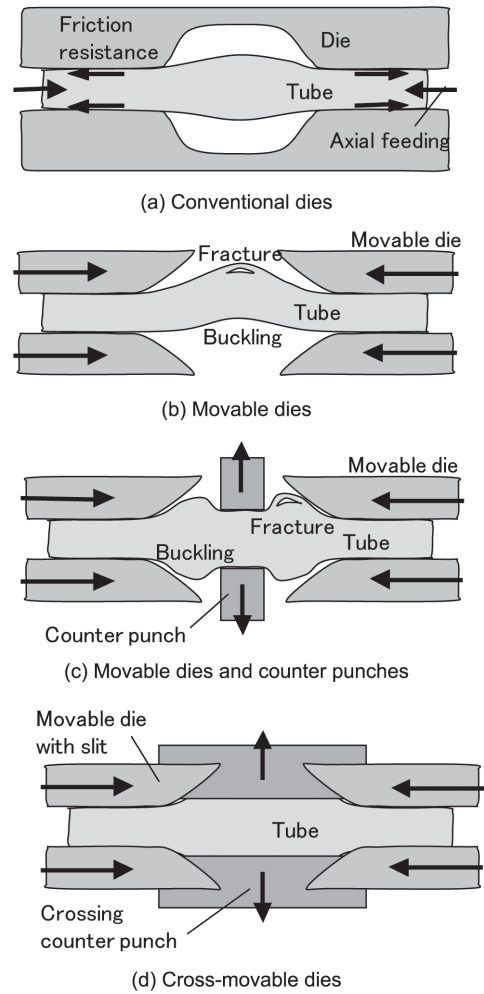


Fig. 8 Comparison of die structures for hydroforming¹⁸⁾



Fig. 9 Axle housing formed by hydroforming at large rate of expansion¹⁸⁾

practiced widely in industries. On the basis of this method, the authors developed hydro-burring, a technique to form a circular flange toward the inside of a formed piece by hole-expansion work. Fig. 10²⁰⁾ shows the process: (a) after hydroforming according to normal practice, (b) a hole is made with a piercing punch while the internal pressure is maintained, (c) and then, by a burring punch, which is driven forward by the shoulder of the piercing punch, the hole is expanded such that a circular flange is formed toward the inside. The internal pressure is maintained throughout these process steps; the higher the pressure, the sharper the hole edge, and the lower the pressure, the larger the drop of the hole edge. However, it should be noted that the risk of cracking at the edge decreases with lower internal pressure. Further details of the process are given in reference literature.²¹⁾

The part shown in Fig. 11²⁰⁾ was made as follows. The center

portion of a steel tube with an outer diameter of 63.5 mm, wall thickness of 2.3 mm, and tensile strength of 460 MPa was hydro-formed into a rectangular section at a rate of expansion of 50%, a hole was made using a piercing punch with a diameter of 10 mm, and then hydro-burring was done using a burring punch with a diameter of 20 mm. The part shown in Fig. 12²⁰⁾ was obtained by applying M22 tapping to the hole of the part shown in Fig. 11. The tapped thread enables joining of the hydro-formed part to another piece with a bolt.

However, the above method cannot be easily applied when the wall thickness of the material tube is too small for tapping or the hole expandability of the tube is poor and a sufficient burring height

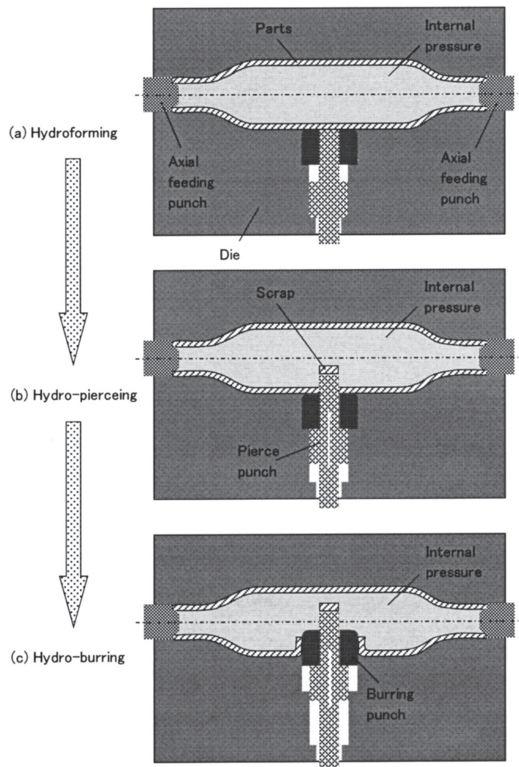


Fig. 10 Process steps of hydro-burring²⁰⁾

cannot be obtained because of high strength. For such cases, a technique to inlay a threaded nut in a hydro-formed part was developed.

Fig. 13²²⁾ schematically illustrates the process. The method is basically the same as the hydro-burring process shown in Fig. 10 except that a threaded nut is used instead of the burring punch and the nut is left inlaid in the formed part. Fig. 14²²⁾ shows an example of nut inlaying in a part similar to that shown in Fig. 11; the material tube is a little thinner here with an outer diameter of 63.5 mm, wall thickness of 2.0 mm, and tensile strength of 440 MPa. This method makes it possible to join a formed piece of a thinner wall thickness to another with a bolt. Nuts of various shapes were tested, and in consideration of characteristics such as sealing with the base material, the resistance to falling in or out after inlaying, drawing load at bolt tightening, and tightening torque, the nut shape shown in Fig. 15²²⁾ was selected as the most suitable.

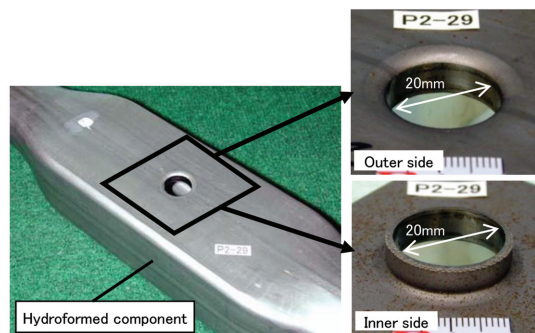


Fig. 11 Example after hydro-burring test²⁰⁾

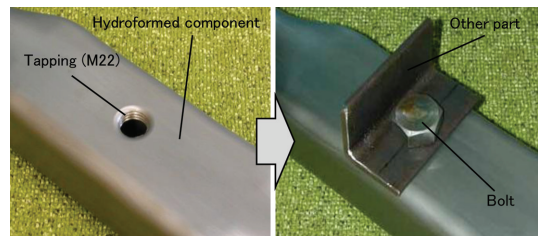


Fig. 12 Bolting hydroformed component to other part after tapping at hydro-burring position²⁰⁾

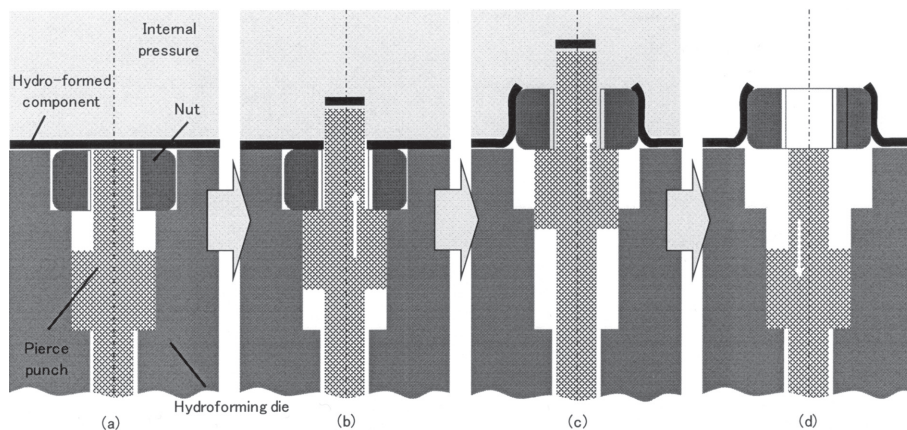


Fig. 13 Processes of nut inlaying into hydroformed component²²⁾

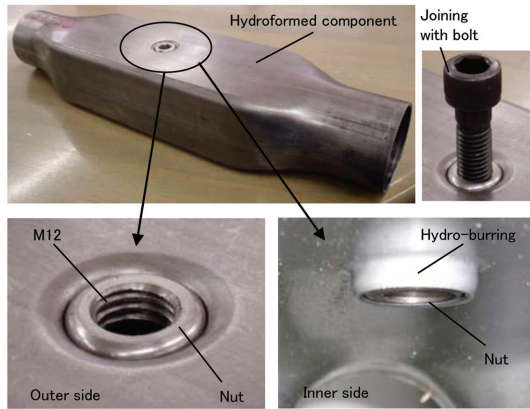


Fig. 14 Example of hydroformed component with inlaid nut by hydro-burring²²⁾

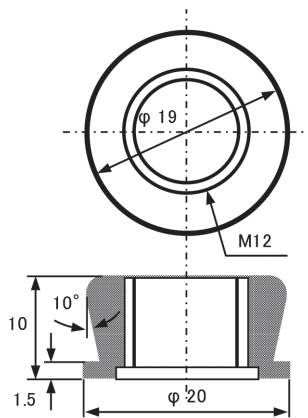


Fig. 15 Detailed sizes of the best nut for inlaying into hydroformed components (dimensions in mm)²²⁾

3.2 Forming of full-length flanges

Hydro-formed parts do not have flanges for welding; for this reason, they are unsuitable for conventional spot welding or bolt fastening at a flange. Forming a flange by pinching the material tube during the hydroforming process with forming dies seems to be a viable solution, but when a material tube is pinched partially, wrinkles or cracks are likely to develop near the portion. Uchida et al.²³⁾ succeeded in forming a flange in a portion of a formed piece using dies to pinch and flatten a part of the piece, but the proposed method required a complicated die structure. To this end, the authors studied a modification of hydroforming to form flanges along the whole length of a formed piece. Forming a flange or flanges along the whole length will eliminate the possibility of cracking or wrinkling in the nearby regions, but since this means flange forming also at both ends of the material tube, it is necessary to devise a sealing method that allows the deformation of the tube ends while the internal pressure is maintained. A flat end sealing method was developed as a solution.

Fig. 16²⁴⁾ schematically illustrates the procedures of the developed flat seal method. First, a material tube is set in the lower die. Here, the tube length must be longer than the die length, and the tube length extending from each end of the die is called sealing length L_s . Axial cylinder punches having flat front faces are driven forward to seal the two tube ends and fill the tube with water as seen

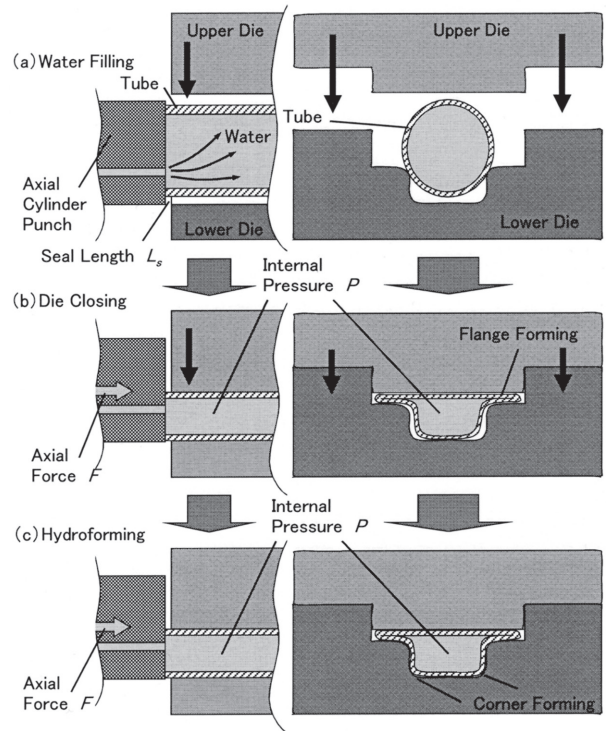


Fig. 16 Hydroforming process with flat seal²⁴⁾

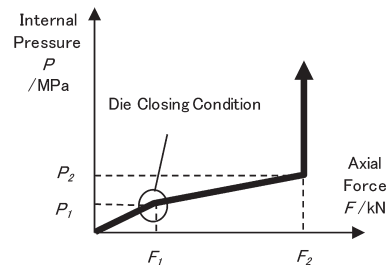


Fig. 17 Hydroforming loading path for flat seal²⁴⁾

in part (a). Then, the internal pressure P is raised to P_1 , and simultaneously, the pressing force F of the axial cylinder punches is increased to F_1 to ensure the sealing. This condition being maintained, the upper die is lowered to form flanges at the same level of the upper surface of the formed piece as seen in (b). Hereafter, the internal pressure P is increased further to P_2 , and simultaneously, the pressing force is increased from F to F_2 . Finally, as seen in part (c), the internal pressure is increased yet further to obtain the intended shape. The loading path in the above process steps is given in Fig. 17.²⁴⁾

Part (a) of Fig. 18²⁴⁾ shows an example piece with full-length flanges; it was formed according to the above process steps using a steel tube with an outer diameter of 60.5 mm, wall thickness of 2.5 mm, and tensile strength of 430 MPa. Part (b) shows an example formed without applying the internal pressure. Although the upper face of the formed part tends to droop without the internal pressure, it is flat when proper internal pressure is maintained by the flat end sealing during the forming process.

Besides the example of the photograph, parts with full-length



(a) Formed under internal pressure kept by flat seal technology



(b) Formed without internal pressure

Fig. 18 Hydroforming samples with full length flange²⁴⁾

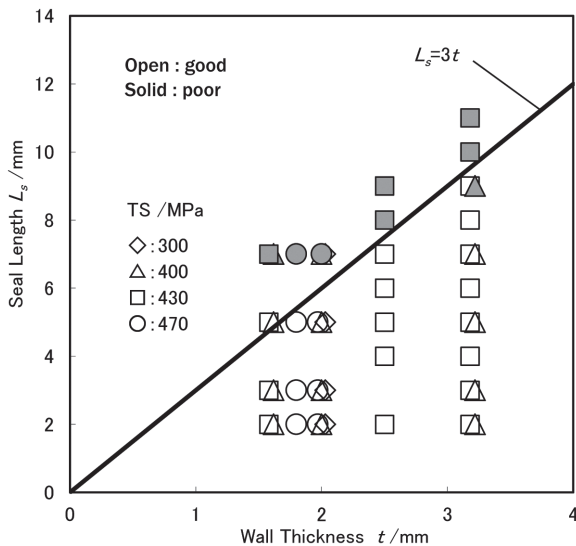


Fig. 19 Effect of seal length on flat seal performance²⁴⁾

flanges were successfully formed by the developed method from material tubes with a wall thickness of 1.6-3.2 mm and tensile strength of 300-470 MPa; the flat end sealing worked satisfactorily in all these cases. In this relation, the authors examined factors that exerted influences over the sealing performance of the flat end seal such as the seal length L_s , seal end properties, and loading path (internal pressure P_1 and P_2 , pressing force F_1 and F_2). Of these, the influence of the seal length L_s are explained briefly. Fig. 19²⁴⁾ shows the performance of flat seals when the seal length L_s was changed. When the seal length L_s is too large, the tube end is likely to buckle during axial feeding, leading to leakage from the seal; the critical seal length is approximately three times the wall thickness t , regardless of the steel strength. Note that, when the seal length is too short, leakage occurs easily because the material is drawn inside during forming. As a conclusion, an adequate seal length L_s is slightly less than three times the wall thickness t .

4. Summary

To expand the applicability of hydroforming by advancing form-

ing limits and facilitating joining of formed pieces to others, the authors developed the following forming methods.

- 1) The height of branching was extended to 2.2 times the diameter of material tube because of developed movable dies to facilitate the influx of material to the branch.
- 2) Forming of two branches extending at right angles to each other was possible by staggering their positions in the axial direction.
- 3) The rate of expansion was increased by restricting the direction of expansion in a forming step, repeating such steps, and changing the direction of expansion. Forming of axle housings, the circumference of the center portion of which is expanded approximately three times that of the material tube, was possible by the use of a set of dies consisting of movable dies and counter punches moving in directions perpendicular to each other.
- 4) A method of hydro-burring was developed, wherein a hole made by hydro-piercing was expanded while the internal pressure was maintained. It became possible to join formed parts to others with bolts by tapping screw threads to the hole or inlaying a nut there.
- 5) Flat seal method was developed, wherein sealing is maintained at the tube ends against the internal pressure while allowing the deformation of the ends, and applying the developed method, it became possible to form parts having flanges along the whole length.

The developed forming methods will certainly promote wider application of hydroforming in the automotive and other industries.

Acknowledgements

The method of forming a high branch using movable dies described in Subsection 2.1 was developed jointly with Toyota Motor Corporation, and that of forming the cross-movable dies with restricted expansion direction presented in Subsection 2.3 was developed jointly with Suzuki Motor Corporation. The authors would like to express their deepest thanks for the cooperation of the two companies in the development activities.

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NIPPON STEEL TECHNICAL REPORT No. 103 MAY 2013

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