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Development of Tube Forming to Contribute to Weight Reduction and High Functionality

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Abstract

Many kinds of tube component are recently being applied to automotive parts. Nippon Steel Corporation has developed various tube forming technologies. In this paper, the newest forming technologies that we have developed are introduced. These technologies are as follows: (1) in the tube bending field, rotary draw bending with an asymmetrical mandrel ball, press bending with moving rolls, and press bending with cross-sectional deformation; (2) in the hydroforming field, local reinforcement with a sheath tube, high-accuracy forming of a camshaft with hydraulic pressure, and a forming method to decrease residual stress of the torsion beam and origami parts made by hydroforming; and (3) in other fields, flaring with eccentricity or bending and forming of tubes with different wall thicknesses by drawing or ironing.

1. Introduction

The automobile industry has been working to improve both collision safety performance and fuel economy for many years. To that end, the strength of steel materials has been dramatically enhanced.[1] Another effective means is the application of a hollow, closed cross-sectional structure. When comparing materials of the same weight, the flexural rigidity of cored steel materials is higher than that of solid materials[2] and the torsional rigidity of a closed cross-sectional structure is higher than that of an open cross-sectional structure. With these characteristics as a background, the application of tube materials to automotive parts has been expanding since the latter half of the 1990s. Hydroforming that can form parts in complicated shapes by applying internal pressure has, in particular, rapidly spread.[3] The author introduced the developed hydroforming technologies in our technical reports (Giho) in 2004[4] and 2012[5].

After that, various tube forming methods were developed in addition to hydroforming methods. Our technical reports issued in 2013 carried three-times-expanding tube hydroforming[6] developed by the former Nippon Steel Corporation and three-dimensional hot bending and quenching (3DQ)[7] developed by the former Sumitomo Metal Industries, Ltd.

In recent years, Nippon Steel Corporation has been developing many tube forming technologies to satisfy the need for further reduction of weight and higher performance. This paper introduces an outline of the technologies developed by Nippon Steel. They are broadly divided into the three types listed below.

- Bending
- Hydroforming
- Other types of processing technologies (flaring and processing to obtain different wall thicknesses)

2. Bending

Bending is most commonly performed among various tube forming techniques. However, deformation defects such as wrinkling, buckling, flatness, thickness nonuniformity, and fracture often form because the structure is hollow. To prevent such defects, various bending methods have been developed in the past based on size, application, and other factors.[8] Nippon Steel has developed its particular bending method, 3DQ, mentioned in the introduction. This epoch-making method, in which continuous bending using robots is performed while quenching, produces high-strength, three-dimensional bent shapes. The details are omitted here since the method

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was described in the paper released in 2013.[7] This paper introduces three bending methods that have not been introduced in our technical reports.

2.1 Rotary draw bending that suppresses local thickness reduction

As mentioned above, there are various bending methods for tubes. Among them, the processing method that is most commonly used in industrial production is rotary draw bending. **Figure 1** illustrates an outline of this bending method. The wiper placed inside the bent portion prevents wrinkling and the mandrel installed in the tube prevents flatness. Therefore, this excellent processing method can suppress processing defects and can form bent shapes with a relatively smaller radius. As a disadvantage, the wall thickness often decreases outside the bent portion, so pressing force is applied from the rear or other countermeasures are taken.[9, 10] However, although these countermeasures can suppress thickness reduction outside the entire bent portion to some extent, suppressing local thickness reduction occurring in the early stage of bending is difficult. Such local thickness reduction in the early stage of bending is more obvious when the initial material is stronger and the n value is smaller.[11] This is a significant problem these days where higher-strength steel materials are demanded.

To solve the aforementioned problem, the authors developed an asymmetrical mandrel ball as shown in **Fig. 2**.[12] It has a shape in which only the half outside the bent portion of the mandrel ball was cut. **Figure 3** shows the distribution of the thickness reduction rate (t_r) when 980-MPa tubes with an outer diameter of 38.1 mm and a wall thickness of 1.0 mm were bent under a bending radius of 76.2 mm and a bending angle of 90°. **Figure 4** shows the distribution of the flattening ratio (f). When the wall thickness before bending is t_0 and that after bending is t, the thickness reduction rate (t_r) is defined as $(t_0 - t)/t_0$. When the outer diameter of the initial material is D, the maximum outer diameter value after bending is D_{max}, and the minimum outer diameter value after bending is D_{min}, the flattening ratio (f) is defined as $(D_{max} - D_{min})/D$. As compared with Case 1 using a conventional mandrel ball, in Case 3 using the asymmetrical mandrel ball, local thickness reduction in the early stage of bending was suppressed and flatness was also at the same level.

Ishigaki et al.[13] reported that the thickness reduction rate (t_r) and flattening ratio (f) changed depending on the location of the mandrel. Therefore, in addition to the conventional case (Case 1), another condition was tested (Case 2) in which the position of the mandrel was shifted to the rear by 10 mm. Figures 3 and 4 show the results of Case 2 as reference. This method works well to suppress thickness reduction in the early stage of bending, but the flatness becomes too large. These results show that the asymmetrical mandrel ball that the authors developed is more advantageous for bending of high-strength tubes.

2.2 Press bending with moving rolls

Press bending has also been used as a bending method for tubes for a long time. The 3DQ developed by Nippon Steel and the rotary draw bending mentioned in the previous section have some advantages—they can form parts in complicated shapes or can bend tubes with a small radius. However, these methods have certain problems, for example, they require special equipment and the processing time is long. Meanwhile, press bending can be applied only if there is a press machine and the processing time is short. Therefore, press bending is favorable from the perspective of cost and productivity. With these factors as a background, the authors developed press bending with moving rolls that enables processing only with a press machine.[14]

Figure 5 illustrates an outline of the process of this bending method. Rolls with movable supports are placed at short intervals at first. While the punch is being lowered, they are moved outward. Force toward the center is applied to the two rolls all through the process and they move along the shape of the punch die. In this method, a tube is gradually bent while being sandwiched between

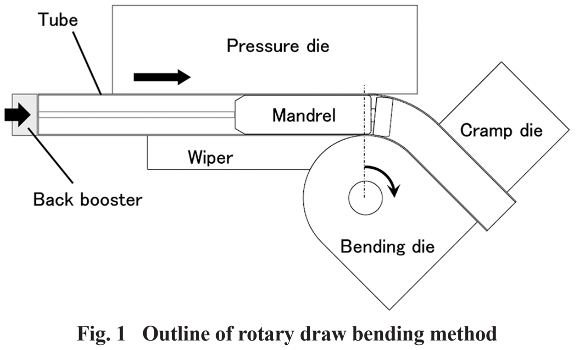

Fig. 1 Outline of rotary draw bending method

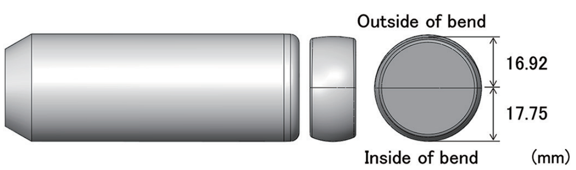

Fig. 2 Shape of asymmetry mandrel ball

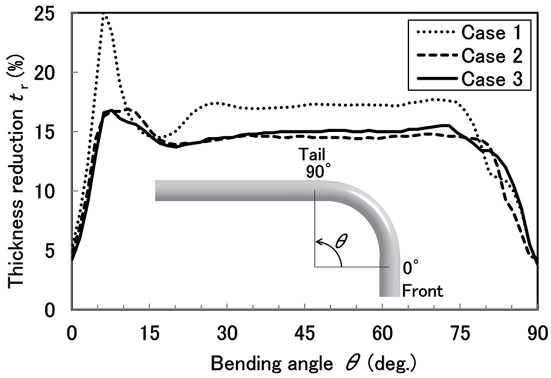

Fig. 3 Distribution of thickness reduction at tension side after rotary draw bending

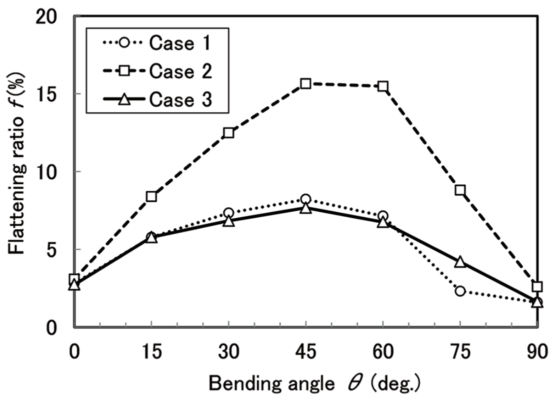

Fig. 4 Distribution of flattening ratio after rotary draw bending

the rolls and the punch, so buckling occurs less than in conventional three-point bending. **Figure 6** shows a sample when a 590-MPa tube with an outer diameter of 25.4 mm and a wall thickness of 1.6 mm was press-bent under a bending radius of 203.2 mm and a bending angle of 90°. In conventional three-point bending, the tube buckled at the center while the tube did not buckle and the target bent shape could be obtained in the press bending with moving rolls.

In addition, the shape of the punches in this press bending method does not need to be a circular arc. Punches of various shapes can be used for bending. A shape having three apparent bending portions as shown in **Fig. 7** can be formed in one stroke using a punch. Therefore, the productivity is higher as compared with rotary draw bending where a tube is bent multiple times. Furthermore, the shape of the grooves on the punch and rolls that sandwich a tube does not need to be a half circle. A rectangular cross section and a shape for which the cross section is changed in the longitudinal direction as shown in **Fig. 8** are possible. As described above, the highly flexible bent shapes and cross-sectional shapes are advantages of this method.

2.3 Press bending with cross-sectional deformation

The buckling strength and degree of shape flexibility of the press bending with moving rolls described in the previous section, which is one of the press bending methods, are excellent. However, the die structure becomes complicated due to certain factors such as movement of rolls and loads to the inside. Therefore, to further lower the hurdle to allow press bending to be applied to actual parts, the authors have developed press bending with cross-sectional deformation that enables processing only with a punch and die.[15]

In this bending method, as shown in **Fig. 9**, a punch and die having grooves of the same shape as that of the target part are used to deform the cross section during bending. The cross section of the initial material is prepared as a circle or made oval in advance to make insertion to the grooves smoother. This bending method does not require much investment in equipment and the productivity is high. In addition, the method has other advantages from the perspective of processing performance, for example, buckling occurs less and springback does not readily occur.[16] **Figure 10** shows examples in which tubes are bent to obtain a 980-MPa rectangular cross section (bent shape) of 40 × 30 mm with a wall thickness of 1.6 mm, a bending radius of 800 mm, and a bending angle of 20°: Buckling occurs less when a circular tube with an outer diameter of 42.7 mm is bent while being deformed to a rectangular cross section (a case like this press bending method), as compared with when a straight tube with a rectangular cross section is bent. This is because, in press bending with cross-sectional deformation, the material moves in the circumferential direction inside the bent portion, which suppresses the local concentration of strain in the axial direction.

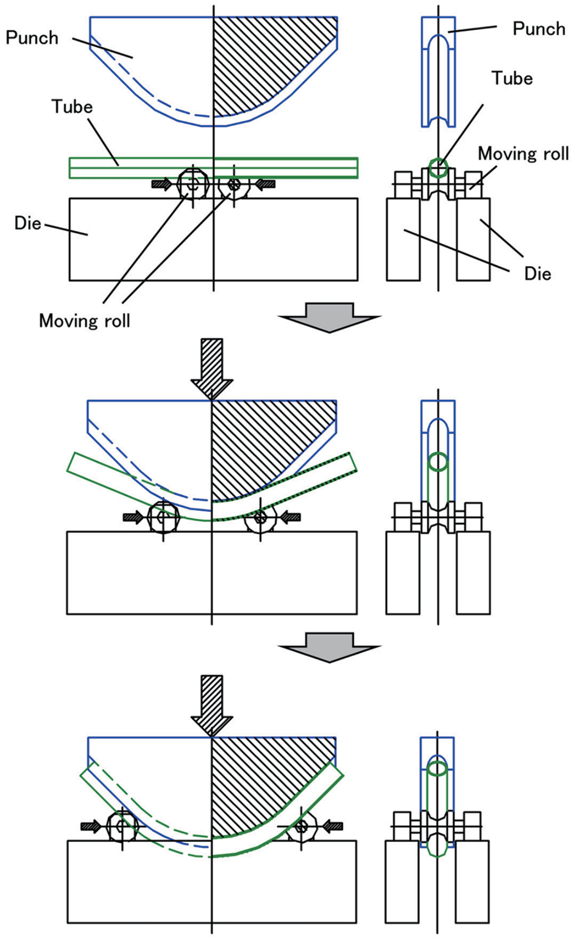

Fig. 5 Forming processes of press bending with moving rolls

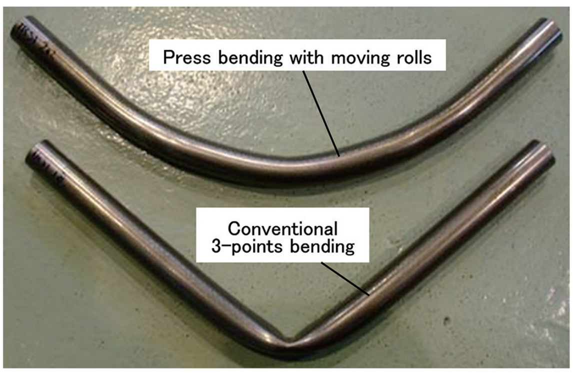

Fig. 6 Comparison of forming shapes between press bending with moving rolls and conventional three-point bending

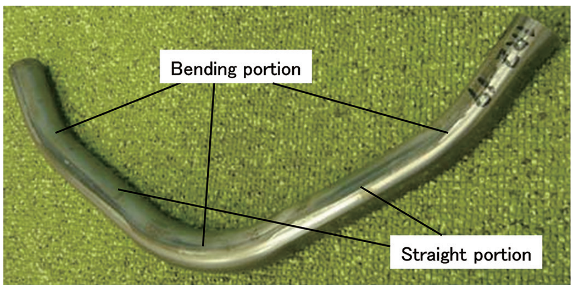

Fig. 7 Sample formed by press bending method with moving rolls to apply to a shape with several bending portions

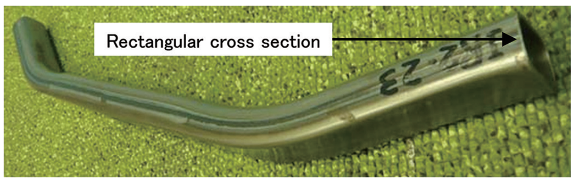

Fig. 8 Sample with rectangular cross section formed by press bending method with moving rolls

Figure 11 shows a springback experiment and FEM analysis results. To obtain a 980-MPa rectangular cross section (bent shape) of 37.5×26.2 mm with a wall thickness of 1.0 mm, a bending radius of 650 mm, and a bending angle of 24.5°, a circular tube with an outer diameter of 38.1 mm was processed by press bending with cross-sectional deformation. As compared with the theoretical values when a straight tube with a rectangular cross section is bent (the broken line in the figure), the amount of springback is approximately half. This is because the stress produced when the corners of the cross section are formed works favorably for the shape fixing property.

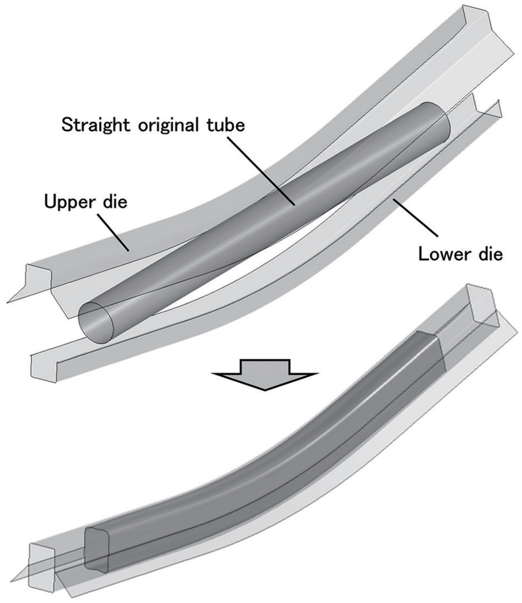

Fig. 9 Outline of press bending with cross-sectional deformation

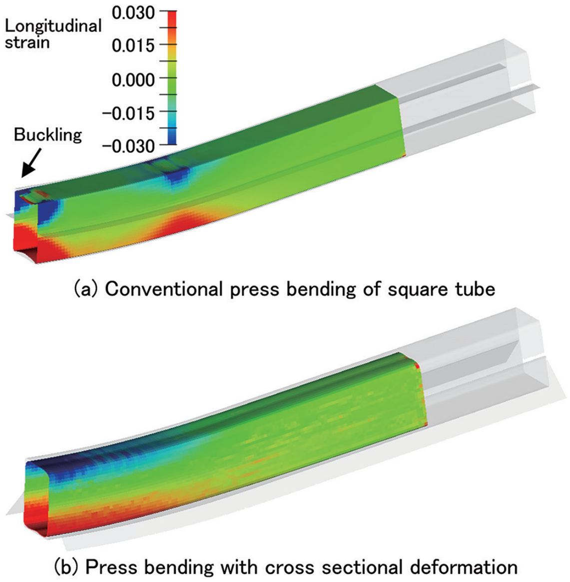

Fig. 10 Comparison of longitudinal strain after press bending

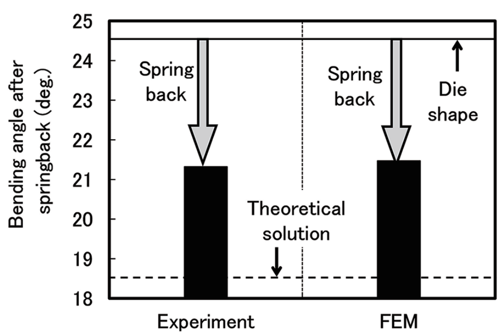

Fig. 11 Springback after press bending with cross-sectional deformation

3. Hydroforming

Nippon Steel has been actively researching and developing hydroforming methods and has introduced some of them in past technical reports.[4–6] In recent years, Nippon Steel has also been developing forming technologies to enhance the performance of formed parts in addition to the development of mere forming methods. Examples of such technologies are introduced below.

3.1 Mechanical joining technology using internal pressure

In hydroforming, high pressure is applied to the inside of a tube to form it into the shape of the outside die. The authors have developed a method that uses such high pressure for mechanical joining. A technology for implanting a nut into a hydroformed part was introduced in a past technical report, so it is omitted in this paper. **Figure 12** illustrates an outline of a technology in which a sheath tube is placed outside a tube before forming and the initial material is expanded by hydroforming along with the sheath tube and joined.[17] The rigidity and strength of the section with the sheath tube be-

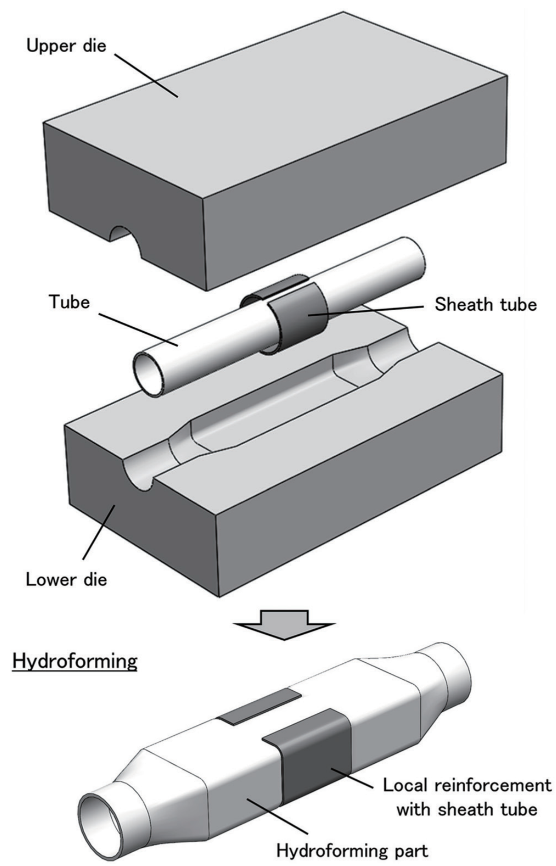

Fig. 12 Local reinforcement by hydroforming with sheath tube

comes locally higher.

In the example in **Fig. 13**, a 370-MPa tube with an outer diameter of 63.5 mm and a wall thickness of 2.3 mm was formed into a rectangular cross section to a tube expansion of approximately 50% by hydroforming; at this time, a 370-MPa sheath tube with an outer diameter of 82.6 mm and a wall thickness of 2.0 mm was used to enhance the local rigidity. Although sheath tubes used can have both a closed cross section and an open cross section, the effect for enhancing the rigidity is higher when a closed cross section is applied. However, a sheath tube with a closed cross section needs to be expanded by hydroforming. Therefore, the deformation resistance varies significantly between the section with the sheath tube and the section without the sheath tube, so setting of hydroforming conditions is difficult. The hydroforming technology for tailored tubes with different wall thicknesses that the authors developed in the past[18] needs to be used. On the other hand, large force is not required to deform sheath tubes with an open cross section, so it is not highly necessary to change the hydroforming conditions from those for the initial material. Therefore, from the perspective of ease of application, sheath tubes with an open cross section are advantageous.

Assembled camshafts are examples for which mechanical joining methods using hydroforming have been used for a long time.[19] In this method, internal pressure is used to expand the initial material to secure cam lobes. It is generally said that the machining accuracy by hydroforming is excellent,[20] but hydroformed parts are not accurate enough to be used as camshafts as they are without further processing and thereby machining is required after assembly. Therefore, to reduce machining to the extent possible, the authors have developed the die structure shown in **Fig. 14** that can form high-accuracy assembled camshafts.[21] The oval-shaped sections of the cam lobes do not come into contact with the die and the projections provided at the bottom of the cam lobes are engaged with the die to secure accuracy as a structure. In addition, dividing the insert die and exchanging them allows the structure to be applied to multiple types of camshafts. **Figure 15** shows the prototyping results of a camshaft in a simple shape formed from a 400-MPa tube with an outer diameter of 25.4 mm and a wall thickness of 2.8 mm. Forming using this die structure achieved dimensions at a high accuracy of ±0.02 mm.

3.2 Processing method to reduce the residual stress on torsion beams

In recent years, a structure for which the cross section of a tube was crushed into a V shape has been applied to torsion beams—a type of suspension part. Torsion beams require fatigue resistance but the residual stress as a result of such severe crushing into a V shape reduces the fatigue resistance. To solve this problem, Nippon Steel provides materials whose fatigue resistance can be enhanced by annealing after processing[22] and they have been used for many automobiles. However, such materials require a heat treatment process and it is thereby unfavorable from the perspective of cost. Therefore, the authors developed a technology for reducing residual stress through processing without heat treatment.

In the first place, residual stress occurs due to uneven stress distribution during processing. The authors thought that crushing a tube into a V shape and then further applying stress could reduce the residual stress and developed a method that uses hydroforming.[23] **Figure 16** compares residual stress among various positions when a 690-MPa tube with an outer diameter of 101.6 mm and a wall thickness of 3.4 mm was processed into the shape of a torsion beam and then hydroformed. At all Positions A, B, and C, hydroforming reduced the residual stress. In hydroforming, internal pressure and axial feeding superpose, but, between the cross sections of B and C with a larger axial feeding amount, the residual stress is smaller, showing that the effect of axial feeding, as well as the effect of the internal pressure, is large.

In addition, as methods to apply stress, mechanical expansion by punch pushing, stretching of the ends of tubes in the axial direction, and compression of the ends of tubes in the axial direction, as well

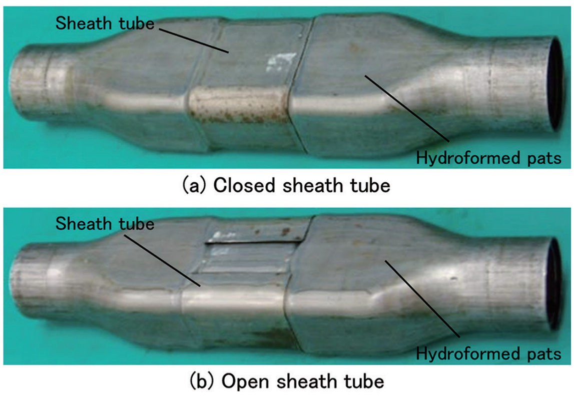

Fig. 13 Hydroforming samples with local reinforcement of sheath tube

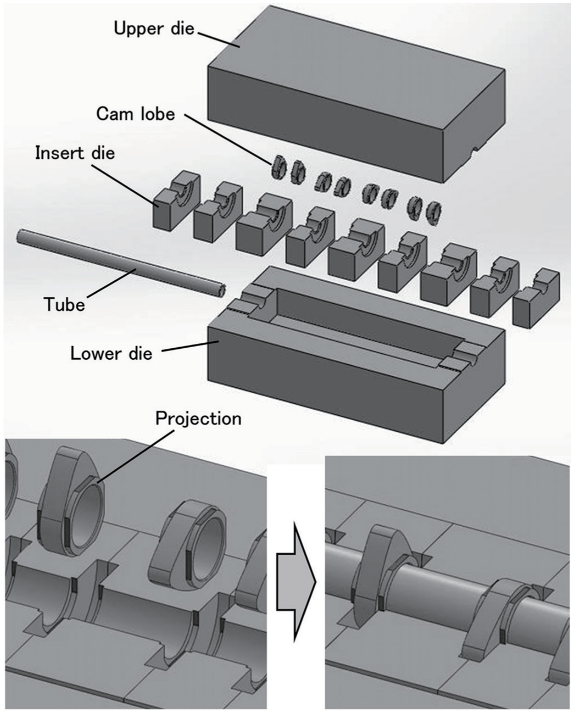

Fig. 14 Hydroforming die structure for high accurate camshaft

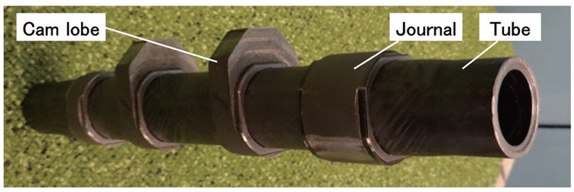

Fig. 15 Simple shape camshaft made with high accurate hydroforming die

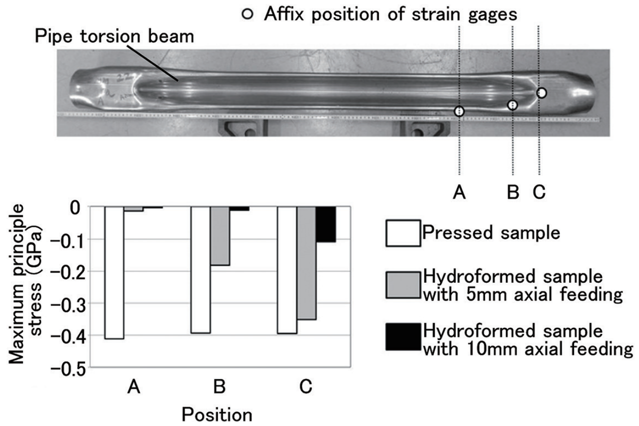

Fig. 16 Residual stress after forming of torsion beam

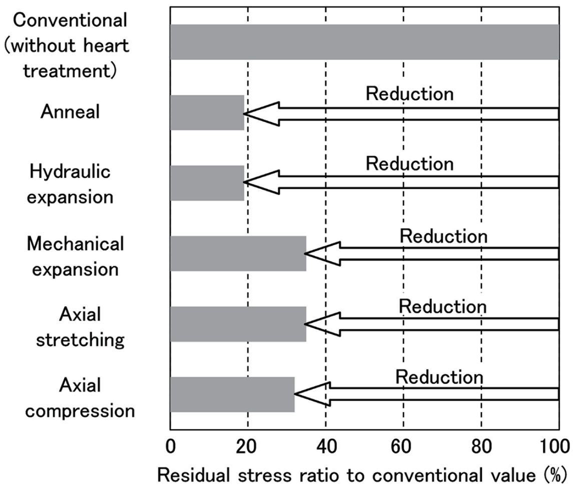

Fig. 17 Comparison of residual stress ratio to conventional value in torsion beam

as hydroforming, are effective. **Figure 17** compares the residual stress reduction effects of those methods by FEM. Although the effects of annealing and hydroforming are large, the other methods can also reduce the original residual stress to approximately one-third. These methods can be effectively employed by manufacturers that do not have heat treatment and hydroforming equipment.

3.3 Origami (paper-folding) structures with a stable axial crushing property

Origami (paper-folding) structures[24] refer to hydroformed parts that have been developed targeting collision parts. Nippon Steel studied the axial crushing properties of such formed parts in cooperation with Tube Forming Co., Ltd. that took charge of the forming technology. As the characteristics of origami structures, the loads at the time of axial crushing are stable at a low level as compared with straight tubes. As another advantage, a part was stably folded in a test using a falling weight with the angle shown in **Fig. 18**.

Figure 19 shows the FEM analysis results. When the falling weight comes into collision at a collision angle of 10°, the straight tube bends sharply (deformation mode), while the origami structure is properly folded, showing excellent robustness against deformation.[25] In addition, loads at the time of axial crushing can be easily designed. Changing the angle of the origami shape (α), inscribed circle diameter ratio (d_1/d_2), and initial wall thickness (t_0) shown in

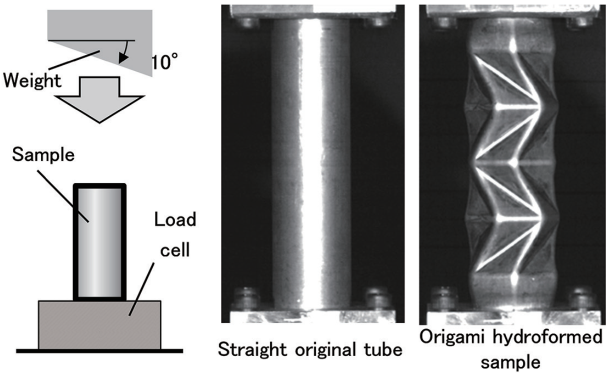

Fig. 18 Impact test procedure

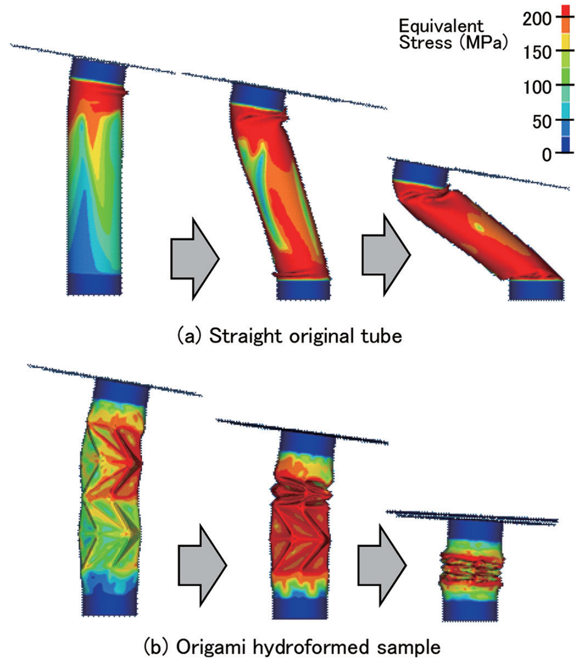

Fig. 19 Comparison of FEM results of axial crashing in case of 10 degrees of impact angle

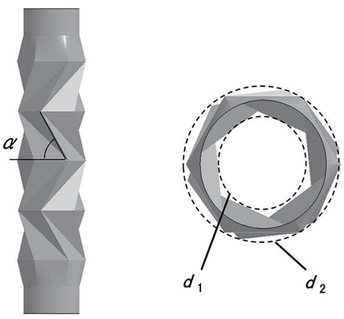

Fig. 20 Design parameters of origami structure

Fig. 20 can produce an origami structure that can obtain the target load.[26] The structures in Fig. 18 and Fig. 19 are example parts hydroformed from STKM11A tubes with an outer diameter of 48.6 mm and a wall thickness of 1.0 mm into a shape with α=60° and d_1/d_2=60%.

4. Other Processing Methods

In tube forming, the ends of tubes are often expanded or shrunk. This section introduces methods of press tube expansion with eccentricity or bending as development examples of tube expansion. In addition, the application of tailored blank technologies[27)] in which the thickness of materials is changed at appropriate places has been increasing as a means to reduce weight. In the tube sector, the need for different-thickness processing in which the wall thickness is changed in the longitudinal direction has also been increasing. This section introduces two types of tubes with different wall thicknesses that Nippon Steel is developing.

4.1 Tube expansion with eccentricity or bending

One method to expand and shrink the ends of tubes is spinning. Spinning is gradual forming, so it can form parts in complicated shapes. For example, Kato et al. developed a method to form shapes with a shrunk section and with eccentricity and bending by spinning.[28)] However, the productivity of spinning is low, so press working is desired for parts to be mass-produced. Therefore, the authors developed methods for tube expansion with eccentricity and tube expansion with bending by multi-step pressing.

Figure 21 illustrates the process of the developed method for tube expansion with eccentricity.[29)] It is an example where a stainless steel tube (SUS409L) with an outer diameter of 22.2 mm and a wall thickness of 1.2 mm is used to form a tube expansion shape with eccentricity with an outer diameter of 40 mm in four steps. Broadly speaking, this developed method has two points. One is that an eccentric punch is not used from the initial step but concentric punches are used to the middle of processing; an eccentric punch is first used in the last step. In this example, concentric punches are used to expand the tube in stages to a tube expansion (λ) of 25, 50, and 75%. In the last step, the upper die is used to compress one side into an eccentric shape and the tube is expanded to a tube expansion of 80%. The other point is making the half angle of the flaring of the concentric punch larger than the angle of the product shape. This provides axial compressive strain to suppress thickness reduction. In this example, the product is in an eccentric shape with an angle of 29° for one side, but, in the middle of the steps, concentric punches having a large angle (50° for the half angle and 100° for the full angle) are used for tube expansion. These measures explained above can suppress thickness reduction of the flaring sections.

Regarding tube expansion with bending, two types of processing methods were studied: 1) a tube is first expanded and then bent while it is partly reduced in the last step; and 2) a tube is first bent and then expanded.[30)] In the first method, punches are thrust from the same direction, so productivity is high. Meanwhile, the degrees of flexibility for the bending angle and bending length are higher in the second method. **Figure 22** shows example processes of the second method. A SUS409L tube with an outer diameter of 25.4 mm and a wall thickness of 1.2 mm is bent and then expanded into a shape with an outer diameter of 47.4 mm and a bending angle of 19.6°. First, the tube is press-bent with the upper and lower dies. Then, the positions are exchanged and the tube end is expanded. In the tube expansion steps, concentric punches are used for tube expansion and an eccentric punch is used in the last step, similarly to the procedure in Fig. 21. **Figure 23** shows sample tubes processed by tube expansion with eccentricity and with bending in accordance with the procedures described above.

4.2 Tubes with different wall thicknesses by drawing

Tubes with different wall thicknesses formed by drawing that were called butted tubes in the past[8)] have been used in practice.[31)] **Figure 24** illustrates the processing steps. When a plug is inserted while the tube is being removed (drawn), the section becomes thin; when the plug is pulled back (sunk), the section becomes thick. Repeating these steps can form a tube with different thicknesses that has thin and thick sections in turns. **Figure 25** shows a prototyped STAM15A sample with an outer diameter of 26 mm and wall thicknesses of 4.0 and 3.1 mm. Most tubes with different wall thicknesses formed by drawing were thick tubes with a small diameter targeting shafts and other similar parts like the sample part. Nippon Steel has been developing large-diameter thin tubes with different wall

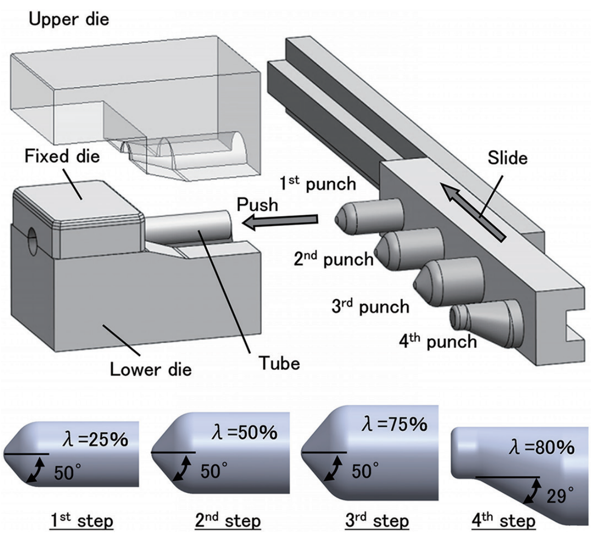

Fig. 21 Punch shape of each step of tube end expanding with eccentricity

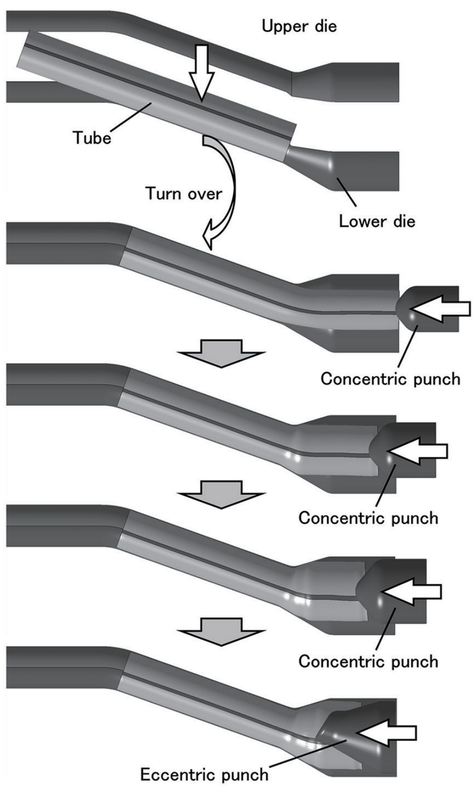

Fig. 22 Forming process of expanding at tube end after press bending

(a) Expanding with eccentricity

(b) Expanding with bending

Fig. 23 Mechanical expanding samples with eccentricity or bending

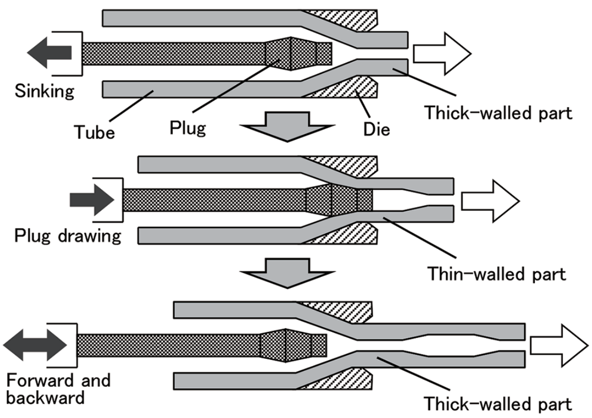

Fig. 24 Forming process of tube with different wall thickness by drawing

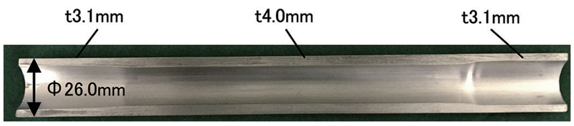

Fig. 25 Forming sample of tube with different wall thickness by drawing

thicknesses to apply them to chassis and bodies. Specifically, 690-MPa initial materials for torsion beams were used to prototype tubes with different wall thicknesses with an outer diameter of 92 mm and wall thicknesses of 2.3 and 2.0 mm, and the parts are under evaluation.

4.3 Tubes with different wall thicknesses by ironing

The aforementioned drawing method can form long tubes with different wall thicknesses continuously, but it is difficult to process large differences in wall thickness (for example, when the thickness of some sections ranges from a half to two times that of the other sections). Therefore, Nippon Steel has been developing tubes with different wall thicknesses by ironing to form tubes whose differences in wall thickness are large.[32] **Figure 26** illustrates such processing steps. First, one end of a tube is slightly expanded with a punch. At that time, the other end is secured with a stopper. Next, the stopper is removed and the punch is further thrust in. With the section expanded in the first step is caught by the die, the inside is ironed

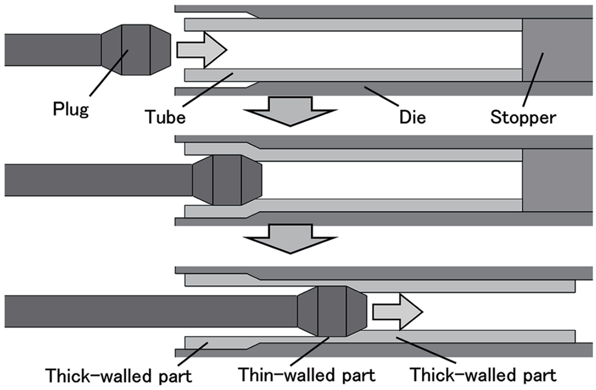

Fig. 26 Forming process of tube with different wall thickness by ironing

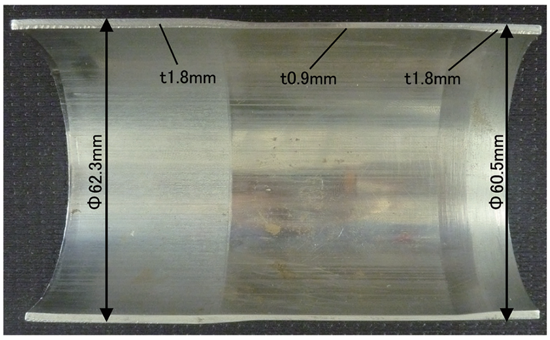

Fig. 27 Forming sample of tube with different wall thickness by ironing

with the punch, which lengthens the entire tube. As a result, the processed tube with different wall thicknesses has a thick section expanded, a thin section ironed, and another thick section that has not been processed as the final shape.

One point in the processing is the lubrication conditions. Conditions where the friction factor on the outside of a tube is high and that on the inside of the tube is low work better. It is difficult using this processing method to form long tubes with different wall thicknesses unlike the drawing method described in the previous section, but this method can make differences in wall thickness larger. For the prototyped sample in **Fig. 27**, a 440-MPa initial material could be processed into a tube with different wall thicknesses with an outer diameter of 60.5 mm and wall thicknesses of 1.8 and 0.9 mm (the thickness of some sections ranges from a half to two times that of the other section).

5. Conclusions

In recent years, an increasing number of tube parts have been applied to automobiles and Nippon Steel has thereby been developing various tube forming methods. This paper focused on the new processing technologies lately developed shown below.

1) Regarding bending, Nippon Steel has developed a rotary draw bending method that suppresses local thickness reduction using an asymmetrical mandrel, a press bending method with moving rolls in which a tube is bent while the supports are moved and for which buckling occurs less, and a press bending method with cross-sectional deformation for which the initial investment is small and springback does not greatly occur.
2) Regarding hydroforming, we developed a method for local reinforcement with sheath tubes using high-pressure loads, a

method to form high-accuracy assembled camshafts, a processing method to reduce the residual stress on torsion beams, and a hydroformed origami part with excellent robustness against axial crushing.

3) As other processing methods, we developed a method for tube expansion with eccentricity and bending that can suppress thickness reduction after processing, a drawing method that forms tubes with different wall thicknesses and that has been applied to large-diameter thin materials, and an ironing method that forms tubes with large differences in wall thickness.

We will further apply the technologies introduced in this paper to actual automobiles in the future to contribute to further reduction in the weight of automobiles and enhancement of their performance.

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