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Development of Three-dimensional Hot Bending and Direct Quench Technology

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Abstract

Recently, the automotive industry has been focusing on developing on lighter vehicles to improve fuel economy and crash safety. In order to meet these requirements, Three-Dimensional Hot Bending and Direct Quench (3DQ) Technology, which enables the formation of automotive parts with a tensile strength of 1,470 MPa or more, has been developed. This 3DQ is a consecutive forming that allows three dimensional complex hollow bending and Quenching at the same time. In this reports, developed 3DQ technology and characteristics of products by 3DQ are described.

1. Introduction

The automobile industry faces two big issues: to reduce the body weight (improve fuel efficiency) to decrease CO_2 emission as a measure against global warming, and to improve in crash safety. To meet these conflicting requirements, Nippon Steel & Sumitomo Metal Corporation, Nippon Steel & Sumikin Pipe Co., Ltd., and Nippon Steel & Sumikin Plant Co., Ltd. have jointly developed a technology of three-dimensional hot bending and direct quenching (hereinafter 3DQ) for hollow tubular structure. The developed technology is an innovative method whereby pipes and roll-formed steel materials are formed into ultrahigh-strength auto parts of three-dimensionally complicated shapes in one operation; the method makes it possible to fully enjoy the advantage of steel to make high-strength structural members at lower costs compared with other materials. In this study, outlines of the 3DQ technology and performance of the products by 3DQ are reported.

2. Background and Objective of Development

In recent years, the urgent needs in the automotive industry are significant reduction of the CO_2 emission through improved fuel efficiency as a measure to check global warming, and enhancement of collision safety and further development is required.

While use of high-strength materials is important for reducing car weight, hollow tubular structure integrated automotive part is also effective compared with welded open cross section structure parts by stamping (**Table 1**). For this reason, tube hydroforming automotive part [1, 2] has been widely employed in appreciation of the following advantages over the conventional stamping parts:

- As forming of complicated hollow tubular structures becomes possible, flanges needed for welding assembly of stamped products can be omitted, the number of components can be reduced, and additional welding can be omitted.
- High strength is obtained by work-hardening.
- Because of good shape fixability (little spring back), high dimensional accuracy is obtainable.

Presently closed-section auto parts are made using steel pipes of a 980 MPa class strength (unless otherwise specified, all the units

Table 1 Forming method for high-tensile automotive parts

		- 980 MPa	1,470 MPa -
Open cross section structure		Cold stamping	Hot stamping
Hollow tubular structure		Hydroforming	3DQ

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used herein are metric).

Hot stamping,[3, 4] on the other hand, has become increasingly popular in Europe and Japan since around 1990 as a method for forming high-strength open-section auto parts of a strength of 1,470 MPa or more. The developed 3DQ technology is époque-making in that it combines the strengthening (quenching) effect of hot stamping and the ability to form closed-section pieces of hydroforming. Thus, 3DQ is expected to reduce car weight and enhance collision safety.

3. Outlines of 3DQ Technology [5, 6]

The 3DQ technology is the world first steel forming method characterized by the following: (i) it is capable of three-dimensionally forming closed-section pieces having a strength of 1,470 MPa or more; (ii) the hot forming process provides smaller residual stress and better shape fixability relative to conventional cold forming methods; and (iii) the forming requires no dies (dieless) and the equipment is compact.

The configuration of the 3DQ equipment is schematically illustrated in **Fig. 1**: part (a) shows the movable roller die type, and part (b) shows the robot type. The latter is shown also in **Fig. 2**. The pipe is fed from an end, heated by an induction coil, and held at a downstream position by a roller die or a robot, which three-dimensionally provides the pipe-forming moment. Either type is capable of three-dimensional forming into desired shapes through position control of the roller die or the robot using servo motors.

Next, **Fig. 3** shows a typical flow of forming procedures by the robot type system. The designated product's CAD data is compiled to a robot arm trajectory curve data in three-dimension. The compiling program is based on a precise plastic deformation analysis, and the robot is able to precisely trace the trajectory. As the result, the 3DQ system provides high reliable quantities in forming work.

Robots of a general-purpose type available in the market are used for 3DQ, which allows very compact configuration and standardization of the equipment. Whereas, by conventional mechanical forming methods, the equipment design tends to be different according to individual object parts, use of the general purpose robots makes it possible to standardize the equipment and shorten the construction lead time. In addition, because the 3DQ method does not use dies and it is very easy to input a new set of trajectory data to the robot, it is also suitable for manufacturing wide varieties of products in small quantities.

Besides pipes and tubes, various types of roll-formed closed-section materials shown in **Fig. 4** can be used as the feed stock for 3DQ. **Figure 5** shows an example of the temperature change during the 3DQ forming process of a square hollow section, 35 mm × 45 mm in size and 1.6 mm in wall thickness; it was measured with thermocouples on the internal surface of the material, which was fed at a rate of 80 mm/s. Here, the material was quickly heated to above the Ac_3 temperature by the high-frequency heating coil, and then rapidly water-cooled to room temperature.

Figure 6 shows the analysis result of the deformation during the process, obtained using the FEM model explained herein later; the graphs show the temperature and strain rate in the axial direction at

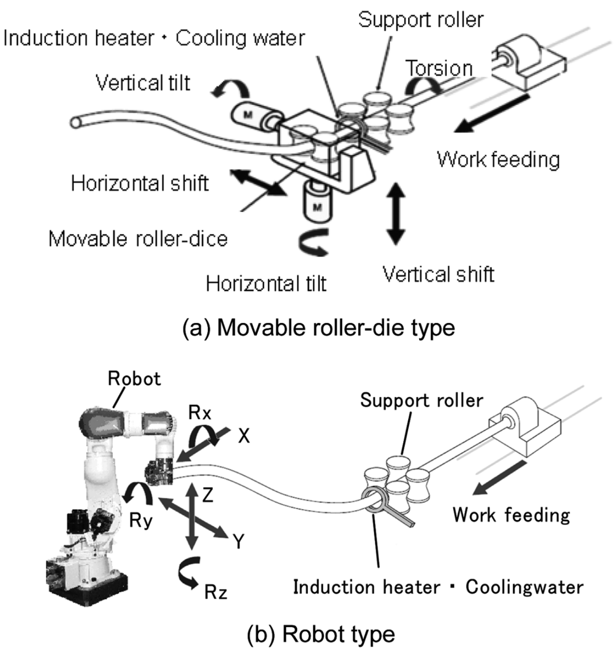


Fig. 1 Schematic illustration of 3DQ machine

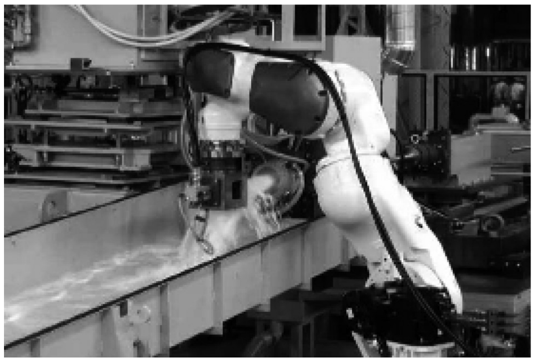


Fig. 2 3DQ machine (robot type)

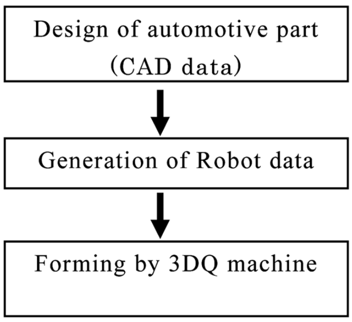


Fig. 3 3DQ system (robot type)

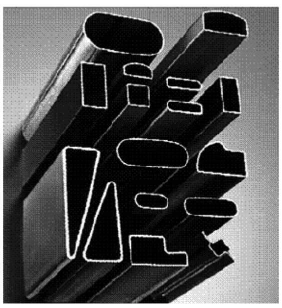


Fig. 4 Various shaped tubes using 3DQ process

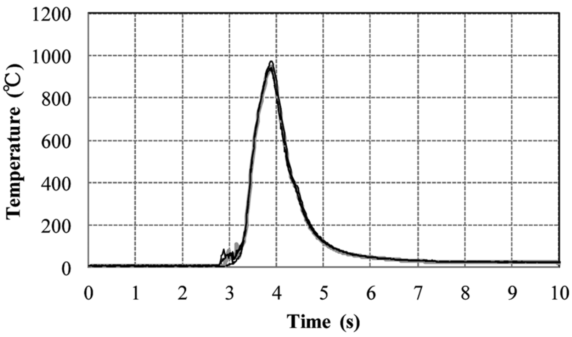


Fig. 5 Temperature behavior in 3DQ process
(feeding speed 80 mm/s, 35 mm height × 45 mm width × 1.6 mm thickness)

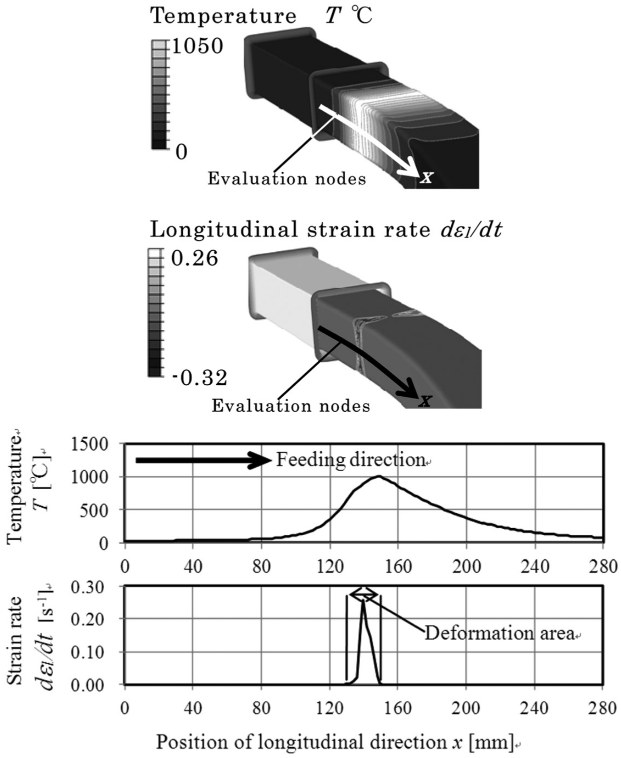


Fig. 6 Behavior of temperature and strain rate in 3DQ process (FEM)
(feeding speed 80 mm/s, 35 mm height × 45 mm width × 1.6 mm thickness)

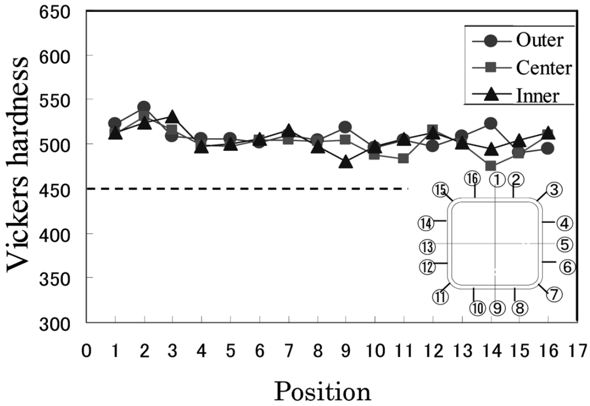


Fig. 7 Example of hardness distribution of product by 3DQ
(40 mm × 40 mm, thickness: 1.8 mm)

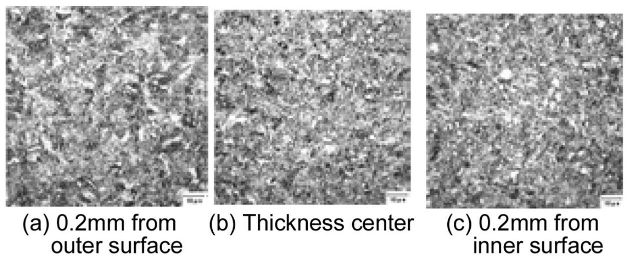


Fig. 8 Microstructure of product by 3DQ
(40 mm × 40 mm, thickness: 1.8 mm)

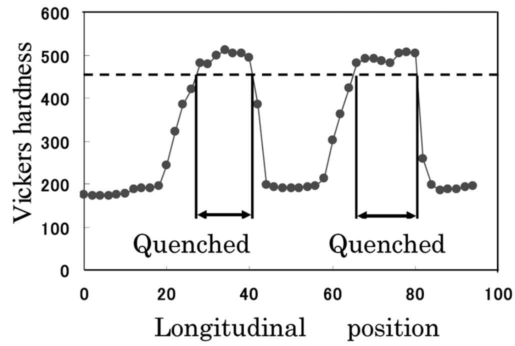


Fig. 9 Hardness distribution of partially quenched product by 3DQ

the thickness and width center of the wall on the inside of the bending. The bending deformation occurs only in the high-temperature zone of the material, namely within a very small range of roughly 20 mm in the direction of travel, according to the analysis condition applied, and immediately thereafter, the material hardens through martensitic transformation. Since the forming work is applied in hot, the residual stress due to the working is very low. Note, in this relation, the deformation resistance at the part where the forming force was applied is less than 1/10 that of the feed material and less than 1/30 that after quenching. The deformation of sectional shape is restricted because the deformation occurs within the small length of the heated part, and the shape of the cold parts before and after it remains unchanged because of high deformation resistance.

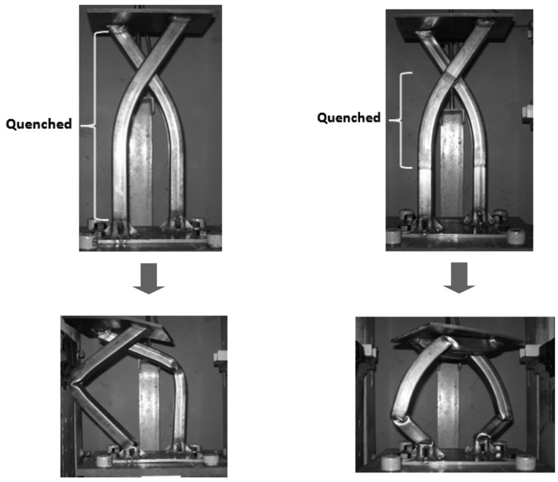
4. Properties of 3DQ Products

The hardness distribution of a product trial produced by 3DQ is given in **Fig. 7**; the readings are those at the thickness center and at the points 0.2 mm each from the outer and inner surfaces of a square hollow section, 40 mm × 40 mm in size and 1.8 mm in wall thickness, after forming by 3DQ. The hardness fluctuation is confined within a very limited range, and the material strength is above 1,470 MPa at all the points. **Figure 8** shows the photomicrographs of the same product; the material consists of a fine martensitic structure.

Figure 9 shows another example of hardness distribution obtained by intermittently applying current to the heating coil to partially quench the work of the same size as given above. The graph shows a hardness change corresponding to the change in the power applied to the coil, which indicates that it is possible to strengthen formed products partially as desired.

Figures 10 and 11 show the results of axial crush test using two kinds of square-section specimens single-bent by 3DQ, one quenched in the entire length and the other quenched along the bent curve only; the drop weight mass was 430 kg, and its initial height 2.4 m. As seen in the photos, the wholly quenched specimen buckled at the curved portion in the initial stage of the impact, and the absorbed energy was low. The partially quenched specimen, in contrast, buckled in the upper nonquenched portion in the initial stage, and the bent portion began to collapse thereafter. The portion of the partially quenched piece corresponding to that of the wholly quenched one that buckled in the initial stage remained unaffected throughout the test. The energy absorbed by the partially quenched piece in the stroke from 0 to 150 mm was larger than that by the wholly quenched one. The above finding indicates that it is possible to control the collapsing modes of automobile structural members by properly quenching different portions of the members by 3DQ.

Figure 12 shows a rectangular hollow section, 20 mm × 60 mm in size and 1.6 mm in wall thickness, twisted by 3DQ; the developed method is able to form ultra-strong materials into complicated shapes, which conventional methods cannot.



(a) Wholly quenched (b) Partially quenched

Fig. 10 Deformation of wholly and partially quenched specimens in axial crash test

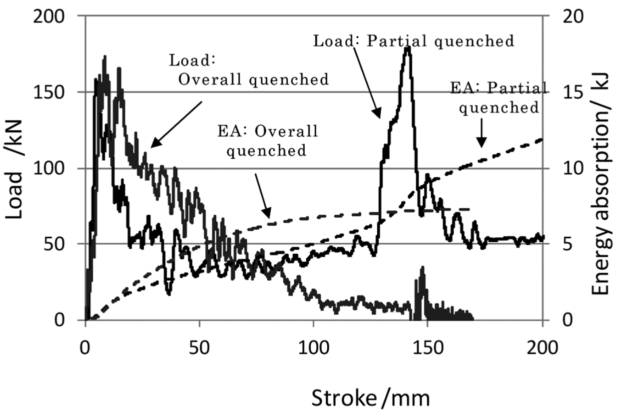


Fig. 11 Energy absorption of partially quenched 3DQ product in axial crash test

5. Development of Analysis Model

The analysis methods so far proposed for the bending work under high-frequency heating calculate the bending moment and wall thickness of materials of comparatively simple round section based on elementary analysis.[7-9] In the development of 3DQ, it was necessary to work out an analysis model applicable to complicated sectional shapes that would be obtained through the process. It is imperative to establish a method for accurately analyzing of the 3DQ process, where a pipe has complicated and irregular sectional shapes. In particular, it is important to optimally design the coil capable of heating the material uniformly in the circumferential direction and estimate the force required for the forming work and occurrence of irregularities (e.g., wrinkles). The FEM analysis model developed for the process is outlined in **Fig. 13**.

5.1 Analysis of electromagnetic field and heat [10]

In the numerical analysis of high-frequency induction heating, the density distribution of the Joule heat is calculated using analysis of electromagnetic field, and then, the temperature distribution in the material is obtained using heat conduction analysis. Usually, an entire pipe is divided into finite element models (FEM) and the analysis continues to change the pipe position relative to the heating

Fig. 12 Example of twisting by 3DQ

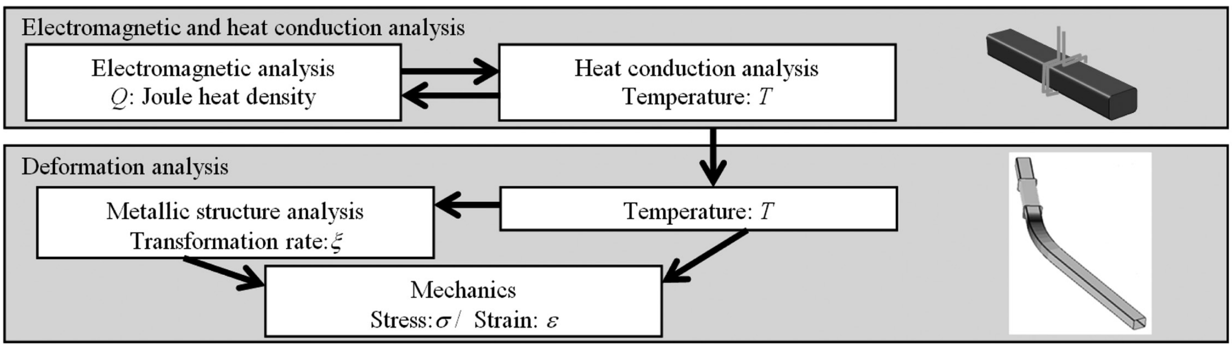


Fig. 13 Outline of 3DQ FEM analysis

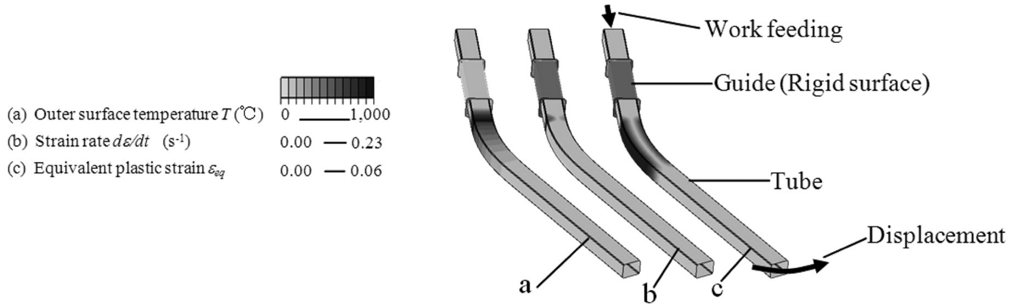


Fig. 14 FEM model of 3DQ and mechanical boundary conditions

coil. It requires enormous computation time to calculate a general full model of 3DQ forming, which includes a very long pipe and a vast air layer.

To solve this problem, the analysis area was limited to that closely surrounding the pipe, and instead of changing its position, an advective term was introduced in the dominant equation of heat conduction to obtain the temperature distribution in the steady state. In addition, an algorithm of proportion-integration-differential control was incorporated in the analysis model to enable automatic calculation of optimum heating power for temperature control.

Since ferromagnetic and nonmagnetic bodies are mixed in the steel material to be processed by 3DQ when its temperature changes across the magnetic transformation point, sufficiently accurate analysis is impossible using a definite magnetic permeability. In consideration of this, the model takes into account the nonlinearity of the magnetic properties of the material, its magnetic transformation point, and the temperature dependence of the electric conductivity and heat characteristics. The analysis model thus worked out has made it possible to optimally design the heating coil and calculate the temperature distribution and other process phenomena during the 3DQ process accurately and efficiently.

5.2 Deformation analysis [11-13]

Three-dimensional temperature distribution is calculated using the electromagnetic and heat conduction analysis described in subsection 5.1. The obtained temperature distribution is mapped to all integration points of the shell elements of the deformation analysis model. To consider the convection heat transfer by the cooling water, the heat transfer coefficient obtained through experiments was used for estimating the cooling behavior. The material structure changes in the 3DQ process: ferrite-perlite structure changes into austenite structure in the heating zone, and martensitic transformation takes place in the cooling zone. The mixture of metal structures is described by volume fraction of each structure. The volume fractions are estimated using transformation models. For example, the transformation temperatures are defined by Kunitake's equation,[14] and the volume fraction of martensite is based on Koistinen–Marburger's rule.[15]

The strain in hot working is defined in Equation (1), where $d\varepsilon^e$ is elastic strain, $d\varepsilon^p$ is plastic strain, $d\varepsilon^{TH}$ is thermal strain, and $d\varepsilon^{TR}$ is transformation strain.

$$d\varepsilon^{total} = d\varepsilon^{e} + d\varepsilon^{p} + d\varepsilon^{TH} + d\varepsilon^{TR} \quad (1)$$

Taking the elasto-plastic strain into consideration, it became possible to analyze large deformation such as wrinkling and wall thickness change. Taking thermal and transformation strains into consideration, it became possible to analyze thermal deformation and the residual stress. The temperature- and metal-structure-dependencies of flow stress were taken into account. The thermal and transformation strains were calculated using Miettinen's density estimation equation [16] and the volume fraction of each metal structure.[17] The strain-rate-dependence of flow stress was defined using the Cowper–Symonds law.

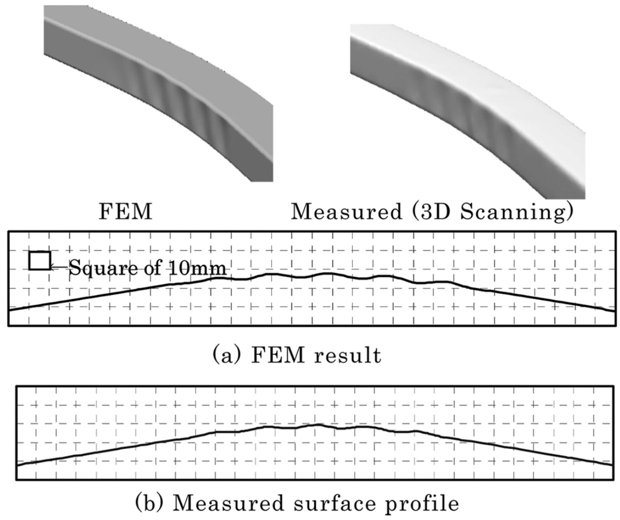


Fig. 15 Comparison of wrinkle by FEM analysis and measured one

5.3 Example of analysis

The work shapes and the boundary conditions for the model are given in **Fig. 14**. As the boundary conditions, displacement is assumed to be applied at the top-end of the material tube, and the guide is assumed to be a rigid body. **Fig. 15** compares an analysis result with an experimental result. The analysis has proved effective at simulating the situation of wrinkling quite well, though somewhat different from that actually measured in terms of the pitch and depth of the wrinkles. This analysis model has made it possible to design auto parts in optimum shapes and to improve the efficiency of auto parts development.

6. Conclusions

The 3DQ process capable of forming auto parts having a strength of 1,470 MPa or more has been developed. The developed process is expected to be instrumental in significantly reducing the weights of automobile parts made of ultrahigh-strength steel pipes (**Fig. 16**). The 3DQ process has been commercially applied, and different types of auto parts are being manufactured in quantities through 3DQ forming lines. The authors are furthering the technical development of the process to expand its application to the auto industry.

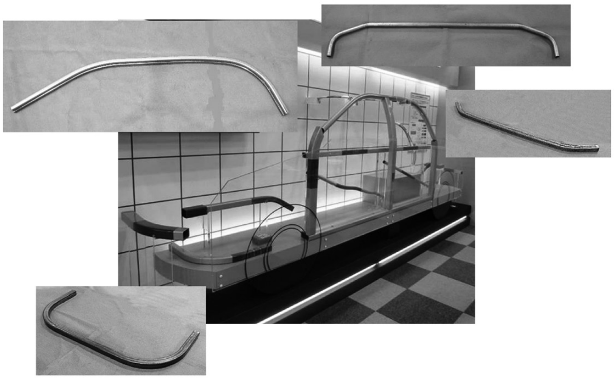


Fig. 16 Examples of automotive parts formed by 3DQ

Acknowledgements

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References

1) Kojima, M. et al.: Proc. of JSTP 195 Int. Joint. Symp. 2000, p. 244
2) Tomizawa, A. et al.: Proc. of Tube Hydro 2009. 2009, p. 1
3) Kojima et al.: Proc. of Conference of Society of Automotive Engineers of Japan (JSAE). 72-07, 2007, p. 13
4) Asai, T. et al.: Proc. IDDRG. 2004, p. 344
5) Tomizawa et al.: Proc. of the 2010 Japanese Spring Conference for the Technology of Plasticity. 2010, p. 207
6) Tomizawa et al.: Proc. of the 63rd Japanese Joint Conference for Technology of Plasticity. 2012, p. 171
7) Kohata et al.: J. of Japan Society for Technology of Plasticity (JSTP). 28 (313), 214 (1987)
8) Asao et al.: J. of JSTP. 28 (313), 206 (1987)
9) Kuriyama et al.: J. of JSTP. 42 (481), 57 (2001)
10) Okada et al.: Tetsu-to-Hagané. 98 (7), 38 (2012)
11) Kubota et al.: Proc. of the 2011 Japanese Spring Conference for the Technology of Plasticity. 2011, p. 49
12) Kubota et al.: Proc. of the 62nd Japanese Joint Conference for Technology of Plasticity. 2011, p. 149
13) Kubota et al.: Proc. of the 2013 Japanese Spring Conference for the Technology of Plasticity. 2013, p. 131
14) Kunitake: Netsu Shori (J. of Japan Soc. Heat Treat.). 41 (3), 164 (2001)
15) Koistinen, D.P. et al.: Acta Metallurgica. 7 (1), 59 (1959)
16) Miettinen, J.: Metallurgical and Materials Transactions B. 28B, 281 (1997)
17) Okamura: J. of Soc. of Materials Science Japan. 5 (5), 529 (2006)

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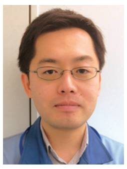

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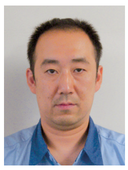

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