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Automotive Solution (2): Equipment Development of 3-Dimensional Hot Bending and Direct Quenching (3DQ)

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Abstract

In the automotive industry, high strength steels has been applied to car body structure in order to improve the crash safety and light weight body. 3-Dimensional Hot Bending and Direct Quench (3DQ) has been developed for this requirement. 3DQ is the process techniques for hollow steel, which is quenching and bending at the same time with optional three-dimensional shape. From the view point of mechanical element techniques, this report introduces 3DQ technology and equipment developments.

1. Introduction

In recent years, needs of high-tensile strength are growing in steel materials applied to car body structure in order to realize improvements in both car crash safety and fuel consumption. In order to cope with the trend, the conventional method for increasing strength and rigidity is to form a closed cross section structure by press-forming a sheet of a high-tensile strength steel (called HI-TEN) sheet, which is spot-welded to a flanged sheet (refer to **Fig. 1**).

3DQ is a processing technology that can simultaneously bend a steel tube according to the required form (three-dimensional form) and quench with enhanced strength (>1 470 MPa). By applying this technology, compatibility of "improvement in crash safety" and "light-weightedness" for automobiles can be expected.

In the 3DQ, both hot bending and high frequency quenching for a closed cross section structure is carried out in a single process. The bending process of a closed cross section structure, which has not been realized in conventional press-forming method, can eliminate the flange portion of a structure. Furthermore, manufacturing process can be shortened to a single stage.

On the other hand, conventionally, quenching process of a straight tube and hot bending processing have been practiced using high frequency heating. Compared with such processing, the 3DQ method can bend a steel tube to form any required forms by using an arm robot. When the bending form of a product is changed, 3DQ method requires to only modify the robot trajectory without modifying the length of the arm tool in the bending machine and the dies of a pressing machine, which are practiced in the conventional technology.

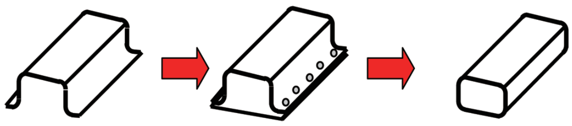

Fig. 1 Schematic diagram of lightweight by various cross section of hollow structure

Compared with the conventional press-forming method, 3DQ has the advantage of manufacturing light-weighted products by eliminating the flange portion. Furthermore, compared with the conventional high frequency heating, 3DQ is superior in its flexibility for various forms of products and is expected to be a technology of a wider range application of automotive parts. Then, this article outlines the 3DQ equipment from the viewpoint of a machine element technology by comparing with that of conventional technology. Furthermore, the equipment development, which has solved technical problems specific to 3DQ, is also reported in this article.

2. Outline of 3DQ Technology[1, 2)]

2.1 Principle of 3DQ processing

Concerning the 3DQ principle, configuration of major devices is shown in **Fig. 2**. A steel tube is heated up to a temperature higher than the A_{C3} transformation point by high frequency heating. Then, the steel tube is bent at the softened region by heating and is quenched immediately thereafter. In the operation, the processing force to bend the steel tube at the high temperature region is continuously supplied by a robot (called bend forming robot hereafter) which chucks the front edge of the steel tube. A supporting guide receives the reaction force to bend the steel tube. As a result, a product of a required form with high strength of martensitic microstructure

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can be obtained.

2.2 Outline of the conventional high frequency heating technology

For comparison purpose, the conventional high frequency technologies are described below. One of them is the rotary type quenching technology for a straight tube. As the steel tube is rotated in the heating and quenching process, it is easy to uniform the temperature in a circumferential direction (refer to **Fig. 3** [3]). Another conventional technology is a method that bends a steel tube to a certain curvature (two dimensional on a plane) by turning an arm with chucking the front end of the tube (**Fig. 4** [4]).

2.3 Problem of 3DQ equipment

The features of 3DQ are compared with the rotary type quenching, wherein the steel tube of products is most similar to the one of 3DQ in size among all conventional technologies. **Table 1** shows the outline of the comparison.

What is common between the conventional rotary type and 3DQ is that the difference in the clearance between the steel tube and the heating coil changes the induction heating efficiency and accordingly influences the heat quantity into the steel tube. Furthermore, as a quenching nozzle is installed at the downstream and adjacent to the heating coil (in the direction of travel of the steel tube), the difference in the clearance between the steel tube and the quenching nozzle influences its quenching effect, which is also common between the conventional rotary type and 3DQ.

The difference between the two methods is that in the rotary type, even when the clearance between the steel tube and the heating coil is not constant due to such a misalignment, the uneven effect of thermal input and quenching in the circumferential direction is relieved by the rotation of the steel tube. As a result, as the temperature distribution in the circumferential direction gets uniform, this processing can be stabilized. However, this technology can be applicable only to the straight tube form product.

On the other hand, in case of 3DQ, the steel tube is not rotated due to bending work. Therefore, as for the thermal input and the quenching effect, nonuniformity in the circumferential direction tends to be developed, unless the clearance between the steel tube and the heating coil is uniform. Moreover, the region length heated to a high temperature (the region wherein the tube is softened with a high temperature) is much shorter in 3DQ as compared with that of the rotary type. This is because the length of the region softened with a high temperature is required to be short in order to stabilize

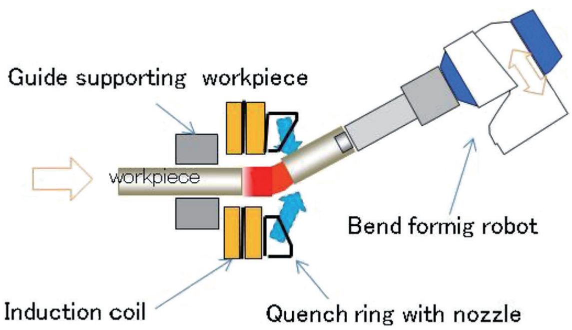


Fig. 2 3DQ process principle

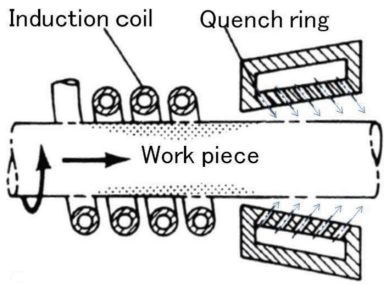


Fig. 3 Example of conventional induction heat system with rotating work piece [3]

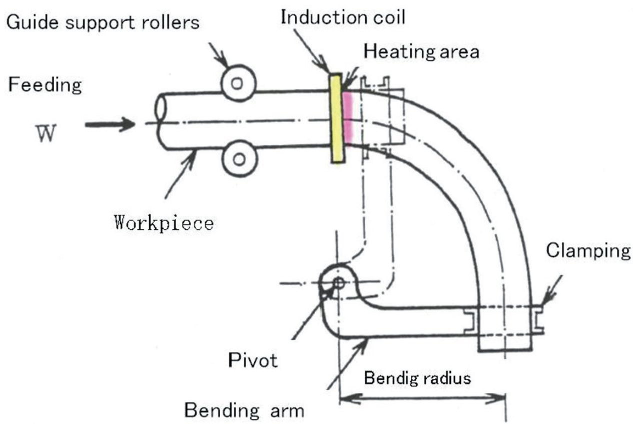
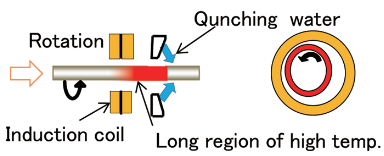
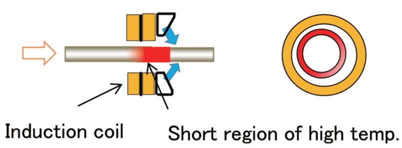


Fig. 4 Example of conventional induction heat system with bending work piece [4]

Table 1 Characteristic of conventional type and 3DQ

Type	Heating and quenchig schematic	Temperature deference in circumferential direction
Rotary (conventional)		Good (It might be low due to rotation, even if clearance is not constant)
3DQ		Poor (It might be high due to high frequency heating focusing, if clearance is not constant)

the form of bending.

As stated above, compared with the conventional rotary type technology, problems specific to 3DQ equipment are caused by their process features of bending the steel tube without its rotation.

2.4 Requirements to 3DQ equipment

From the viewpoint of comparison with the conventional high frequency technology, characteristic requirements to 3DQ equipment are stated below.

2.4.1 Enhancing position accuracy in holding steel tube

As for the heating and quenching process, in order to obtain uniformity in the circumferential direction of steel tube, both of the clearances of the steel tube as to the heating coil and the quenching nozzle are required to be uniform in the circumferential direction, In addition, therefore, the position of the steel tube is needs to be stabilized. Therefore, high accuracies are required to chuck and support the steel tube with 3DQ devices.

2.4.2 Shortening of high temperature region

For stabilization of the bending process, the high temperature region of the steel tube (where the tube is softened with a high temperature) is required to be short. To shorten the high temperature region, the quenching nozzle is arranged adjacent to the heating coil for the rapid cooling of the steel tube.

2.4.3 Diverse requirements to equipment

As the form of automotive parts is diverse, the conditions of forms of products, such as the radius of curvature and the length of the straight section, are also diverse. Therefore, the equipment is required to comply with any changes in condition. The equipment has been developed so as to comply with such requirements.

2.5 Equipment components of 3DQ and flow of processing

Equipment components of the entire system are shown in **Table 2** and **Fig. 5**. We describe the components of the equipment by introducing an example of the process flow. As a preliminary operation, the front end of the steel tube is chucked by a bend forming robot. At the same time, the support guide clamps and holds the steel tube that is adjacently closed to the induction coil. The feeding device chucks the rear end of the steel tube and feeds the steel tube. The bend forming robot operates to bend the steel tube by controlling its trajectory for molding a required product form. The travel of the feeding device is synchronized to the movement of the bend forming robot. The induction heating coil simultaneously provides the steel tube with an induction heater. The steel tube is heated to high temperature and immediately thereafter, the spray nozzle supplies the quenching water to the steel tube.

Quenching water stored in a water tank is fed to the quenching nozzle by a pump. The quenching water sprayed onto the steel tube is collected in a recovery pan and returned to the tank via a deforming equipment.

Photo 1 shows the state of water sprayed from the quenching nozzle before the start of processing. It shows the external view of the spraying seen from the side of the device. It is found that considerable amount of water is flowing for rapid cooling of the steel tube. **Photo 2** shows the external view of the bend forming robot manipulator chucking the front end of the steel tube. It is found that the steel tube gets red-hot, and the quenching water is sprayed to the downstream direction. Quenching water after being sprayed is collected in a recovery pan.

2.6 Type of equipment

There are three types of bending methods in 3DQ equipment according to the features of the form and the size of products. Features specific to respective method are described in summary as follows (refer to **Table 3**). What is common to all three types is to use a general purpose robot including a manipulation. In general, for a machining equipment, each mechanical structure is independently designed and built in order to comply with the product form. However,

Table 2 Component of 3DQ system

Classification of apparatus	Main item of apparatus
Holding	Feeding, guide supporting and chucking for work piece
Heating	Induction coil
Cooling	Storage tank, pump, quenching ring
Bending	Bend forming robot

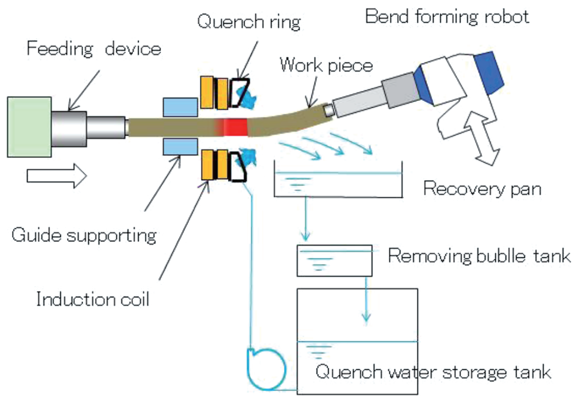


Fig. 5 3DQ system schematic

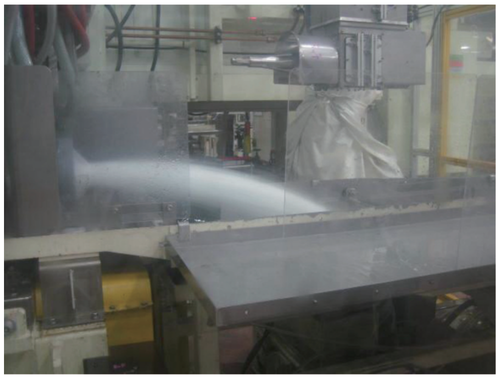


Photo 1 Water spray from quenching ring

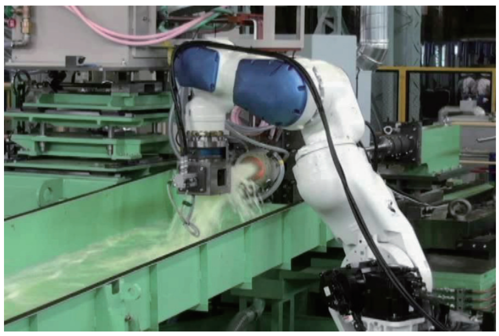


Photo 2 Bend forming robot during process

in 3DQ, assuming that product requirements are diverse, in order to quickly cope with such diversity, we have devised a work-saving process in designing, manufacturing, and maintenance by enhancing the universality of each unit equipment.

2.6.1 Single arm type

An equipment in which one manipulator exerts processing force is called single arm type (refer to **Fig. 6**). It is applied for processing simple form products with small and medium diameter steel tubes. By the trajectory flexibility of a bend forming robot, it is possible to mold products with diverse radius of curvature.

2.6.2 Double arm type

The double arm type consists of three manipulators, which are cooperative-controlled. The configuration of this type is as follows: one manipulator chucks the end portion of a steel tube instead of the support guide in a single arm type, one manipulator holds the heating coil and the quenching nozzle, and one manipulator is equivalent to the bend forming robot in single arm type. Mainly, this type is complied with the product form of U-shaped and has the following features (refer to **Fig. 7**).

First, in single arm type, the robot action range is limited as only one bend forming robot works as bending. Therefore, the dimension and the form for processing are also limited. On the other hand, in double arm type, as a plurality of robots installed in the system work as bending, the entire robots capable range gets expanded due to the plurality robots action added up. Therefore, such type is applicable to processing special form products.

Second, in single arm type, due to the large distance between the front edge of the steel tube that the robot chucks and the region wherein the steel tube is heated, both the movement and the acceleration at the front end manipulator become larger, which tends to cause vibration of the robot and delay time more easily. On the other hand, in double arm type, as a plurality of the robots share the whole movement for processing, both the movement and the acceleration of each robot can be lowered. Therefore, deterioration caused from a robot action in processing accuracy can be reduced in double arm type.

Table 3 Type of bend forming robot with 3DQ system

Robot type	Cross section of work piece	Shape of product	Bending force
Single arm	Small and medium	Simple	Middle
Double arm	Small	U-shaped bend	Low
Parallel link	Large	Complex	High

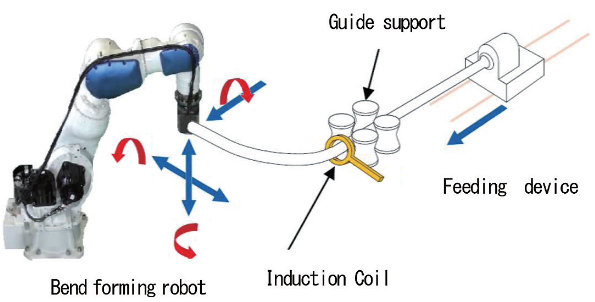


Fig. 6 Single-arm robot type system schematic

2.6.3 Parallel link type

For processing a large diameter steel tube, it is necessary that a bend forming robot works with high load with a high rigidity manipulator. A parallel link type is complied with this kind of products. The robot consists of three manipulators. The front edges of the all respective manipulators are cooperative-controlled as a whole. To hold the steel tube, rollers are installed on their front edges and designed to process bending forces. We explain an example of this type as follows. By installing the other robot that chucks the front end of the steel tube and by cooperative-controlling three manipulator robots that provide driving force for bending, it is possible to process bending even for a large diameter steel tube (refer to **Fig. 8**).

2.7 Examples of application to products

Figure 9 shows the examples of the products to which 3DQ can be applied. There is a variety of products such as bumper, A-pillar, door beam (door reinforcing member), and seat reinforcing member (seat cross member). Presently, door beams and seat cross members are mass-produced as products. The door beam is a reinforcing member installed inside of a door. Moreover, the seat cross member is a part installed under the rear seat.

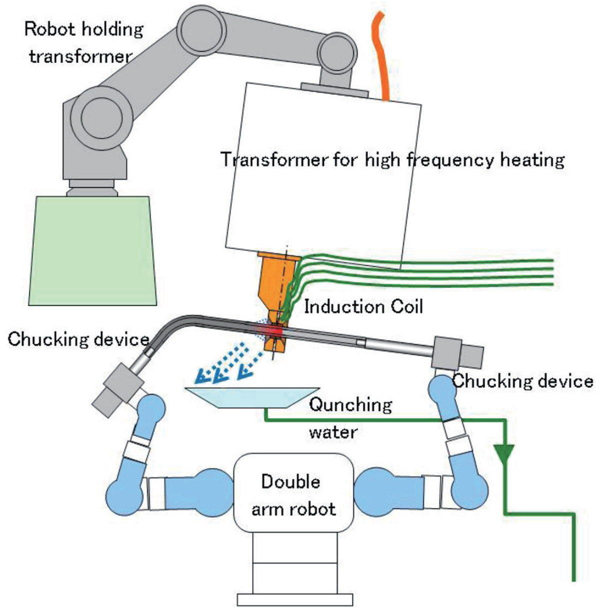


Fig. 7 Double arm robot system schematic

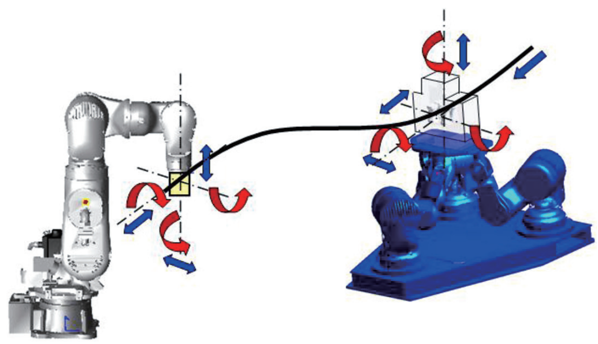


Fig. 8 Parallel link robot system schematic

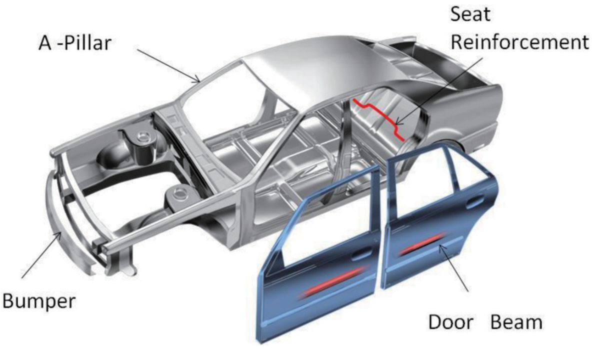


Fig. 9 Various examples of 3DQ product application to automobile parts

3. Development of Machine Element Technology

Performance of the 3DQ equipment depends on heating and quenching, holding steel tube, characteristics of trajectory of bend forming robot, and so on. Hereafter, we describe how we developed the machine element technology in the whole system.

3.1 Chucking device

At the front end of a bend forming robot, a chucking device (the chucking device is called chuck hereafter.) is installed, which provides processing force by chucking the end of a steel tube. We introduce the chuck device as an example of machine element technology development (refer to **Fig. 10**).

3.1.1 Characteristics of chucking length

In order to obtain excellent accuracy in bend forming, it is necessary to chuck stably with less slip between a steel tube and a chuck. When the contact pressure between the chucking section (called chuck pawl hereafter) and the inner side of the steel tube is higher, the chucking performance becomes better. However, if the chucking force is excessive, the steel tube section tends to deform. **Figure 11** shows an example of a largely deformed cross section of a steel tube due to excessive chucking force.

In general, large deformation of the cross section of a steel tube is not preferred for products. Therefore, in order to prevent the deformation of a cross section, we devised lower contact pressure by elongating the chuck pawl. In addition, the region contacted by the chuck pawl is normally not heated to avoid damage by heating. Therefore, quenching hardness is not obtained in the chucked region. As a result, the portion unavailable for product increases with respect to the entire length of a steel tube, which causes the yield to deteriorate. Due to such a background, as for chuck processing, a compromise is sought for between contradictory factors of "shorter chucking length to secure yield" and "longer chuck pawl to lessen sectional deformation and stabilize chucking force" (refer to **Table 4**).

3.1.2 Efforts for chuck device development

We have developed a structure, trying to determine an optimum point as to the chuck pawl shape and its length. In addition to the abovementioned chucking length characteristics, the difficulty in the development is that the chucking force and/or the deformation of the cross section are influenced by the change in steel tube diameter and the wall thickness in due to changes the state of contact between the chuck pawl and the inside of the steel tube. Furthermore, when the shape of the cross section of the steel tube is different, such as round or quadrilateral, the position of contact of the chuck pawl with the inside of the steel tube becomes an influential factor on chucking force and or deformation of a cross section. Under the condition with varying influential factors, finding the optimum chucking performance was a subject.

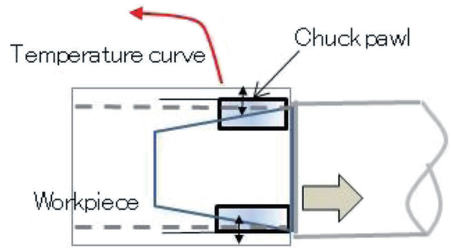


Fig. 10 Side view of chucking work piece

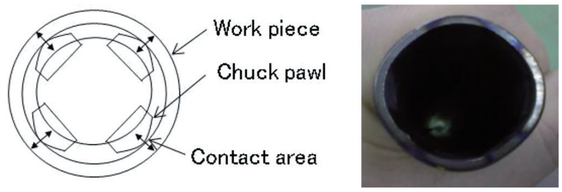


Fig. 11 Cross sectional view of chucking work piece

Table 4 Characteristic of chucking length

Contact area of chucking work piece	Long	Short
Work piece yield rate	Poor	Good
Holding performance	Good	Poor

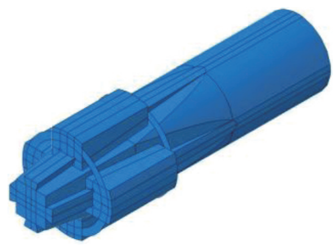


Fig. 12 Analysis model for chucking work piece

To solve the subject, development is being carried out by analyzing the slip phenomenon based on fundamental experiment of the chucking representative condition and using computer aided engineering (CAE). **Figure 12** shows a model that predicts the bending load working on the chuck and the state of contact in slipping for a specific form of the section of a steel tube. A method has been developed that can simulate the phenomenon of changeover of the state of contact face between the chuck and the inner surface of the steel tube from the start of contact to the stable state. With this, even when the factors change, such as wall thickness of the steel tube and bending force, we can predict the state of the tube section deformation and the chucking performance. We can also realize man-power saving in chuck structure designing.

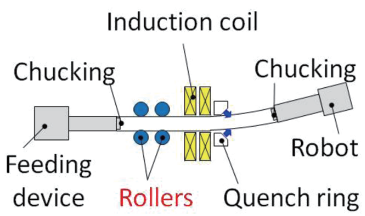
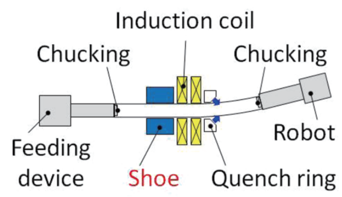
3.2 Supporting device

A bend forming robot gives working force to a steel tube. A supporting device receives the reactional force from the steel tube. Then, the steel tube is machined in the required shape. We report the development of the support device as an example of the machine element development.

3.2.1 Subject in developing supporting device

We have a roller type supporting device and a sliding type sup-

Table 5 Characteristics of guide support devices

Support type	Roller	Sliding
System components		
Strong point	High wear resistant	High yield rate due to supporting the end <u>**edge**</u> of workpiece by the shoes
Weak point	Non-high yield rate due to supporting the end <u>**part**</u> of workpiece by rollers	Deterioration in machining accuracy due to clearance expansion of frictional wear

porting device (refer to **Table 5**). In roller type, in order to avoid contact of roller outer peripheries with the heating coil, the distance between the heating coil and the region supported by the rolls become longer as compared to that of sliding type. Therefore, as the region of supporting relative to the entire length becomes shorter, the end portion of the tube becomes unacceptable as a product. As a result, the yield is deteriorated.

On the other hand, in sliding type, as the shoe contacting a steel tube is worn, control of the clearance between the steel tube and the shoe becomes necessary because clearance exerts influence upon the accuracy of processed dimension. As shown in **Fig. 13**, if the clearance grows large, the state of supporting changes and the required processing force is not exerted. As a result, difference from aimed dimension is developed. Therefore, there has been a problem of "deterioration in dimensional accuracy due to enlarged clearance." However, as the sliding type has been widely employed, we have made efforts to solve the problem related to the influence of enlarged clearance between a steel tube and a shoe.

3.2.2 Activities for development of supporting device

Conventionally, influence of the clearance between a steel tube and a shoe upon the dimensional accuracy had to be examined by experiment, and clearance had to be adjusted accordingly. Therefore, it was considered that an appropriate clearance control criteria would be useful from the viewpoint of productivity if such criteria could be predetermined. Then, based on experiment and the analysis of the phenomenon using CAE, a model capable of analyzing the influence of the clearance on the load has been developed. Change in state of contact between the shoe and a steel tube at enlarged clearance and decrease of reactional force to processing have been predicted (**Fig. 14**).

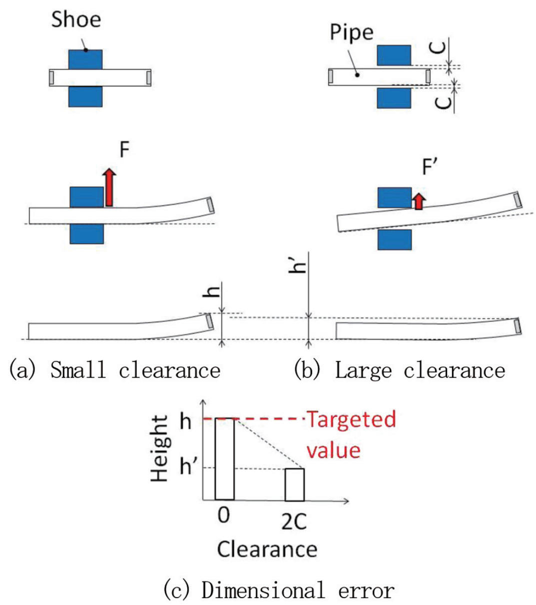


Fig. 13 Influence on dimensional accuracy due to clearance expansion

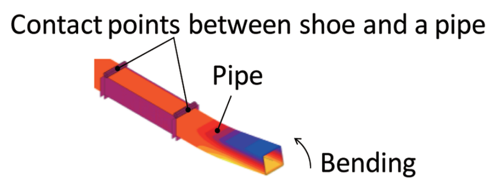


Fig. 14 Analysis model for shoe clearance

3.3 Defoaming equipment of quenching water

Quenching water is one of the factors that influence the quenching performance of 3DQ, and a defoaming equipment that reduces air bubbles contained in the quenching water has been developed.

3.3.1 Problem of quenching water (air bubble)

In 3DQ, as compared with the conventional high frequency heating, a larger amount of quenching water is sprayed onto a steel tube by a multi-hole cooling nozzle for rapid cooling of the steel tube. The quenching water impinges on the steel tube at a high water flow rate. After the impinged water exchanges heat with the steel tube, it spatters around. Furthermore, the spattered water comes to contain air bubbles through contact with open air and sometimes becomes clouded. In the production line of automotive parts factories in particular, since the production operation is continuous, it does not have enough time for the air bubbles to disappear; moreover, the generation of air bubbles tends to be sequential. In general, for elimination of air bubbles, in many cases, water tank capacity is enlarged to promote natural floatation due to long time storage. However, conventionally, in the production field site of automotive parts factories wherein a 3DQ equipment is introduced, it is difficult to enlarge water tank capacity due to constraint in space. Therefore, repetition of cooling of quenching water with air bubbles gives undesirable influence on rapid cooling because of deterioration in heat transfer effi-

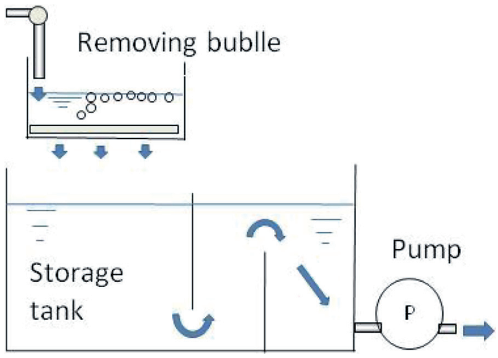


Fig. 15 Apparatus of removing bubble in quenching water

ciency.

3.3.2 Development of defoaming equipment (refer to **Fig. 15**)

For quenching water containing air bubbles, we have developed a defoaming equipment utilizing the principle of natural floatation. If quenching water is temporarily stagnated in a shallow depth, air bubbles tend to float during. It is an equipment that eliminates air bubbles by returning the water near the bottom with less air bubbles to the storage tank. In the processing of automotive parts, as considerable number of parts production is required within a limited time, circulation of quenching water is almost incessant. Even under such condition, air bubbles have been reduced by the defoaming equipment. Then, stable processing performance has come to be exerted.

3.4 Subject for development of equipment in future

When wider application of 3DQ products in automobiles is expected, the future subject in development of equipment is to expand the utilization range of the analysis model.

3.4.1 Needs in development in future

In order for 3DQ products to be applied more widely, equipments capable of complying with various forms in a flexible manner are sought for. Requirements for equipments that comply with any product forms are various; moreover, the development that meets the requirements is also sought for. Then, in order to satisfy such requirements, a large amount of manpower and time tend to be spent if the development and the designing are carried out independently. Under such circumstances, standardization of design method of equipment is considered to be effective.

3.4.2 Expansion of analysis model utilization range

We have enhanced efficiency of equipment development by clarifying phenomena with analysis models. The analysis models introduced in this article concern that chucking device and supporting device have been available for typical section shapes of steel tubes. In order to realize further standardization of design method, expansion of analysis model utilization range needs to be studied.

First, there are factors such as shape, size, and wall thickness that represent the sectional condition of a steel tube. Even if such factors are changed, maintaining the reliability of the analysis model becomes an important issue. Namely, the subject is that analysis models have to comprehensively cover all related various conditions.

Second, phenomena in devices other than chucking device and supporting device should also be clarified. For example, the realization of of a dynamic balance model in a steel tube under processing force and the fluid flow model of quenching water need to be clarified. This means to expand the field of utilization of analysis models.

If these are realized and the field of utilization of analysis models is expanded, it is considered that the standardization of design method of equipment to meet changes in conditions for various products will become possible. Therefore, expediting of development and high equipment reliability can be obtained.

4. Conclusion

From the viewpoint of machine element technology concerning 3DQ, the equipment outline and the efforts for developing an equipment have been reported in this article. Compared to press forming method, though 3DQ can eliminate the flange portion and therefore can render the merit of light-weightedness of products, it has its own specific equipment problems when compared with the conventional high frequency heating. In order to solve the problems, we introduce the importance of a chucking and supporting device of a steel tube, and a defoaming equipment as an example of a rapid cooling device. We wish to continue to further develop the technologies introduced here and develop 3DQ to comply with its further needs.

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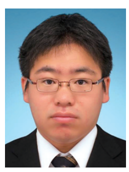

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