# INFLUENCE OF INITIAL THICKNESS DEVIATION IN TUBE PERIPHERY ON TUBE DEFORMATION DURING FREE HYDRAULIC BULGING

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**ABSTRACT**

Deformation behavior of circular tubes during free hydraulic bulging was studied. Initial thickness deviation in tube periphery affects the deformation. Deformation of aluminum alloy tube and copper tube was investigated by FEM simulation and experiment. In the FEM simulation, which is based on dynamic explicit method, bulging speed was controlled by the amount of pressure medium in the tube. This volume control method of the pressure medium was easier than pressure control method to get the maximum pressure that can load on the tube. It was clarified that increase in thickness deviation during the free bulging depended on tube material and boundary condition at the tube ends.

**INTRODUCTION**

Tube hydroforming (hereafter, THF) is an important manufacturing technique employed by the automotive industry, which seeks to reduce the weight of parts, the number of manufacturing processes, and production cost. THF is a manufacturing method combining conventional processes for tubes and includes not only hydraulic bulging, but also bending and stamping of tubes.

In relation to hydraulic bulging after bending, Manabe et al. have employed FEM simulation to study the influence of bending radius on hydraulic bulging (1999). Their results suggest the possibility of a bent tube of small bending radius attaining uniform thickness distribution as a result of hydraulic bulging. However, their study is based on the assumption that the bent tube has not undergone work hardening and its wall is of

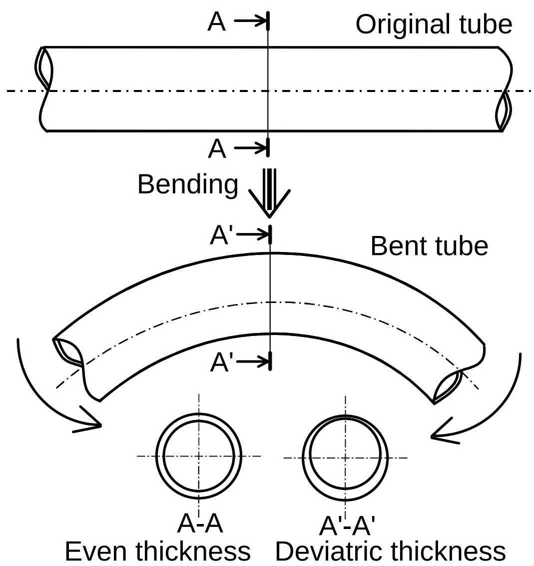



FIG.1 THICKNESS DEVIATION AFTER BENDING.

uniform thickness. In actuality, several factors affect hydraulic bulging following bending, especially:

* Curvature of tube axis after bending
* Deformation of cross sectional shape
* Thickness deviation
* Work hardening distribution

Contact conditions between the tube and die might involve additional factors, and FEM simulation can take many factors into account. Consequently, when the calculated results fail to agree with the results of real forming, techniques for checking the calculated results become necessary. Moreover, when process changes are planned, some knowledge of the processes becomes necessary. In such cases, knowledge from basic forming conditions or simplified conditions based on assumptions such as those employed in Manabe's study could serve as the guiding principles.

In our research, influence of initial thickness deviation in tube periphery on tube deformation during free hydraulic bulging (hereafter, FHB) was studied. It is a kind of simplified cases of hydraulic bulging process following bending process. FIG. 1 shows a schematic of thickness deviation after bending. In this research, curvature of tube axis, deformed cross sectional shape and work hardening after bending were disregarded. In FHB process, there is not any effect of friction between the employed die and bulged part of tube. It might be necessary to avoid effect of friction on the tube deformation when pure deformation characteristics of tube materials are needed. According to Ngaile et al. (2001), effect of lubricants on tube deformation is different even within a single tube depending on metal flow and stress state at each position of the tube. Friction between die and tube may make the tube deformation too difficult to understand. FHB of tubes with initial thickness deviation is simple, however it can help understand a combined process. In addition, it is easy to examine the forming results by FEM simulation and experiment.

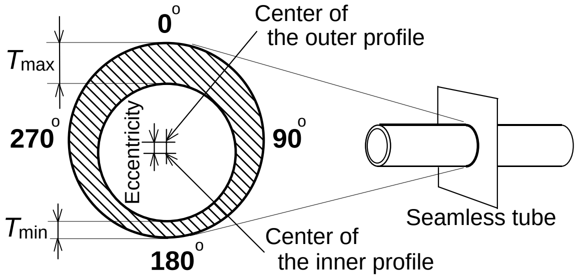



FIG. 2 SCHEMATIC OF THICKNESS DISTRIBUTION OF STRAIGHT TUBE WITH INITIAL THICKNESS DEVIATION.

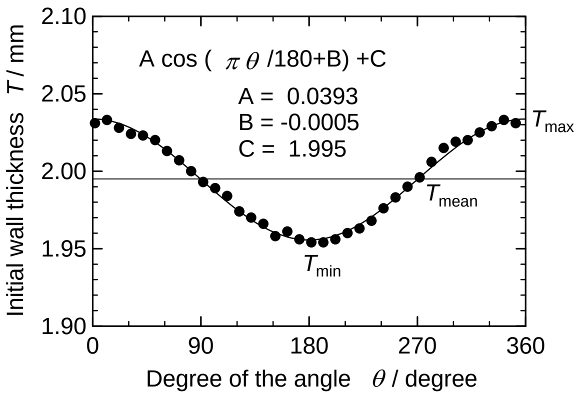



FIG. 3 EXAMPLE OF INITIAL THICKNESS DISTRIBUTION.

TABLE 1 SIZES AND MECHANICAL PROPERTIES OF THE SPECIMENS (AFTER ANNEALING).

| Specimen | Aluminum alloy tube (A6063) | Copper tube A (C1220) | Copper tube B (C1220) |
|---|---|---|---|
| Thickness $T$ / mm | 2 | 2 | 2 |
| Initial thickness deviation $\tau_{ini}$ / % | 1〜2 | 3〜4 | 8〜9 |
| Outer diameter $D$ / mm | 40 | 40 | 40 |
| Strain hardening exponent $n$ | 0.41 ($\varepsilon_{eq} \leq 0.04$)<br>0.24 ($\varepsilon_{eq} > 0.04$) | 0.54 ($\varepsilon_{eq} \leq 0.16$)<br>0.34 ($\varepsilon_{eq} > 0.16$) | 0.60 ($\varepsilon_{eq} \leq 0.14$)<br>0.39 ($\varepsilon_{eq} > 0.14$) |
| Plastic coefficient $k$ / MPa | 263 ($\varepsilon_{eq} \leq 0.04$)<br>148 ($\varepsilon_{eq} > 0.04$) | 588 ($\varepsilon_{eq} \leq 0.16$)<br>405 ($\varepsilon_{eq} > 0.16$) | 684 ($\varepsilon_{eq} \leq 0.14$)<br>460 ($\varepsilon_{eq} > 0.14$) |
| $r$-value (normal anisotropy) | 0.55 | 0.78 | 0.86 |

## EXPERIMENT

### Tube Materials

TABLE 1 shows the sizes and mechanical properties of the tubes used in the experiments. These mechanical properties were obtained by the uniaxial tension test. The tubes are aluminum alloy seamless tube JIS A6063 and phosphorus deoxidized copper seamless tubes JIS C1220. The aluminum alloy tube was annealed for 2 hours at 673 K and the copper tubes were also annealed for 1 hour at 828 K. There are two kinds of copper tubes, the copper tube A and B, they are different in the amount of initial thickness deviation and mechanical properties. These differences were derived from the difference in their lots. All the tubes have a nominal outer diameter of 40 mm and a nominal thickness of 2 mm. Tube wall thickness is distributed in the tube periphery as shown in FIG. 2 and 3. This thickness distribution might have formed while the tubes were fabricated by drawing process. The amount of thickness deviation of tube is defined as following in this study.

$$\tau = ( t_{max} - t_{min}) / t_{mean}$$

Here, $t_{max}$ is the maximum thickness, $t_{min}$ is the minimum thickness and $t_{mean}$ is the mean thickness in a tube specimen ($T$ in FIG. 3 shows initial thickness). The amount of the initial thickness deviations ($\tau_{ini}$) of the aluminum alloy tubes is approximately 1% to 2% and those of the copper tubes are approximately 3% to 4% or 8% to 9%.

### Experimental Setups

FIG. 4 shows the main parts of the experimental setups. Only internal pressure is applied to the tube specimen with these setups and the specimen is bulged freely. The pressure medium is industrial lubricating oil. FIG. 4 (a) shows the setup for the experiment in the case of fixed tube ends. Both of the tube ends are not allowed to move to any direction by the dies. This setup is the same one for the study by Fuchizawa et al. (1993). FIG. 4 (b) shows the setup in the case of free tube ends. Both of the tube ends are able to move to the direction of the tube axis. $MoS_2$ is used as a lubricant between the tube and the dies for smooth material flow in the dies. The bulged length is set at 80 mm in the both experiments. This bulged length was selected to avoid the influence of bulged length on the deformation behavior at the axial center of the tube specimen in free bulging.

### Experimental Conditions

There are three types of materials including the aluminum alloy tube and the copper tubes as shown in TABLE 1. All of them are different in the initial thickness deviation. On the other hand, there are two types of experiments, which are the conditions of fixed tube ends and free tube ends. Then, the number of all the combinations of the tube materials and the experiments can be resulted in six. However, there were not enough tubes to carry out the six kinds of experiments. In addition, the experiments in this study were not originally aimed to examine the both effects of the initial thickness deviation and material properties on tube deformation in a unified experimental condition. In any case, the experimental conditios in this study are as follows.

* free tube ends condition with the aluminum alloy tube

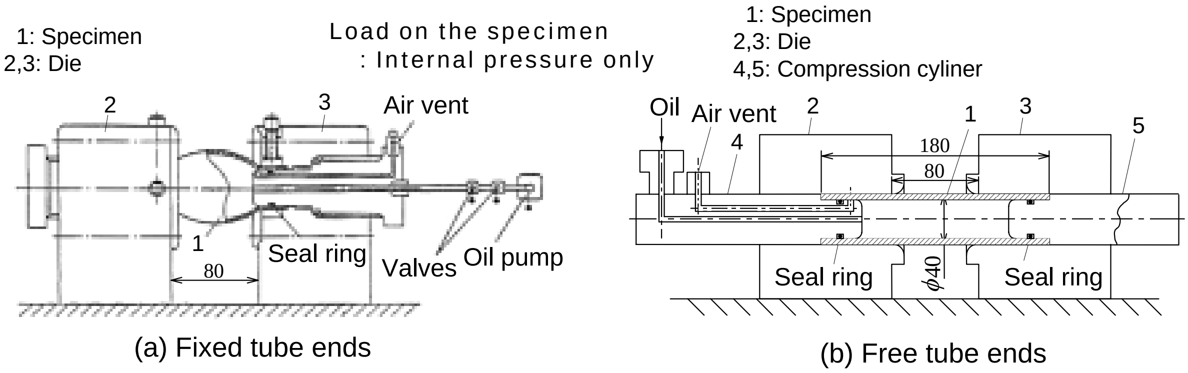



FIG. 4 EXPERIMENTAL SETUPS (MAIN PARTS).

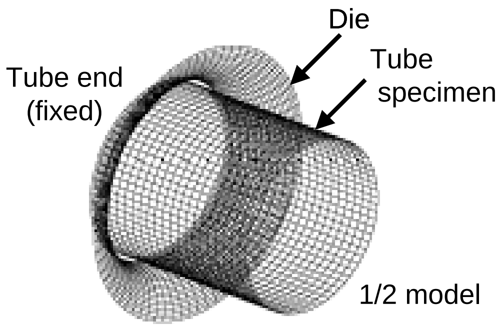
* free tube ends condition with the copper tube A
* fixed tube ends condition with the copper tube B

The results of these experiments were used to examine the results of the FEM simulation.

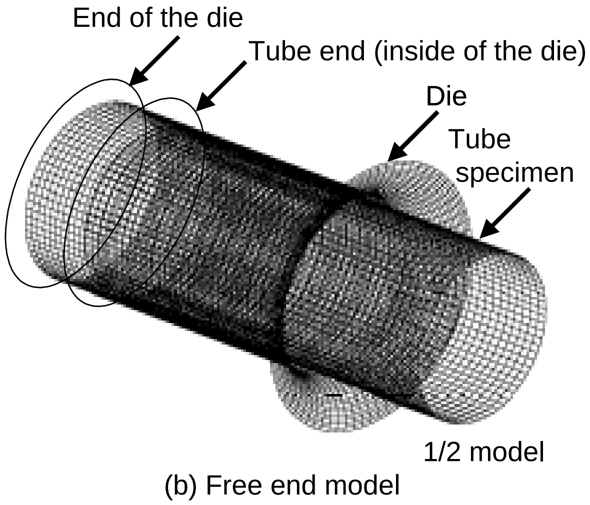
## FEM SIMULATION

The amount of internal pressure or inflow of pressure medium into tube specimen has to be controlled in FHB processes. In general, internal pressure is usually applied on tube in combination with axial feeding. The combination is described as “loading path” and is important to accomplish hydraulic bulging processes. In this FEM simulation, inflow control of the pressure medium is adopted.

LS-DYNA (ver. 950d) was used as the FEM




(a) Fixed end model




(b) Free end model

FIG. 5 FEM SIMULATION MODELS FOR THE TUBE WITH INITIAL THICKNESS DEVIATION.

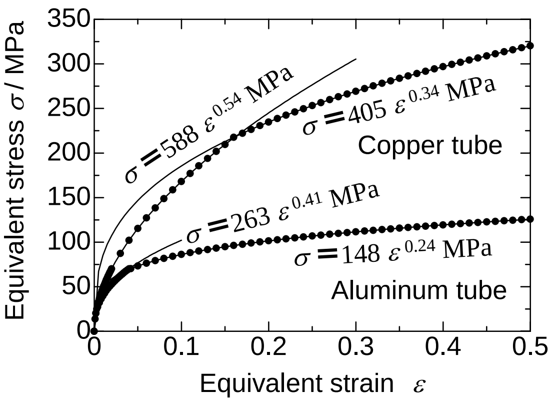



FIG. 6 STRESS-STRAIN CURVES OF THE ALUMINUM ALLOY TUBE AND THE COPPER TUBE (A).

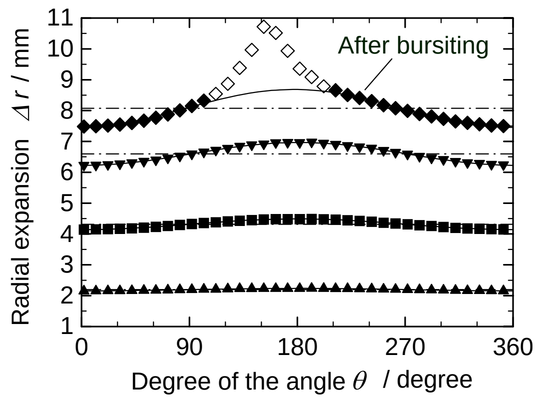
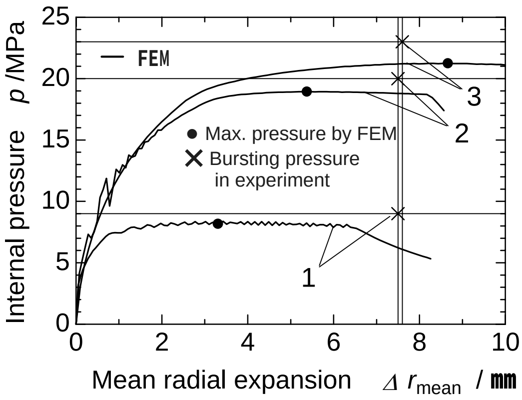



FIG. 7 DISTRIBUTION OF RADIAL EXPANSION OF COPPER TUBE AT THE AXIAL CENTER OF THE TUBE ($\tau_{ini}$ = 3.9%).




1. Free tube ends with aluminum alloy tube ($\tau_{ini}$ = 1.0%)
2. Free tube ends with copper tube ($\tau_{ini}$ = 3.9%)
3. Fixed tube ends with copper tube ($\tau_{ini}$ = 8.5%)

FIG. 8 RELATION BETWEEN INTERNAL PRESSURE AND RADIAL EXPANSION AT THE CENTER OF THE TUBE.

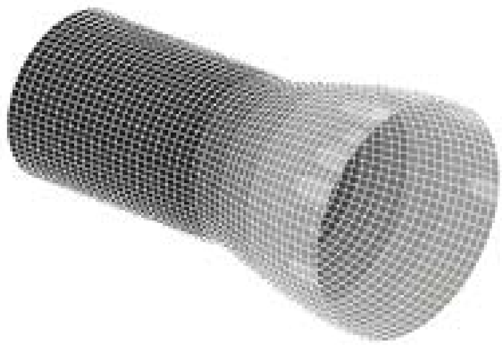
simulation code. FIG. 5 shows the simulation models. 1/2 model of the whole geometry consisting of the tube specimen and the dies was used in consideration of the inflow control and symmetric property of the tube deformation. By the way, if the amount of internal pressure were controlled instead of the inflow control, the size of the model would be able to be reduced to 1/4 because it would be simply based on the symmetric deformation property. Belytschko-Tsay shell elements were applied for both of the specimen and the die. The material properties that were used in the simulation were of the aluminum alloy tube and the copper tubes as shown in TABLE 1. FIG. 6 shows the stress-strain curves of the aluminum tube and the copper tube (A). Strain hardening characteristics are different in the range of small strain and in the range of large strain. The Coulomb's friction was applied at the interface between tube and die. Its coefficient was set at 0.1.

Some difficulty exists in determination of the loading speed in the FEM simulation. It usually has to be faster than the real loading speed to get adequate results with a simulation code like LS-DYNA that is based on dynamic explicit method. In this simulation, the speed of the inflow was set at 10 /sec, i.e., the volume of the specimen is proportionally increased by 10 times of the tube initial volume in a second. This is approximately 10,000 times higher than the real loading speed.

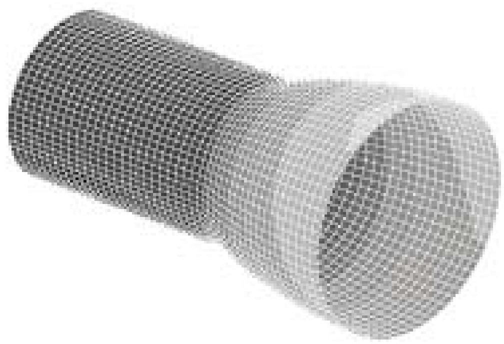
**RESULTS AND DISCUSSION**

<u>Relation between Pressure and Radial Expansion at the Center of the Tubes</u>

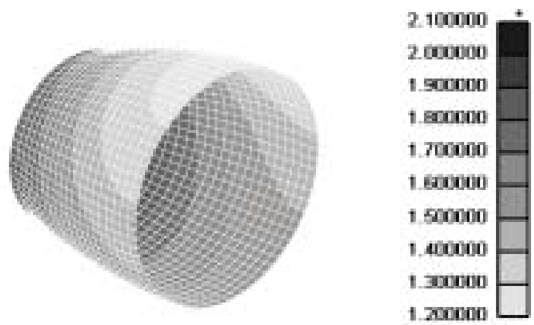
FIG. 7 shows an example of the circumferential distribution of the tube expansion under the free tube ends condition in the experiment. The distribution was measured at the axial center of the tube. The specimen is the copper tube (A) with the initial thickness deviation $\tau_{ini}$ = 3.9%. The largest radial expansion in the tube periphery occurred at the point of the thinnest tube wall. On the other hand, the smallest expansion occurred at the thickest point. In addition, the position where the radial expansion was the smallest kept the position of 0 degree (the position where the initial thickness was the greatest) regardless of the degree of the tube expansion. Accordingly, the distribution fitted on a sine function during the tube deformation. The amplitude of the sine function became larger as the tube expanded. The pattern of the distribution was similar in all the experiments. Both of the aluminum alloy tube and the copper tubes gained approximately 7.5 to 8 mm in radial expansion until the tubes burst.



(a) Aluminum alloy tube under free tube end condition (initial thickness deviation 1.0%)



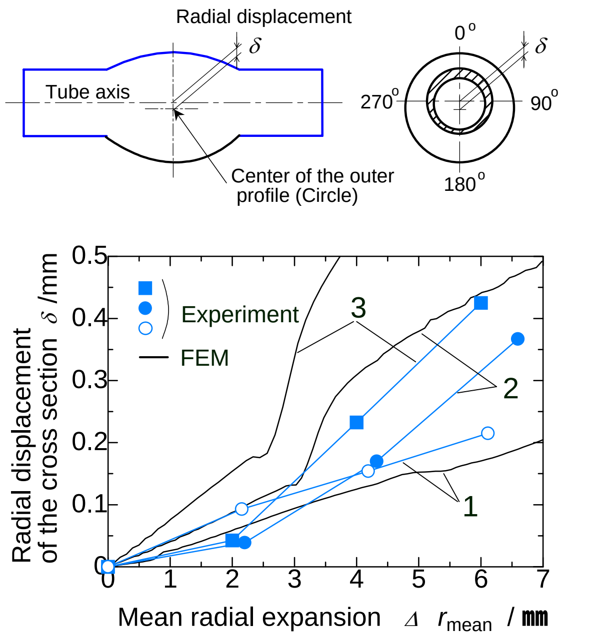
(b) Copper tube under free tube end condition (initial thickness deviation 3.9%)




(c) Copper tube under fixed tube end condition (initial thickness deviation 8.5%)

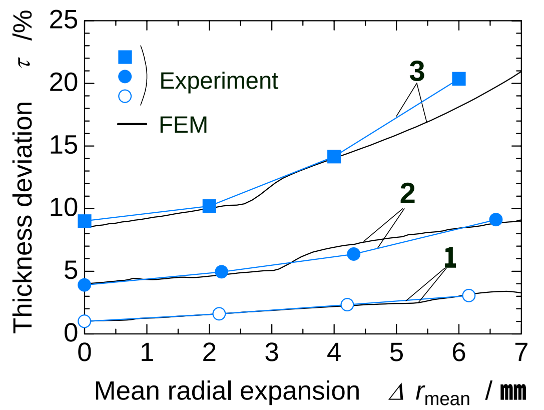
FIG. 9 BULGED TUBE PROFILES AND THICKNESS DISTRIBUTION (FEM, MEAN RADIAL EXPANSION: 7.5 mm).

FIG. 8 shows the relation between pressure and radial expansion at the center of the tubes. The thick solid lines show the calculated results by the FEM simulation and the crosses show the experimental results at the tube bursting. It is impossible for FEM simulators to calculate any value at tube bursting without bursting criterion. In the case of bursting of tubes with initial thickness deviation, for example, Ragab et al. (1985) proposed the application of their strain instability criterion. In our calculation, any bursting criterion was not adopted. However, it is possible to estimate the bursting pressure from the calculated results because it is in the vicinity of the maximum pressure that can load on tubes. The dots on the calculated results (thick solid lines) show the points of the maximum pressure. It is not much too difficult to get the value of the maximum pressure by the inflow control of the pressure medium. However, it is difficult for pressure control method to get the maximum pressure because it needs some methods to decrease the amount of pressure. Under the inflow control, the amount of pressure automatically varies in accordance with the amount of tube deformation. In any case, it is impossible for FEM simulator to estimate the amount of the radial expansion at tube bursting without any bursting criterion. Incidentally, according to the experimental results by Hiroi et al. (1996), the maximum expansion of aluminum tube would not be affected by the initial thickness deviation under 5%. Hence, the maximum



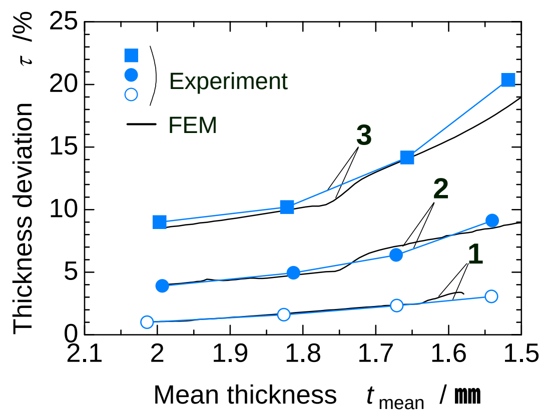

1. Free tube ends with aluminum alloy tube ($\tau_{ini}$ = 1.0%)
2. Free tube ends with copper tube ($\tau_{ini}$ = 3.9%)
3. Fixed tube ends with copper tube ($\tau_{ini}$ = 8.5%)

FIG. 10 RADIAL DISPLACEMENT OF THE CENTER OF THE BULGED OUTER PROFILE.




1. Free tube ends with aluminum alloy tube ($\tau_{ini}$ = 1.0%)
2. Free tube ends with copper tube ($\tau_{ini}$ = 3.9%)
3. Fixed tube ends with copper tube ($\tau_{ini}$ = 8.5%)

(a) Relation between radial expansion and thickness deviation at the center of the bulged tube




1. Free tube ends with aluminum alloy tube ($\tau_{ini}$ = 1.0%)
2. Free tube ends with copper tube ($\tau_{ini}$ = 3.9%)
3. Fixed tube ends with copper tube ($\tau_{ini}$ = 8.5%)

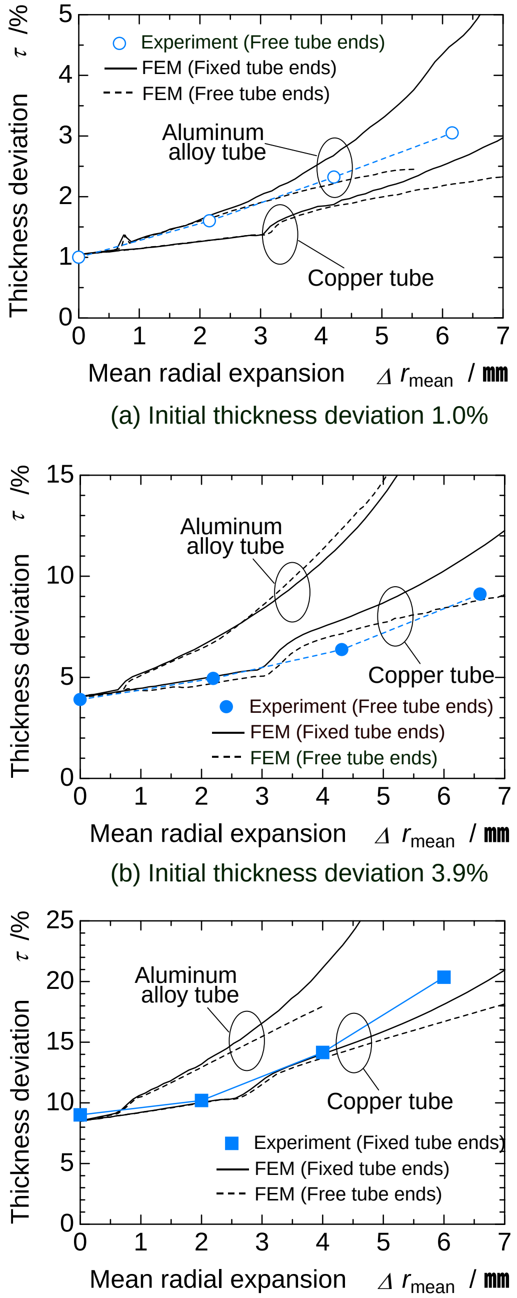
(b) Relation between thickness and thickness deviation at the center of the bulged tube

FIG. 11 THICKNESS DEVIATION AT THE CENTER OF THE BULGED TUBE.

expansion of the aluminum alloy tube with the initial thickness deviation from 1% to 2% in our experiment might have gained the maximum expansion corresponding to the case of the tube with uniform thickness.

## Bulged Tube Profiles and Thickness Distribution

FIG. 9 shows the deformed tube profiles and thickness distribution that were calculated with the FEM simulator. Their radial expansions are approximately 7.5 mm on the average. The calculated results show the tube deformation corresponding to the states after tube bursting in the experiments. Tube wall thickness largely changed at the center of the tube. In the case of the aluminum alloy tube, FIG. 9 (a), the thickness distribution like multi-necking appeared. Multi-necking actually had appeared in the experiment with the aluminum alloy tube.




(a) Initial thickness deviation 1.0%

(b) Initial thickness deviation 3.9%

(c) Initial thickness deviation 8.5%

FIG.12 CHANGE OF THICKNESS DEVIATION AT THE CENTER OF THE BULGED TUBE.

## Deformation Behavior at the Center of the Bulged Tube

Radial Displacement of the Center of the Bulged Outer Profile. FIG. 10 shows the radial displacement of the center of the bulged outer profile. The radial displacement occurred because the amount of the radial expansion distributed in the tube periphery as shown in FIG. 7. The calculated results show good agreement with the experimental results in the tendency to increase. However, it could not estimate the right values with the FEM simulator.

Thickness Deviation. FIG. 11 (a) shows the relation between radial expansion and thickness deviation. FIG. 11 (b) shows the relation between thickness and thickness deviation. The amount of the thickness deviation commonly increased during FHB processes in the three conditions. All the calculated results agreed well with the experimental results.

It was impossible to obtain and compare the experimental results of different kinds of tubes with a same initial thickness deviation in our experiment. It is because the amount of the thickness deviation could not be controlled in advance of the experiment. However, it virtually becomes achievable in FEM simulation. FIG. 12 shows the difference between the aluminum alloy tube and the copper tube in the growth of the thickness deviation. The amount of the thickness deviation of the aluminum alloy tube tends to become larger than that of the copper tube in all the condition. In addition, it seems that the fixed tube ends condition makes the tube easier to increase its thickness deviation. These results by the FEM simulation might be as reliable as the results in FIG. 11. According to the result of our former researches (2000), the degree of increase in thickness deviation of the aluminum alloy tube is supposed to be greater than that of the copper tube because the aluminum alloy tube has smaller *n*-value and *r*-value than the copper tube.

## CONCLUSION

Deformation behavior of circular tubes during free hydraulic bulging was studied by FEM simulation and experiment. Initial thickness deviation in the tube periphery affected the deformation. Deformation of aluminum alloy tube and copper tubes was investigated. In the FEM simulation, bulging speed was controlled by the amount of pressure medium in the tube.

It was clarified that increase in the amount of thickness deviation during the free bulging depended on tube material and boundary condition at the tube ends. Generally, the amount of thickness deviation of the aluminum alloy tube was likely to become larger than that of the copper tube. It might be because the aluminum alloy tube had smaller *n*-value and *r*-value than the copper tube. In addition, the free bulging process under the fixed condition at the tube ends tended to make the thickness deviation larger than the process under the condition of free tube ends.

There was advantage of using the inflow control of the pressure medium to get the maximum pressure that could be loaded on the tube. Under the inflow control, the amount of pressure automatically varied in accordance with tube deformation. Then, it was not so difficult to get the value of maximum pressure by the inflow control.

## ACKNOWLEDGEMENTS

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