A Study of Three-Roll Bending Process and Its Control

by

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Abstract

A three-roll bending process for a workpiece with a U-shaped cross section is studied. The relationship between the position of the rolls and the curvature of the workpiece is approximately obtained by several methods. An automatic control system based on the relation is then applied to the process. A learning control is also employed to the control system to treat the errors occurring in the process. The experimental results show that the control system is very effective.

INTRODUCTION

The roll-bending process is a kind of forming process employed in metal-working industries to produce bars or plates with desired curvatures. The workpiece can be successfully bent to arbitrary curvatures by adjusting the relative position of the rolls. However, dimensional control is rather difficult in the roll bending process because the relationship between the curvature of the product and the relative position of the rolls is very complicated. Therefore, the roll-bending process has so far been controlled manually by an operator who has a wealth of experience and a high degree of skill.

The roll-bending process was studied by Soda et al.[1] and N. E. Hansen[2]. They derived an approximate relation between the relative position of the rolls and the curvature of the workpiece (a beam of square cross-section) for a pyramid-type three-roll bending machine. The application of an automatic control system to the roll bending process has also been attempted by several

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investigators[3),4)]. Since the roll-bending process is considered to be a flexible manufacturing process, which is capable of producing a wide range of different parts with one set of tools, it is worth applying an automatic control system to the process, and thus make the process more effective and flexible.

In this study, the three-roll bending process for a workpiece with a U-shaped cross section was investigated. The relation between the roll position and the final curvature of the workpiece is represented approximately by a simple equation. A control system based on the relation is applied to the roll bending process.

BENDING PROCESS

The configuration of a pyramid-type three-roll bending process is shown schematically in Fig. 1. Two side rolls, ROLL 1 and ROLL 3, whose central axes are fixed, are driven by an actuator, while the center roll, ROLL 2, is positioned on the vertical line O_1O_3 at its center, and is able to move along the vertical line. A workpiece fed by ROLL 1 and ROLL 3 moves into the machine from contact point A, which is called the "entrance", and comes out from C, which is called the "exit". Following a particular point in the workpiece from the entrance, it can be seen that the curvarure first increases linearly with increasing bending moment referring to the elastic deformation. Then, when a critical moment is reached, the edge of the cross section begins to yield and

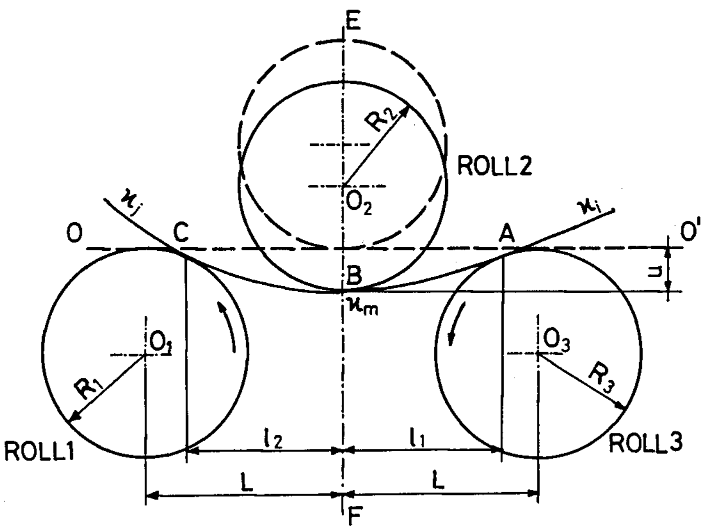


Fig. 1. Configuration of a pyramid-type three-roll bending machine

plastic deformation occurs. At a maximum bending moment, which occurs at contact point B, the curvature reaches a maximum value, κ_m. Beyond point B toward the exit, the bending moment begins to decrease, and the workpiece is unloaded to decrease its curvature because of springback until the moment vanishes at point C. At the exit, the workpiece has its final curvature κ_j. The

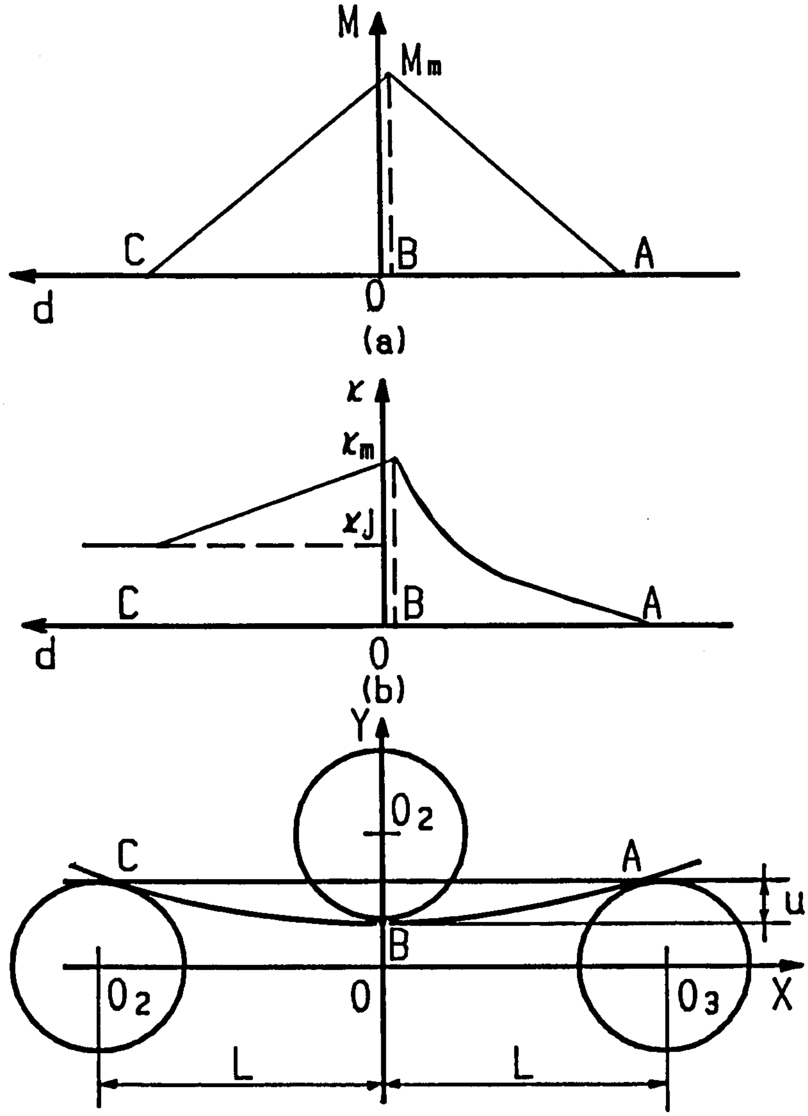


Fig. 2. Distribution of bending moment (a) and curvature (b) along the workpiece

distribution of the bending moment and the curvature of the workpiece is shown schematically in Fig. 2.

The process is to make the final curvature, κ_j, be the desired curvature by adjusting the displacement of the center roll, u. u is considered to be a function of κ_j for the workpiece concerned. It is important to obtain an accurate relationship between u and κ_j.

PROCESS MODEL

The following two methods were considered for setting up the relation:

1) Method 1:

The relation can be obtained, being based on the results of a preliminary experiment which will be shown later in Fig. 9. An empirical equation can readily be made by assuming the equation to be of the following form:

$$u=C_1 \cdot \kappa_j^2+C_2 \cdot \kappa_j+C_3 \quad (1)$$

where

$$C_i=C_{i1} \cdot \kappa_i^2+C_{i2} \cdot \kappa_i+C_{i3} \qquad i=1, 2, 3$$

κ_i and κ_j represent the initial curvature and the final curvature, respectively. The coefficients C_{ij} may be determined by the least square method.

2) Method 2:

The shape of the workpiece during the roll bending process is assumed to be a simple model, as shown in Fig. 3. Here, the curvature of the workpiece between contact points A and B is assumed to change linearly and so is between B and C. The average curvature between points A and B is, then, considered to be $(\kappa_i+\kappa_m)/2$ and between B and C to be $(\kappa_m+\kappa_j)/2$. Therefore, the curvature of curve ABC may be approximated by:

$$\kappa=(\kappa_i+\kappa_j+2 \cdot \kappa_m)/4 \quad (2)$$

Where κ_m is the maximum curvature at point B.

Further, by assuming the thickness of the workpiece to be zero, a geometric relation between u and κ is expressed as:

$$u=1/\kappa-\{(1/\kappa+R)^2-L^2\}^{1/2}+R \quad (3)$$

where R is the radius of the center roll and L is a half of the distance O_1O_3. Both R and L are constant.

From the relation between the bending moment and the curvature, the

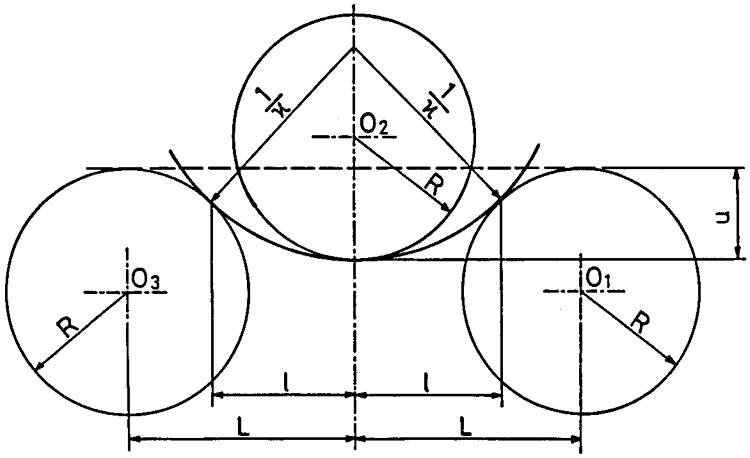


Fig. 3. A simple model for three-roll bending process

curvature at contacting point B, κ_m, can be represented approximately as:

$$\kappa_m = A \cdot \kappa_j + B \qquad (4)$$

where A and B are coefficients depending on the elastic-plastic properties of the material. Hence, from Equations (2), (3) and (4), the displacement u can be expressed in terms of the final curvature, κ_j, and the initial curvature, κ_i.

CONTROL OF THE PROCESS

As discussed in the previous section, the roll bending process is usually operated manually in the real production. Hence, the determination of value u from the desired curvature depends on the experience of the operator. Here, errors are likely to occur, and the resultant curvature may exceed the desired curvature. This is called "overbending", which means failure of the process. It is extremely difficult to obtain a product with a desired curvature from an overbent workpiece. To avoid this failure, the whole process was divided into some steps. (Each step is called a "pass".) The value u employed in each pass was chosen to be the one to produce the workpiece with 80 to 90% of the desired curvature. This is to prevent overbending and to make the resultant curvature in each pass approach the desired curvature gradually.

This method was applied to a simple control system. The determination of the displacement u was performed by Model 1 or Model 2. About 80 or 90% of the desired curvature was employed for the calculation of u. Several passes were needed for the process, as in ordinary manual operation. In the control system with Model 2, a learning control was employed to adjust the coefficients of Equation (4), depending on the error in each pass. Because coefficients A and B of Equation (4) depend on the elastic-plastic properties of the material, they change with an increase of the curvature. Therefore, the learning control was employed to adjust the coefficients in each pass by picking up the error between the desired curvature and resultant one.

EXPERIMENTS

The material used in this experiment was an aluminum alloy bar (JIS A 6063 S) with a U-shaped cross section ($W=10$, $H=10$, $c=1$ and $t=1$, all in mm. See Fig. 4.) The bending moment applied to the workpiece is shown by the solid line. The stress-strain curve was obtained by a tensile test. The testpiece for the tensile test was made from the workpiece shown in Fig. 5. The yield stress was 213.2 MPa.

The apparatus for the experiment is shown in Fig. 6. The radii of ROLL 1, 2 and 3 are 50 mm. The distance between ROLL 1 and ROLL 3, 2L, is 120

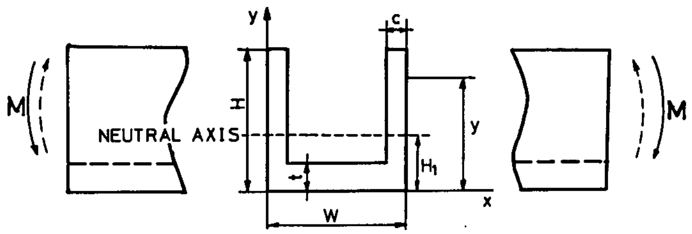


Fig. 4. Shape of workpiece

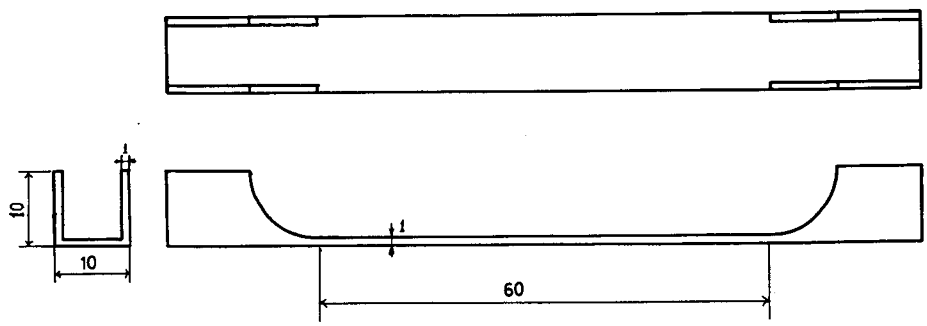


Fig. 5. Testpiece for tensile test

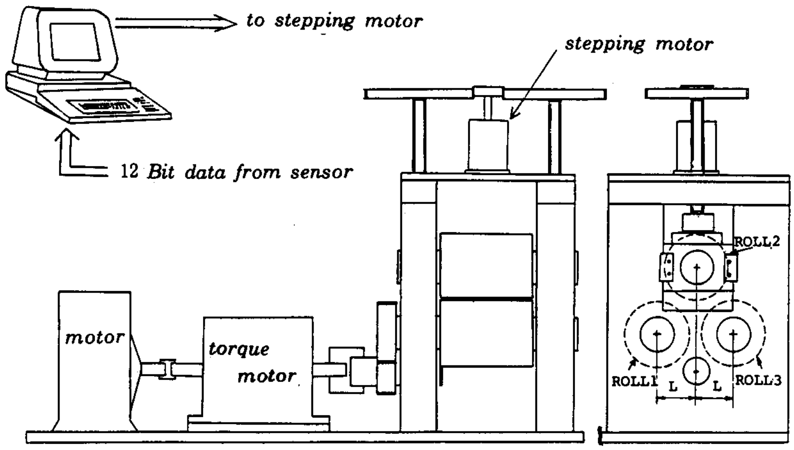


Fig. 6. Apparatus for the experiment

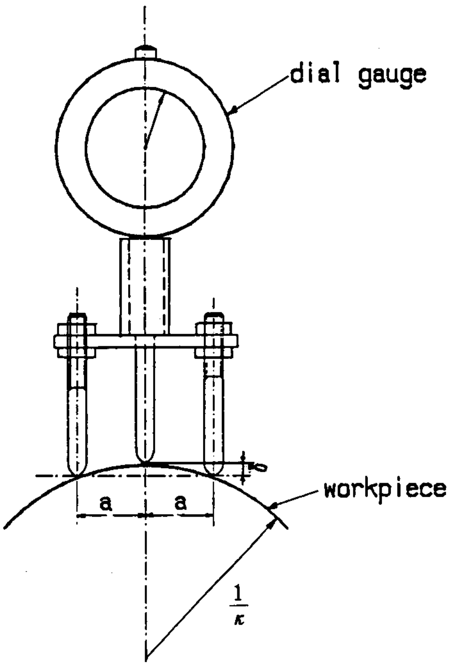


Fig. 7. Curvature measuring device

mm. The rotating speed of the rolls was chosen to be 4.2 mm/s throughout the experiment.

The control system is composed of a microcomputer, a curvature measuring device and a stepping motor. The curvature measuring device is made of a dial gauge and two fixed pins positioned at both sides of the pin of the dial gauge with the same distance as shown in Fig. 7. The curvature of the workpiece was measured by the curvature measuring device after each pass, and was put into the microcomputer through an A/D converter. The displacement of the center roll was controlled by a stepping motor which was actuated by pulse signals from the microcomputer. The microcomputer, the central unit of the control system, was used to calculate the value of u and to adjust the coefficients of Equation (4), depending on the error occurring in the process. The control system and flow of the information for the process is shown in Fig. 8.

As a preliminary experiment, an attempt was made to obtain the relationship

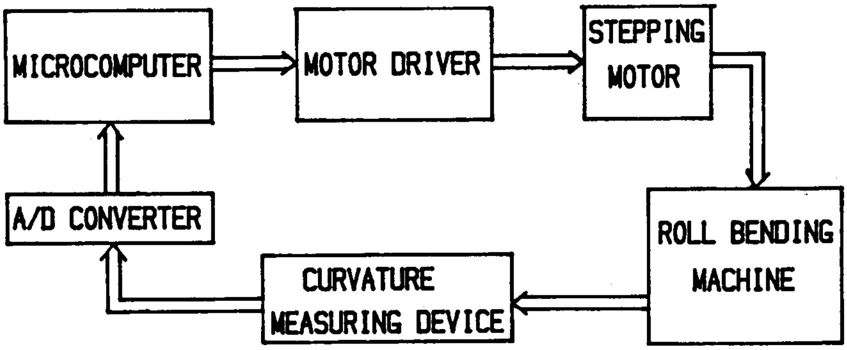


Fig. 8. Control system and flow of information

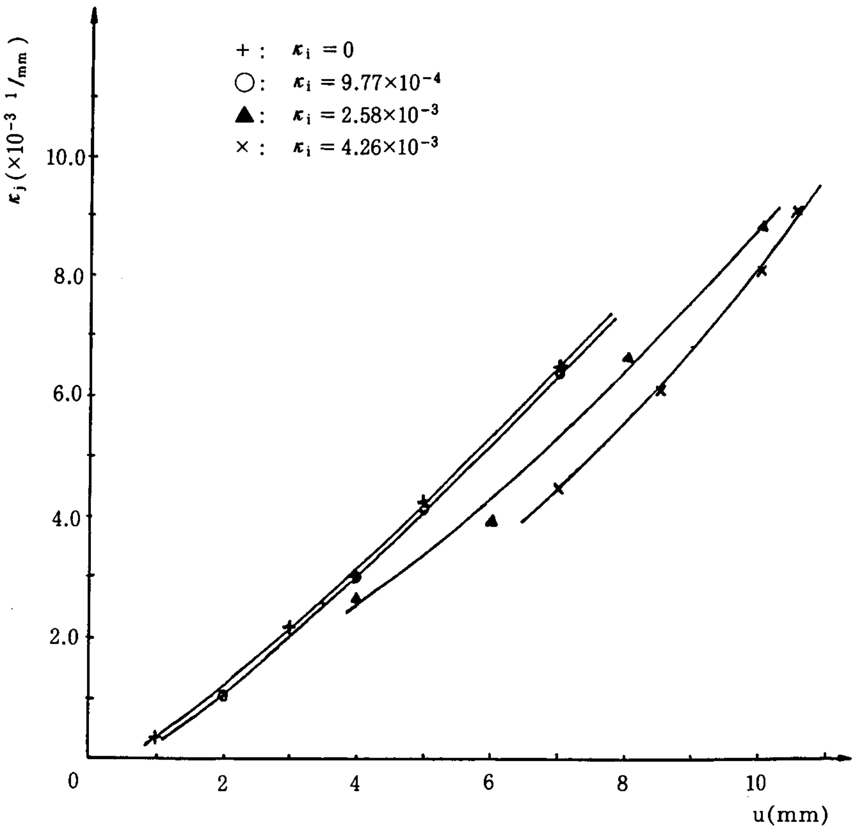


Fig. 9. Relation between κ_i, κ_j and u

between u and κ. The workpieces, with it's various initial curvatures, were bent by applying various displacements of the center roll, u, and the final curvatures were measured. The results are shown in Fig. 9. This shows that, for obtaining a constant final curvature, the value of u must be changed remarkably for a change in the initial curvature of the workpiece. The results shown in Fig. 9 were used to determine the coefficients in Equation (1) for Model 1. In the preliminary experiment there was no need to apply a control system.

An off-line control of the process was performed with Model 1 and also with Model 2.

1) Experiment with Model 1

Fig. 10 illustrates the results of the experiment by employing Equation (1) in the off-line control system. The broken line shows the predicted final curvature in each pass, and the solid line shows the resultant curvature of the process. To prevent overbending, the predicted curvature for each pass was always chosen to be 80 to 90% of the desired curvature. The percentage was adjusted depending on the error between the predicted final curvature and the resultant one. Therefore, a smaller percentage would be chosen if the errors were big and the process needed many passes. On the other hand, when the errors were small, a larger percentage would be chosen and, then, the process can be completed by fewer passes. From the results, the process needed 3 or 4 passes.

2) Experiment with Model 2

Because Model 2 was built based on a simple geometrical model, the process may not be well approximated by this model as compared with Model 1. Therefore, the percentage for calculation of u in each pass should be smaller than the process with Model 1, and more passes should be necessary. To improve the accuracy of the model and reduce the number of the passes, the coefficients in Equation (4) were adjusted, depending on the error occurring in each pass based on the learning control. The results of the experiment are

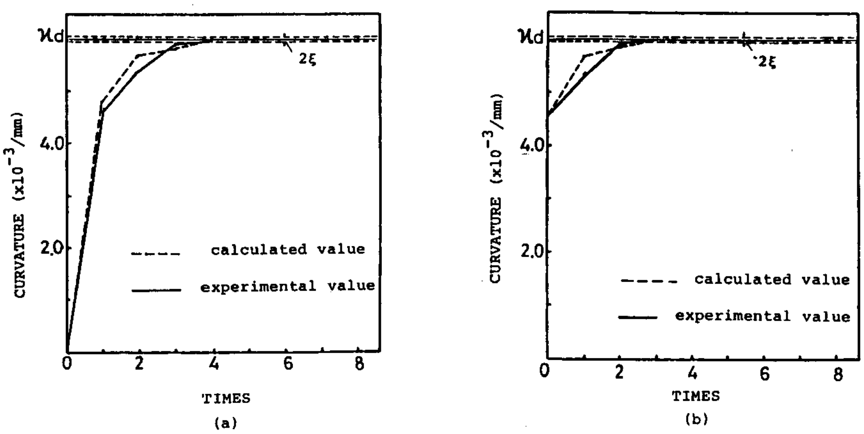
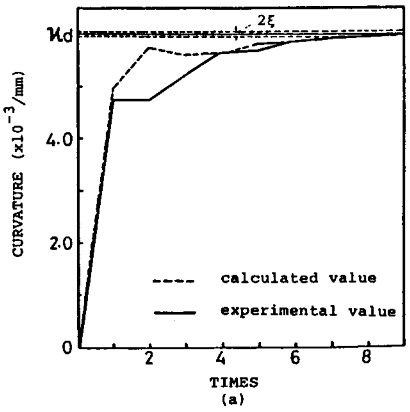


Fig. 10. Experimental result by Model 1 (a) $\kappa_i = 0$, (b) $\kappa_i = 4.7 \times 10^{-3}$



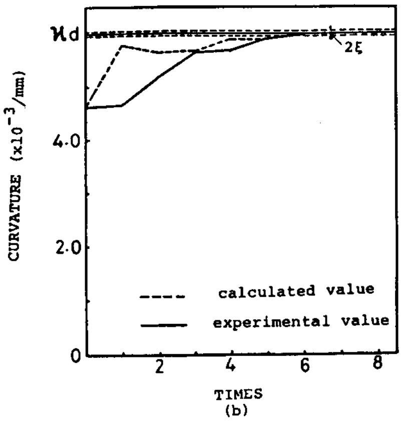


Fig. 11. Experimental result 1 by Model 2 (a) $\kappa_i = 0$, (b) $\kappa_i = 4.7 \times 10^{-3}$

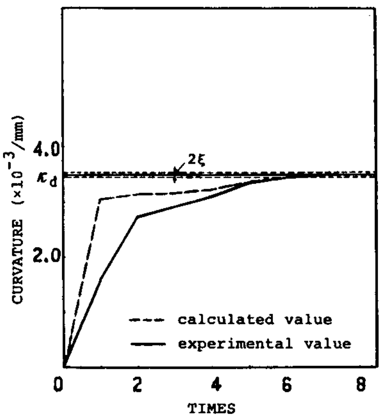


Fig. 12. Experimental result 2 by Model 2

shown in Fig. 11. From the results, the process needed 6 to 8 passes.

By comparing the results of Model 1 with those of Model 2, it is seen that Model 1, which is based on the experimental data, is much more accurate than Model 2, which is based on an approximate geometrical model. Thus, the process with Model 1 can be performed more efficiently than the one with Model 2. However, since Model 2 was based only on the geometric property of the process, it is possible to apply this model to bend different materials. That is to say that Model 2 has a larger applicability than Model 1.

As an example, an attempt was made to bend the same workpiece in such a way that the bending moment was applied in the opposite direction, as shown by the broken lines in Fig. 4. When applying Model 1, it is of course necessary to carry out a preliminary experiment to obtain the relationship between u and κ for determining the coefficients in Equation (1). This is because the characteristic of the workpiece is different from the previous case. When applying Model 2 for the control system, however, the bending can be performed directly without any preliminary experiment. The result is shown in Fig. 12. The values of coefficients A and B in Equation (4) for this case are of course different from the previous case. It is seen that the desired curvature is similarly obtained with a few passes, as in the case shown in Fig. 11.

CONCLUSIONS

The application of the control system to the roll bending process is considered to be very effective. The process with the control system can be performed as well as the manually operated one. It means that the process is no more necessarily operated by an operator with a wealth of experience and a high degree of skill. In this study, two models were built for the off-line control system. All of these control systems have their own characteristics as shown below.

1) The control with a model based on an empirical equation

Since the model is based on the experimental data, the error occurring at each pass is very small, and the desired curvature is reached within only a few passes. Therefore, the process can be carried out quite smoothly, and also can produce the products accurately. Thus, it is considered to be useful in actual production process.

2) The control with a model based on a simple geometrical model

Since the error is quite large in the beginning of the process, the treatment of the error is very important. Unless a proper treatment is provided, more passes are needed to obtain the product with the desired curvature. However, because the model is not dependent on the property of the material, but dependent only on the geometry of the roll bending process, the model can be applied to the process of any material by modifying the coefficients for the model by using a learning control system.

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REFERENCES

1) C. Soda; Journal of JSTP; Vol. 3, 474 (1962)
2) N. E. Hansen and O. Janneup; Trans. of the ASME, J. of Engineering for Industry; Vol. 101, 304 (1979)
3) E. Trostmann, N. E. Hansen and G. Cook; Trans. of the ASME, J. of Dynamic system, Measurement and Control; Vol. 104, 173 (1982)
4) D. E. Hardt, M, A, Roberts and K. A. Stelson; Trans. of the ASME, J. of Dynamic system, Measurement and Control; Vol. 104, 317 (1982)