Predicting Material Properties of Flow Formed Work-piece Based on a Finite Deformation Method

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Abstract

Flow Forming Process is a manufacturing process to deform rotating axis symmetric work-piece with rotating rollers. It is difficult to predict the behaviour of work-piece during the process because the shear and compression deformation occurs simultaneously in the shape of helix along the axis. This study presents a model which can predict the deformed geometric shape and material properties using geometric shape change and material properties of work-piece. This model is based on finite deformation theory, and assumes that the structure of the material is isotropic lattice structure. To simulate the flow forming process, firstly the axial displacement is calculated using the stress-strain relation. And then the radial displacement is calculated using the volume constancy theory. The material properties of flow formed material are easily calculated with the deformed geometry. The presented model is verified by experimenting actually, and a tensile test demonstrates the predicted material properties.

1. Introduction

Flow Forming Process is the application of plastic deformation. In a general procedure, axis symmetric work-piece is installed on a mandrel, and as mandrel rotates, rollers pass the work-piece on the desired tool paths. Flow forming process is similar to spinning process but with one main difference. In spinning process, the work-piece is a plate or tube in general, and it would be shaped to a certain form without changing its thickness. Whereas in flow forming processes, the work-piece is more likely to be a preformed shape which can change its thickness and form freely in the process.

There are many studies concerning spinning process and flow forming process. It is hard to conduct the experiments of several cases of 3D Model to this process: First of all, the angular velocity of a work-piece is very high, so it is likely that the calculations will not be precise. Moreover, the process is complex, because Compression stress and Tensile stress occur at same time, while the roller contacts the work-piece on a small area making ongoing deformations at minimal intervals of time. For this reason, an enormous number of iterations are required for each step, resulting to extended calculation time for each case. C. C. Wong *et al.* suggested the 3D FEM model for flow forming process of cylindrical work-pieces at 1 roller [1]. F. A. Hua *et al*. suggested FEM Model of tube spinning at 3 rollers process [2]. M. Zhan *et al.* analyzed spinning process with cone shaped work-pieces with 3D FEA [3]. L. Wang and H. Long investigated the spinning process which deformed cone shaped work-pieces with multi-pass, by experiment and FEM [4]. O. Music and J. M. Allwood studied spinning process of plate deformed by rollers which move along the curved tool path [5]. M. Hayama *et al.* studied the factors for deciding the path schedule of roller in spinning process [6]. Y. Jianguo and M. Makoto presented an experimental study on spinning for tube diameter reduction process [7]. S. H. Yeom *et al.* investigated the relationship of forming depth and lead angle with forming process [8].

J. H. Kim *et al.* suggested the theoretical model of cone spinning [9].Upper bound method is a trend of theoretical approaches with plastic deformation process. Upper bound method can explain the characteristics of the plastic deformation processes relatively accurately, but that is hard to use because of the many differential equation. R. Ebrahimi *et al.* applied the upper bound method to tube extrusion process [10].J. W. Park *et al.* analyzed the tube spinning process with upper bound method [11].

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In this study, the presented prediction model is based on finite deformation theory. The model is designed to obtain the material properties from geometric information and condition of the process directly. The model in this case is considered as a static problem rather than a transient problem. In order to verify the model, experiments and finite element analysis for the flow forming process of cup shaped work-pieces were conducted. First, FEA was conducted and then it was compared with the results from the experiments. After FEA was validated, several cases of FEA were conducted and compared with the model.

2. FINITE DEFORMATION OF FLOW FORMING PROCESS

Purpose of the prediction model is to get the material property from controllable variables. The variables are geometric information of roller and work-pieces such as deformation thickness, federate, etc. Material properties which are the results of model are elongation, yield stress, residual stress, etc.

To derive the material properties of the work-pieces, stress – strain relationship and volume constancy is considered. The problem is simplified by ignoring the middle step of flow forming process. The boundary conditions which occurred from the rotation of work-pieces and mandrel were ignored for the reason that the effect of the rotation is too small to consider: The roller rotates in the opposite direction of the mandrel, as a result, when friction of tangential direction occurs because of the contact between them, it cancels out. So the problem can be presumed to be a 2-dimensional deformation problem.

2.1. THEORETICAL STUDY

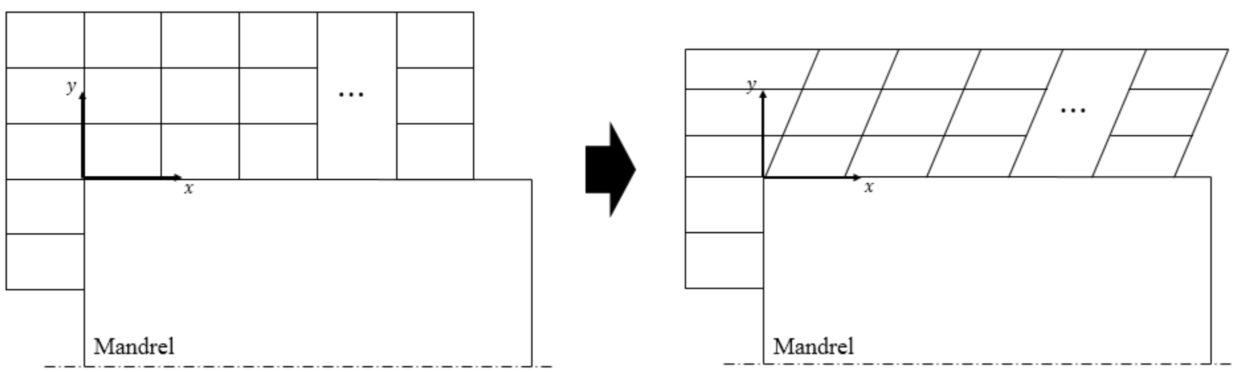

Figure 1. Diagram of lattice structure of the work-pieces.

Work-pieces is assumed to be a lattice structure. Fig 1 shows the diagram of lattice structure. Based on finite deformation theory, if the middle steps can be ignored, the final coordinates can be expressed by initial coordinates:

$$X_f = \alpha_1 X_i + \beta_1 Y_i \qquad (0 \leq X, 0 \leq Y) \tag{1}$$

$$Y_f = \alpha_2 X_i + \beta_2 Y_i + \beta_3 \tag{2}$$

$\alpha_1, \beta_1, \alpha_2, \beta_2, \beta_3$ are functions of input variables. X_i and Y_i are the matrices of initial coordinates of assumed lattice structure. X_f and Y_f are matrices of final coordinates predicted. In this case, only thickness does change and the shape doesn't change, so

$$\alpha_2 = 0 \tag{3}$$

β_2 can be expressed by ratio of change of thickness to the deformation.

$$\beta_2 = \frac{dt_f}{dt_0} \tag{4}$$

β_3 is the restoration of thickness by elastic force. It can be expressed as

$$\beta_3 = \frac{dt_0 \sigma_Y \tanh(E\beta_2/\sigma_Y)}{E} \tag{5}$$

dt_0 is the initial thickness of an element of the lattice. $\mathrm{dt_f}$ is the final thickness of an element and can be calculated using volume constancy.

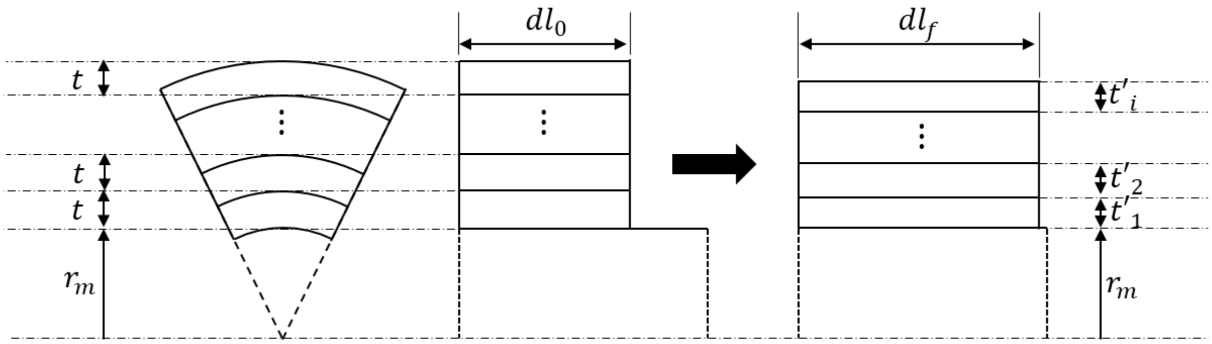

Figure 2. Section of cylindrical workpice.

Fig2 shows the section of work-pieces of radial direction. From the constraints, simultaneous equations can be derived. The first equation is

$$\{(r_m + t'_1)^2 - r_m^2\}dl_f \frac{\theta_2}{360}\pi = \{(r_m + t)^2 - r_m^2\}dl_0 \frac{\theta_1}{360}\pi \tag{6}$$

dl_0 is the initial length of an element of the lattice. dl_f is the final length of an element in the end of the process.$\theta_1, \theta_2$is initial and final rotational angle of the element, relatively.θ_2 is same as θ_1.

$t'_i$is the height of the mandrel from the i-th element in the axial direction. r_m is the radius of mandrel and t is the initial height of each element.

$$\{(r_m + t'_2)^2 - (r_m + t'_1)^2\}dl_f \frac{\theta_2}{360}\pi = \{(r_m + 2t)^2 - (r_m + t)^2\}dl_0 \frac{\theta_1}{360}\pi \tag{7}$$

Equation of *i*-th element from mandrel is expressed as:

$$\{(r_m + t'_i)^2 - (r_m + t'_{i-1})^2\}dl_f \frac{\theta_2}{360}\pi = \{(r_m + it)^2 - (r_m + (i-1)t)^2\}dl_0 \frac{\theta_1}{360}\pi \tag{8}$$

Equation of the last elements which are furthest from mandrel is expressed as:

$$\{(r_m + t'_i)^2 - r_m^2\}dl_f \frac{\theta_2}{360}\pi = \{(r_m + it)^2 - r_m^2\}dl_0 \frac{\theta_1}{360}\pi \tag{9}$$

t'_i can be calculated as:

$$t'_i = \beta_2 t_0 + \beta_3 \tag{10}$$

Solving the equations (7) ~ (9), change of height of each element $t'_1, t'_2, \cdots, t'_{i-1}, dl_f$ can be calculated.

$\alpha_1$is the ratio of change of length of work-pieces.

$$\alpha_1 = \frac{dl_f}{dl_0} \tag{11}$$

To calculateβ_1, sheer stress-strain relationship is used.

$$f = \mu F = \tau = K\gamma^n \tag{12}$$

$$\gamma = \left(\frac{f}{K}\right)^{\frac{1}{n}} \tag{13}$$

$$\beta_1 = tan\gamma = tan\left(\frac{f}{K}\right)^{\frac{1}{n}} \tag{14}$$

In the way of calculating the final formation of the structure, yield stress of the workpiece during the process and elongation can be calculated.

$$\sigma = \sigma_Y \, tanh\left(\frac{E\varepsilon}{\sigma_Y}\right) \tag{15}$$

Stress-strain equation which is suggested by Prager is used [12]. σ_Y, E can be calculated from tensile tests.

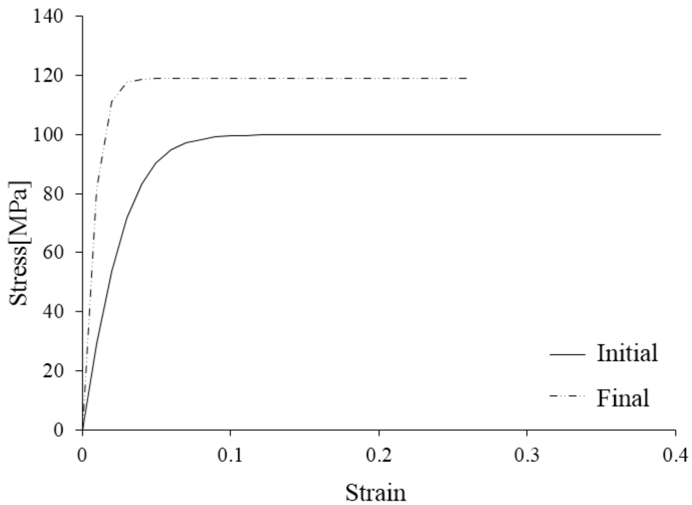

Figure 3. Stress-strain relationship of material.

Fig 3 shows the stress- strain curve. The curve is shortened with strain direction and expanded with stress direction when reduction ratio is increased. To calculate the stress-strain curve of the processed workpiece, the energy equation is used:

$$\int \sigma_0 - \int \sigma_1 = u_t = \int_0^{\varepsilon_1} \sigma_0 + u_r + u_f \tag{16}$$

σ_0 is the stress-strain curve of the initial workpiece, ε_1 is the strain which caused by the flow forming process. σ_1 is the stress-strain curve of the final workpiece. u_t, u_r, u_f are the total energy, redundant work and friction energy, respectively. Friction energy can be ignored in this case because the friction of tangential direction is canceled by the rotation of the roller, and friction of axial direction can be ignored because the axial direction speed of roller is very smaller than the rotating speed. Energy from redundant work is ignored to simplify the problem. So the equation can be arranged as:

$$\int \sigma_0 = \int_0^{\varepsilon_1} \sigma_0 + \int \sigma_1 \tag{17}$$

2.2.3D Finite Element Analysis

For the model established in this paper, FEM and experiment is conducted. By comparing the result of FEA with the experiment, conditions which cannot be controlled in experiments can be simplified to small amounts of constraints in FEA. And if the results of FEA are verified, model can be verified with FEA with the factors which cannot be measured in experiments.

Table 1. Condition for FEA.

Character of Part	Roller	Rigid body
	Mandrel	Rigid body
	Workpiece	A1050
Feedrate		300 mm/min

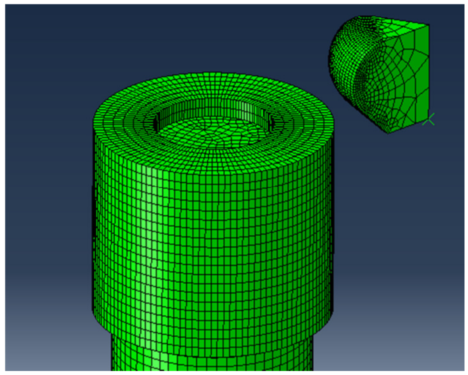

Figure 4. Axisymmetric mesh for FEM.

Fig 4 shows the 3D finite element method model and Table1 presents the boundary condition for the flow forming process. ABAQUS/Explicit is used for the case. Mandrel and work-pieces rotate at 300 rpm, while the roller doesn't rotate. Friction effects exist only at axial direction. For the example Coulomb friction coefficient is used.

2.3. Experiment Conditions

Experiments were conducted to verify the FEM Model. Fig 5 shows the experiment equipment of flow forming process. Table 2 shows the specifications of the equipment.

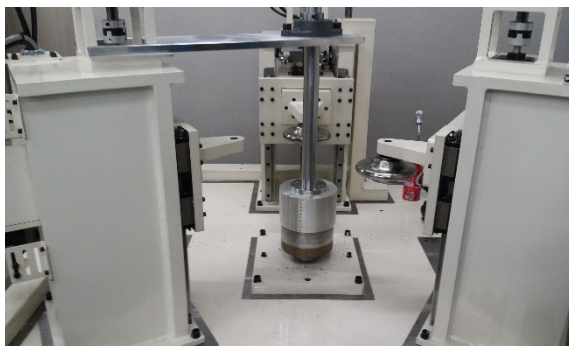

Figure 5. Flow fomring machine for experiments.

Table 2. Condition of the experiments.

Feedrate	300 mm/min
Spindle speed	300 rpm
Temperature	17℃

The work-pieces has a cup shape and a roller moves along a linear path to deform the thickness of the work-pieces. A second roller is the idle roller, which helps the axis of the mandrel to maintain verticality.

To compare the result of the experiment with FEA and the established model in this paper, two different small holes with different depth are machined on the work-pieces. The holes are filled with colored powder and sealed. By cutting the work-pieces to axial direction, the aspect of the material's motion, when the work-pieces is deformed can be observed.

3. Result and Discussion

Precision of the shape is the most important factor of the flow forming process. In order to verify the accuracy of the model, experiment and finite element analysis have to be conducted. First, two or three experiments are conducted and compared to the model and the result of analysis. Then, variable case of FEA is conducted to verify the model established in this paper.

3.1. VERIFICATION WITH FEA AND EXPERIMENT

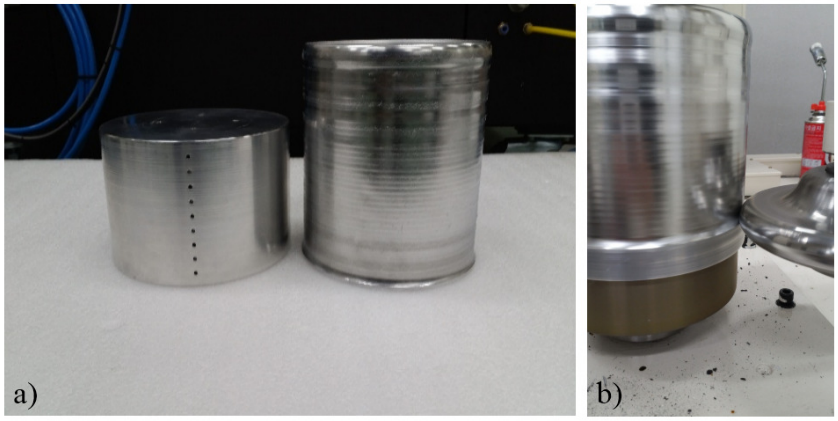

Figure 6. Result of the Experiment.

Figure 6 a) shows the final result of the experiment, and Figure 6 b) shows the flow forming process. The height of the work-pieces is 100mm, and the thickness is 5mm. The thickness was reduced to 3mm, and the height of the work-pieces was extended to 155.36mm.

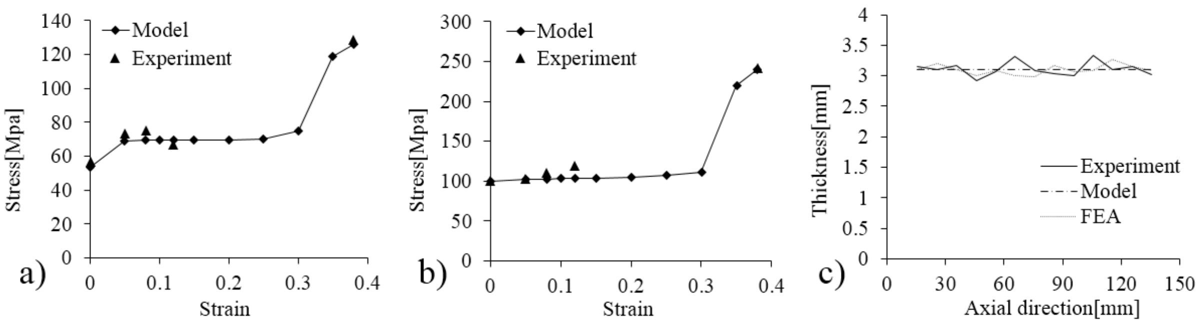

Figure 7. a) UTS comparison between the model, experiments b) Yield stress comparison between the model, experiments c) Final shape comparison between the model, experiments and FEA.

Figure 7 a) shows the aspect of the yield stress and figure 7 b) shows ultimate tensile stress according to reduction ratio. 4 cases of the experiment is conducted. Each case is predicted by the model. The maximum error of UTS between experiment and model is 13.08%, and the average value of the error of UTS is 4.29%. The maximum error of yield stress between experiment and model is 7.85%, and the average value of the error of yield stress is 5.03%. Yield stress and Ultimate tensile stress increase nonlinearly. Figure 7 c) shows the comparison of thickness at the case 4 which the thickness reduction amount is 1.8mm. The results of FEA are compared with model and experiment. The maximum error between experiment and FEA is 9.41%, and the mean value of the error is 0.20%.

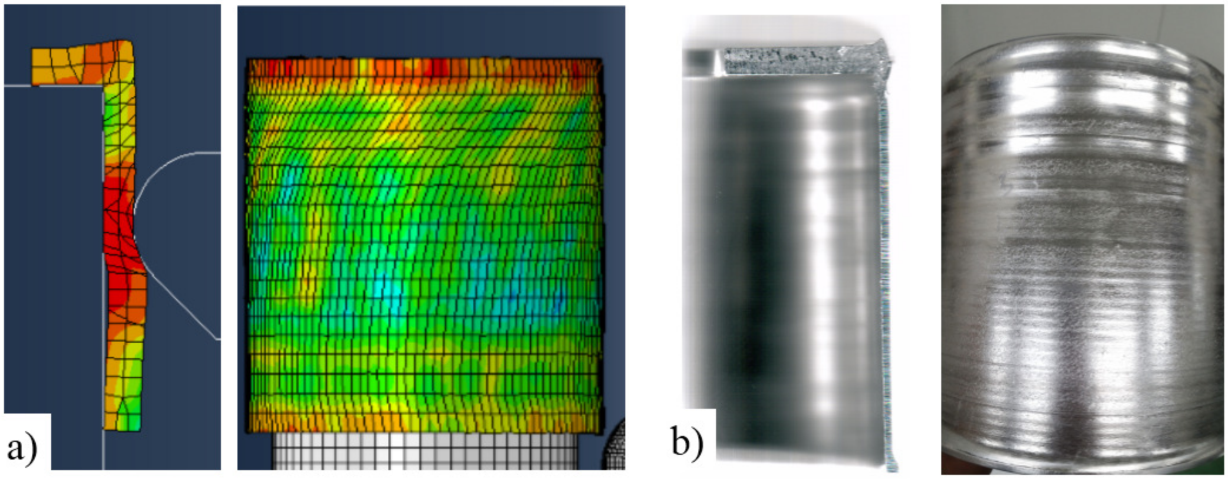

Figure 8. Result of the FEA and Experiments.

Figure 8 shows the result of FEA and the Experiment. Slip in tangential direction can be observed. This is caused by the flow stress and the friction that doesn't get canceled by the rotation of the work-pieces. The result of the flow forming process is presented. The edge of the right side of the work-pieces is moved upwards because of the elastic force of the free end.

3.2. Verification with FEA for More Cases

To verify the model and observe the aspect of the flow forming process in more cases, parametric study with FEA is conducted. The factors are thickness of work-pieces and thickness reduction ratio. The condition of FEA is presented at Table 3.

Table 3. Factors and condition of FEA.

Factor	Thickness of work-pieces[mm]	Thickness reduction[%]
No. 1	5	40
No.2	10	10
No. 3	10	20

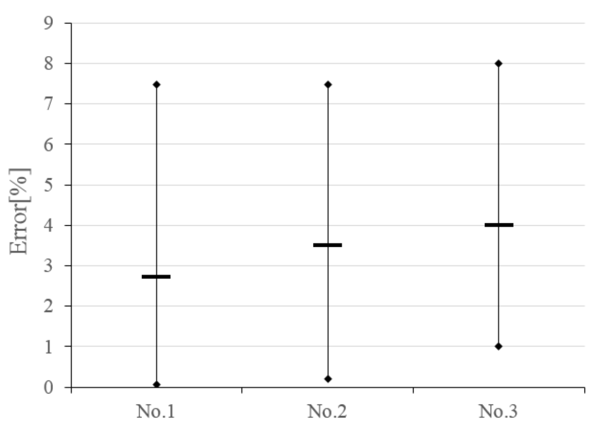

Figure 9. Error of the Process in FEA and model.

Error of the flow forming processes is presented in Figure 9. The mean value of the error is 2.77%, 3.49%, 4.03%, relatively. The maximum error between the model and FEA is almost same for all cases. The deformation thickness becomes greater and excessive deformation occurs so the error factors are more evident. Therefore, the mean value of the error is proportional to the initial thickness of the work-piece, as well as the thickness decrement of.

4. CONCLUSION

A model is used to analyze the flow forming process and the following results are obtained:

1. Prediction model for flow forming process is established, and verified by Experiments and FEA.
2. Through the case study, reliability of the model is approved.
3. Error of the model increases when the initial thickness of the work-piece increases, and the thickness decrement of the work-piece becomes higher.
4. Slips which cannot be predicted in model are observed during the process.

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