Experimental and numerical analyses on three-roll planetary rolling process

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Abstract

This study conducts experiments on a planetary three-roll experimental apparatus and uses plasticine as the working material. Certain rolling characteristics were observed and compared with the data from finite element simulation, which include diameter of workpieces after deformation, the pitch length and threaded angle of spiral marks, and the cavity at the leading end of rolled plasticine. The comparison confirms the correctness of the simulation model for PSW.
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1. Introduction

Conventionally, most stainless steel rods are manufactured during the roughing rolling process, with a large reduction ratio by several two-high rolling mills. Six to eight conventional mills can be replaced by using one three-roll planetary rolling mill (Planetensh rägwalzwerk, PSW, as shown in Fig. 1 [1]) in the roughing rolling process. The PSW mainly includes three conical rolls and an external ring. As shown in Fig. 2, the rolls are inclined and are located equally around the axis of the workpiece, and the rolls' axes intersect with that of the workpiece by an offset angle. This offset angle forces workpiece to move forward as the rolls rotate. The rolls are driven by a main motor through the planetary gear system and are positioned by the ring, which is driven by a secondary motor. The secondary motor drives the sun wheel of a planetary gear system as a superimposed driver to make the ring rotate in a direction opposite to that of the rolls. In addition to fixing the rolls, the main purpose of the ring attempts to eliminate any slight rotary motion of the rod in the mill [2] and to counteract the twisted deformation of the workpiece during rolling process, to help keep the rods round during rolling. Using a PSW reduces the operational cost, the maintenance and the space occupied in the plant. Moreover, the advantages of the PSW include flexibility of ingot size, low rolling load, low lateral spread of material

[3,4] and a low temperature drop between the leading and the tail end of the rolled bar [5]. These characteristics increase precision, and thus homogenize the quality and increase the competitiveness of the products.

Some research has addressed the three-roll planetary rolling process. Most experimental research involves the rolling experiments on an experimental three-roll rolling mill with plasticine as the working material, because of the difficulty of experiment on a real, operating mill. The material properties of plasticine are similar to those of stainless steel at elevated temperatures. Aoyagi and Ohta [6] observed the flow of the material, the load and torque on the rolls, and the pressure distribution on the rolls during rolling process, with different cross-sectional reduction rates. Additionally, the effect of the offset angle on the exit velocity of the rods was determined. Nishio et al. [7] discussed the quality characteristics of rolled products with different offset angles and roll profiles. Chen [8] designed a planetary three-roll experimental machine to confirm the possibility of rolling clay, plasticine, aluminum and lead, to determine the relationship between the rolling parameters and the spiral mark on the products after rolling. Shih et al. [9] developed a finite element model for the three-roll planetary rolling process and simulated the deformation of the stainless steel during rolling. The simulated results also compared to the results from Aoyagi's experimental work.

However, the references specify no particular plasticine and configuration of experimental mill, the comparison has not yet been validated completely. Therefore, this work used

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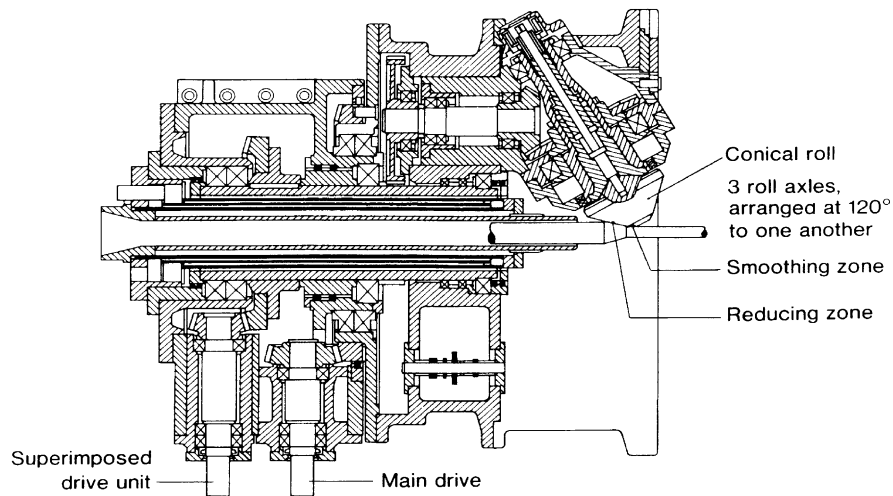*E-mail address:* chhung@cc.nctu.edu.tw (C. Hung).

Fig. 1. Cross-section of PSW [1].

the white plasticine as the working material on the planetary three-roll experimental machine and the experimental results were compared to those from the finite element simulation to verify the correctness of the simulation model.

2. Experiment on planetary three-roll experimental machine

2.1. Planetary three-roll experimental machine

The planetary three-roll experimental machine, fabricated by Chen [8], was designed to be able to roll aluminum. Fig. 3 shows the configuration of this experimental machine. The rolls of this machine are designed to reach a maximum reduction of 80%. The profile of the roll, shown in Fig. 4, is formed with three straight lines and is divided into three zones.
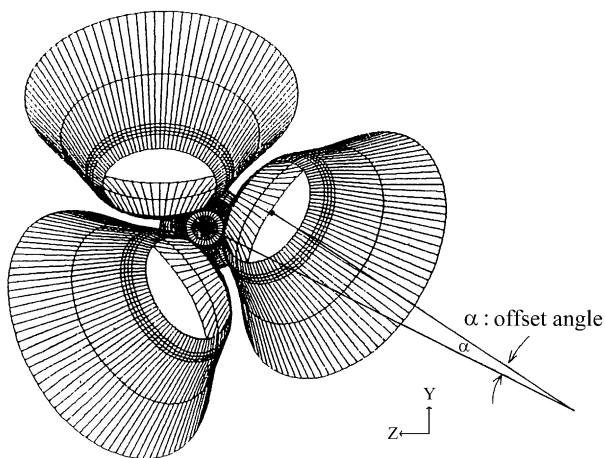

Fig. 2. Roll of PSW (courtesy of Walsin Cartech specialty steel corporation).

(1) Large deforming zone: provides the main deformation of the workpiece.
(2) Small deforming zone: deforms the workpiece to the final size.
(3) Smoothing zone: eliminates the spiral marks on the workpiece while maintaining accurately the size of the workpiece during rolling process.

The parameters of the experimental machine are consistent with the setup of a practical rolling mill and are specified below:

- Inclined angle of roll (β): 53°.
- Offset angle of roll (α): 7°.
- Rotational speed of rolls: 2.35 rpm.

Both the rotational and revolution speed of the rolls are adjustable but in the experiments the revolution was suspended. Thus, the operational boundary conditions of the experimental machine were the same as those of the FEM model. The position of the rolls can be controlled so that the final diameters of the rolled workpiece can be changed. The maximum initial diameters of the workpieces were 60 mm, and the final diameters of the workpieces ranged from 32 to 20 mm after rolling.

2.2. Preparation of plasticine workpiece

Before conducting the rolling experiment on experimental machine, the plasticine workpieces were made first. The white plasticine manufactured by Peter Pan Playthings was selected as the working material. The commercial plasticine is packed in the form of a cuboid, which is composed of 25 long sticks. The sticks of plasticine were first heated to 40 °C to make them softer and easier to combine them together by repeatedly kneading. Few drops of oil were added into the kneading plasticine to provide higher adhesion. Having been repeatedly kneaded, cretin amount of plasticine was
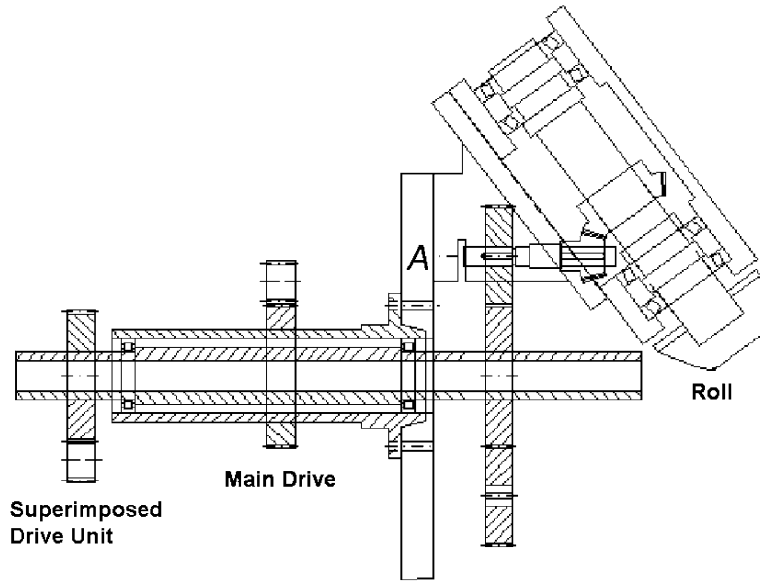
Fig. 3. Configuration of planetary three-roll experiment machine [8].

put inside a pair of half-cylindrical molds and was then compressed to form an experimental rod. After compressing the mold tightly, the plasticine was fully filled the mold and the redundancy that extruded out the mold at both ends was removed. To fully fill the mold to increase the homogeneity

Table 1
Configuration of experimental workpiece[a]

Initial diameter, D_0 (mm)	Final diameter, D_f (mm)	Area ratio, r_A (%)
30	27	19
30	24	36
40	24	64

[a] Area ratio, r_A (%) $= ((D_0^2 - D_f^2)/D_0^2) \times 100$.

of workpiece, the amount of plasticine was taken more than necessary.

Three types of the plasticine rods, 100 mm in length, were rolled. Table 1 lists the initial and final diameters of these rods.

3. Finite element simulation of planetary three-roll experimental machine

3.1. Simulation model

The simulation model of the planetary three-roll experimental machine was established by following the procedures specified in the previous work that utilized equation of meshing to handle the boundary conditions [9]. The geometrical specifications of the simulation model were the same as those of the experimental machine. Fig. 4 shows the profile of the rolls. The profile of workpiece was built corresponded to the cylindrical rod used in the experiments. Fig. 5 shows the mesh system of the complete setup and the workpiece.

The rolls are assumed to be rigid and isothermal and the heat transfer between rolls and workpiece is ignored. For
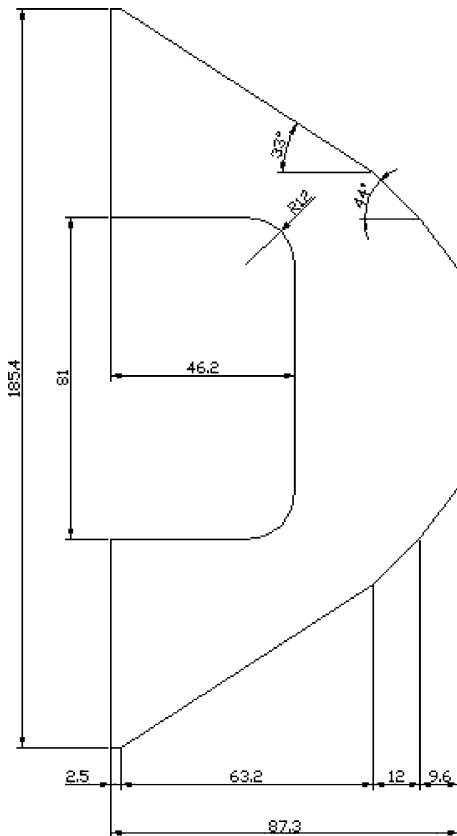

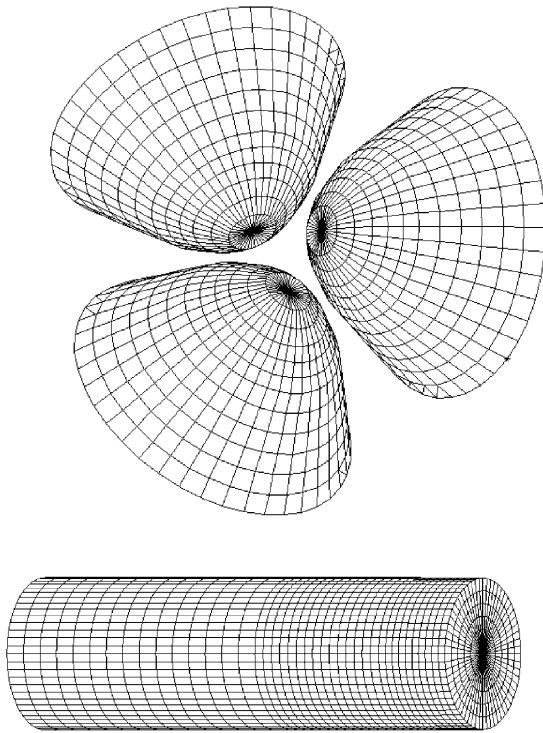Fig. 4. Roll profile of the experimental machine [8] (unit: mm).

Fig. 5. Mesh system of the planetary three-roll experiment machine.

Fig. 6. Diameter of rolled workpiece.

hot working, the typical coefficient of friction was found experimentally to be $\mu = 0.4$ [10]. Since the material properties of plasticine are similar to those of steel at high temperature, the coefficient of friction in the interface between the rolls and plasticine workpiece was assumed as $\mu = 0.5$.

3.2. Material properties of plasticine

White plasticine was selected as the working material on the experiment. In the finite element analysis, the material properties of plasticine, such as yield stress and Young's modulus, must be obtained first. The stress–strain relationship can be obtained either from the tensile test [11] or the compression test [12]. This study performed a compression test because of the large reduction during rolling processes. The plasticine, which was available after kneading procedure, was shaped into cylindrical specimens with both diameter and height of 25.4 mm. The true stress–true strain curve was obtained, and was fitted by a power law equation:

$$\sigma = 0.246\varepsilon^{0.183}\,(\text{MPa}) \tag{1}$$

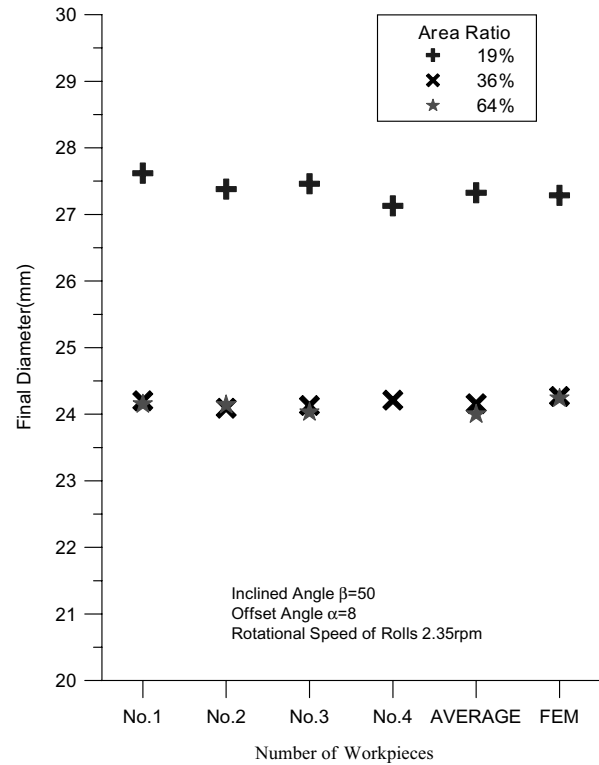This constitutive relationship was then used in the finite element simulation.

4. Results and discussion

The experiments were performed five times for each area ratio. In Figs. 6, 10, 11 and 14, Arabic numerals in the abscissa axis indicate the number of the workpiece.

4.1. Diameter after deformation

The size of the products rolled from the planetary experimental machine is adjustable. Movable axes were design to adjust the position of rolls and thus maintain the symmetry of three rolls. Changing the position of rolls controls the final diameter of rolled workpieces.

After changing the position of roll, the diameter of workpiece after rolled is roughly obtained. Thus it is necessary to verify the final diameter. A workpiece was first rolled and then measured its diameter. If the diameter was not qualified, changing the position of rolls and the plasticine is rolled again. Repeat the above processes until the final diameter was confirmed to the required size.

Fig. 6 shows the experimental results of final diameters. The figure shows that the results of each area ratio are very close but a little bigger than the original design. The difference might result from the peak of the spiral marks and from the inaccurate adjustment in the position of rolls.

Fig. 6 also shows the average of the diameter from experiment and compares to those from the simulation. This figure shows that the simulated results are close to the
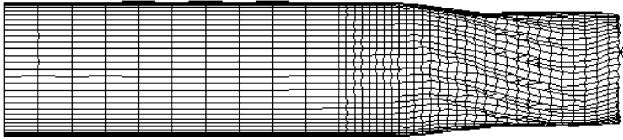
Fig. 7. The mesh of deforming workpiece.

experimental data. The mesh in the circumference of the workpiece was very scraggy because of the large deformation. Therefore, the diameters obtained by FEM did not exactly fit the experimental data. The mesh system should be created denser in the circumference direction to minimize these descritization errors. The mesh of a deforming workpiece is shown in Fig. 7.

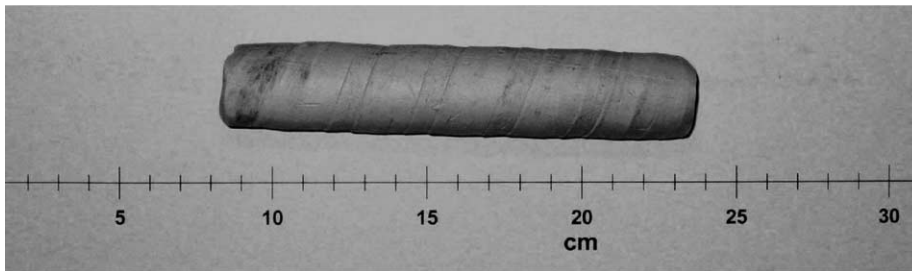### 4.2. Characteristics of the rolled workpiece

Fig. 8 shows rolled workpieces with different area ratios. Conspicuous threaded marks are clearly seen on the surfaces.

One spiral mark is more significant than the other two. Spiral marks are equally separated and almost parallel to each other. Pitch length (Δx) and threaded angle (Φ) are defined for these spiral marks, and are shown in Fig. 9.

As Nishio mentioned, the formation and appearance of spiral marks are affected by rolls. The profile of the rolls, especially the profile of the smoothing zone, determines the presence of spiral marks. The offset angle of rolls affects the pitch length of the spiral marks and also influences their threaded angle of spiral marks. The inclined angle of the rolls also relates to the threaded angle of the spiral marks. Properly designing the roll's profile can eliminate the spiral marks.

Observation during the experiment reveals that the spiral marks were scored on the surface of the workpiece by the border between the small deforming zone and the smoothing zone of the rolls (Fig. 4). One spiral mark is more prominent than the other two because achieving perfect symmetry of alignment of the three rolls is very difficult.

(a) Area ratio=1.23
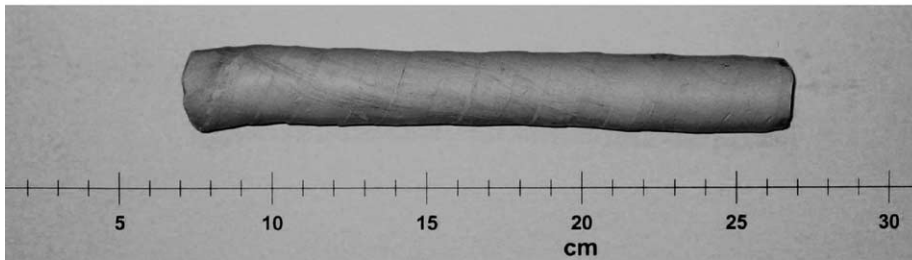
(b) Area ratio=1.56

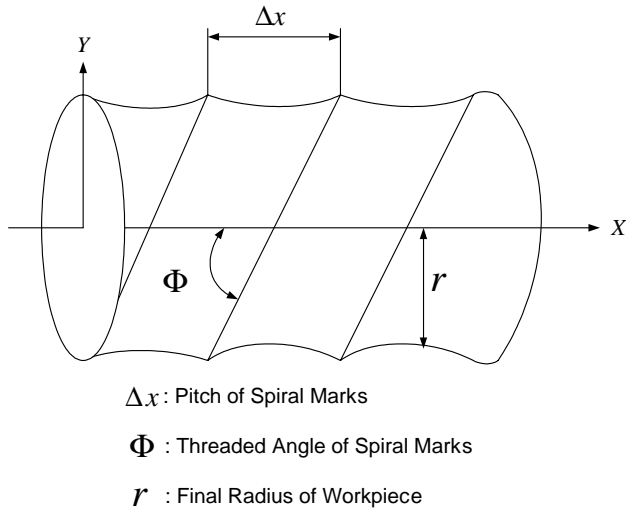

(c) Area ratio=2.78

Fig. 8. Rolled products.

Δx : Pitch of Spiral Marks

Φ : Threaded Angle of Spiral Marks

r : Final Radius of Workpiece

Fig. 9. Characteristic of workpiece [7].

4.2.1. Pitch of spiral marks

Fig. 10 shows the pitch length of the spiral marks obtained experimentally. Because the bending and twisting of rolled workpiece, the workpiece needs to be stretched slightly before measurement. However, the shape of workpieces is still curved.

Above results also show that rods with the same final diameter after rolling ($r_A = 64\%$ and $r_A = 36\%$) are scored with spiral marks of the same pitch length. Furthermore, for a given initial diameter ($r_A = 19\%$ and $r_A = 36\%$), the pitch increases as the area ratio decreases.

During the simulation, the pitch of the spiral marks was determined from the locus of a point on the surface during the rolling process, yielding results similar to those obtained experimentally. Fig. 10 indicates that the difference between the experimental results and simulation results is approximately 2 mm. The figure also shows that rods with the same final diameter after rolling ($r_A = 64\%$ and $r_A = 36\%$) are scored with spiral marks of the same pitch length. Furthermore, for a given initial diameter ($r_A = 19\%$ and $r_A = 36\%$), the pitch increases as the area ratio decreases.

4.2.2. Threaded angle of spiral marks

Fig. 11 presents the relationship between the threaded angle and the area ratio. The experimental data for each area ratio is close. Similar to the pitch length, the bending of rolled workpiece affects the threaded angle of the spiral marks. For the workpiece with a particular final diameter ($D_f = 24$ mm, $r_A = 36\%$ and $r_A = 64\%$), the threaded angle of the workpiece with area ratio $r_A = 36\%$ is bigger than that with $r_A = 64\%$. And for rod with the same initial diameter ($D_0 = 30$ mm, $r_A = 19\%$ and $r_A = 36\%$), threaded angle increase with the area ratio.

The FEM results in Fig. 11 show that rods with a particular diameter after rolling ($D_f = 24$ mm, $r_A = 36\%$ and $r_A = 64\%$) have the same threaded angle of spiral marks
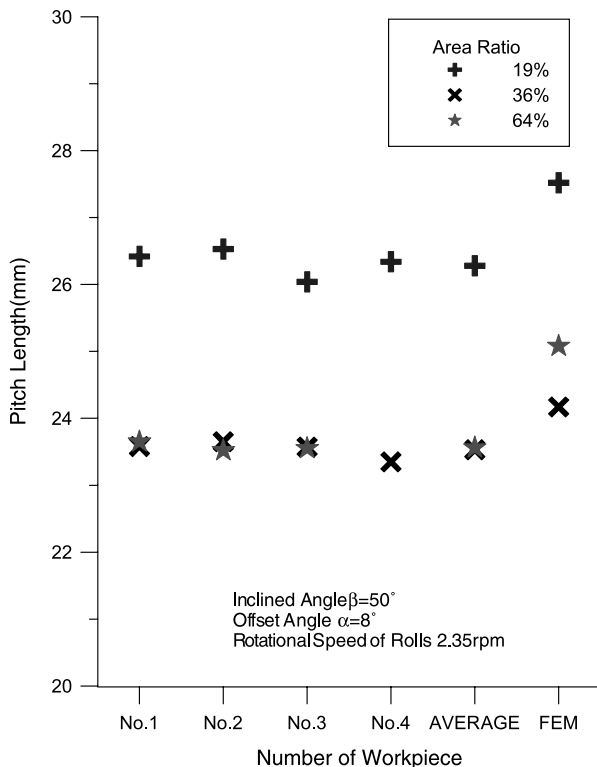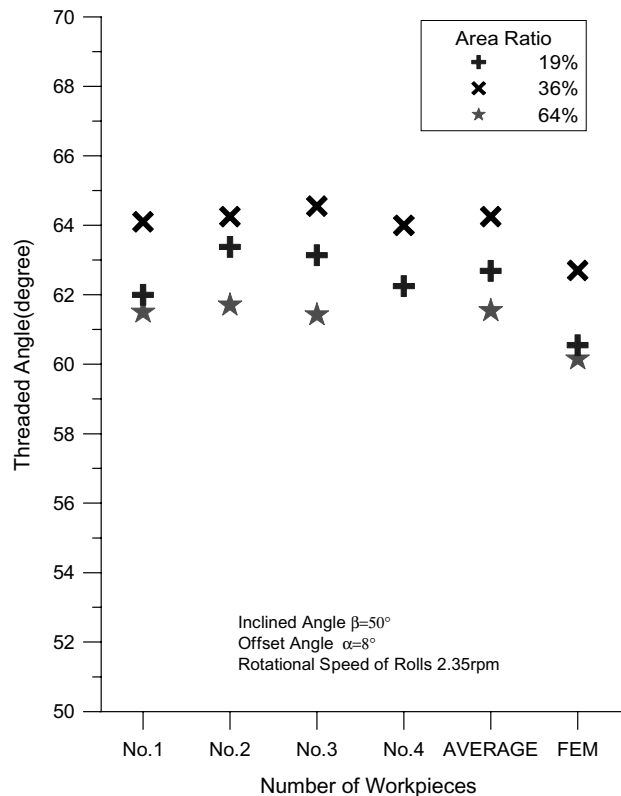

Fig. 10. Pitch length of the spiral mark.
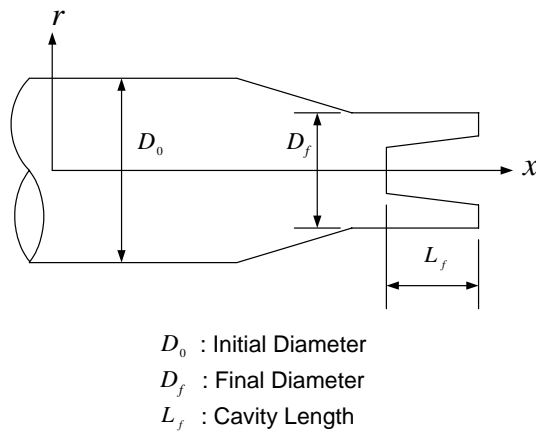

Fig. 11. Threaded angle of the spiral mark.

D_0 : Initial Diameter
D_f : Final Diameter
L_f : Cavity Length

Fig. 12. Characteristic of end cavity [7].

Fig. 14. Cavity depth on the workpiece.

after rolling. For rods with the same initial diameter ($D_0 = 30$ mm, $r_A = 19\%$ and $r_A = 36\%$), rolled workpieces with a smaller area ratio have a larger threaded angle. Additionally, the experimental results have the similar tendency and approximate magnitude as the simulated results. The difference between the experimentally obtained data and the simulation results is about $2°$.

4.3. Inhomogeneous deformation of rolled rod

A cavity is always present at the leading end of traditionally rolled products, and the same is true for products rolled from the three-roll planetary rolling mill. Fig. 12 illustrates the cavity of the rolled workpieces [7]. The rotation of rolls forces the workpiece to move forward and rotate around its own axis. This mechanism causes the velocity of material flow in the outer part of the workpiece to differ from that in the inner part. The outer part of the workpiece moves faster than the inner part and results in a cavity at the leading end of the rolled workpiece. Fig. 13 shows the end cavity of the rolled plasticine rods. Fig. 14 shows the depth of the cavity in the rolled plasticine increases with the area ratio.

If the plasticine is not kneaded uniformly and not fully filled the mold, the workpiece will not have homogeneous

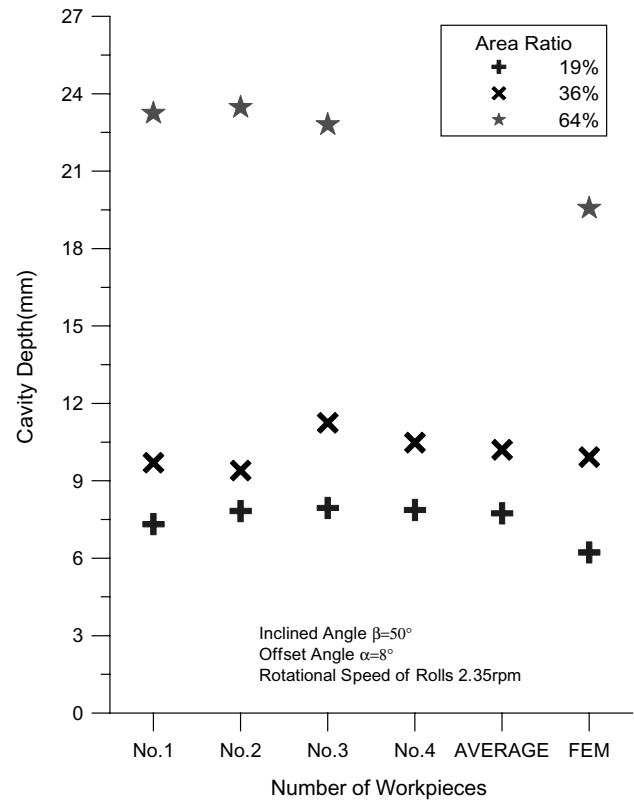Fig. 13. End cavity of the rolled workpiece.

properties, especially at both ends of the workpiece. The cavity of the leading end might be influenced, especially for workpiece with initial diameter $D_0 = 40$ mm, because the homogeneity of the both ends could not be controlled easily for large workpiece. Thus the difference between the experimental data can be referred to the homogeneity on the leading end of the workpiece.

The pushing distance might be the another reason that affected the cavity depth. The workpiece must be pushed forward with certain distance to ensure sufficient contact area between the rolls and the workpiece. The distance should be identical to and depend on the size of workpiece. However, this distance may lack consistency in the experiment.

The simulated data and the experimental data both show that the cavity depth increases with the area ratio. Fig. 14 also represents that the depths determined from the simulation are less than those measured experimentally, especially for large area ratios. The difference might result from the homogeneity of workpiece at both ends.

5. Conclusion

Using plasticine and a planetary three-roll experimental machine is a reasonable way of conducting experiments that are difficult to perform in the practical three-roll planetary rolling mill. The comparisons of final diameter, pitch length and threaded angle of spiral marks and cavity length in the

leading end between simulation and experiment are very similar. The finite element model constructed in previous work is thus confirmed, and can be used to further study in planetary rolling process.

However, some rolling characteristics, such as rolling load and torque, should be further determined in rolling experiments. The comparison between experimental data and simulation analyses could be made more complete by measuring the rolling load and torque during rolling processes.

Acknowledgements

References

[1] W.L. Roberts, Hot Rolling of Steel, Marcel Dekker, New York, 1983.
[2] E.J.F.E. Bretschneider, The 3-roll planetary mill, in: Iron and Steel Engineer Year Book, Association of Iron and Steel Engineers, 1976, pp. 120–122.
[3] W.J. Ammerling, H. Brauer, Application of 3-roll technology for rolling specialty rod and bar products, Iron Steel Eng. 65 (9) (1988) 22–27.
[4] W.J. Ammerling, Kocks 3-roll technology for high precision specialty rod and bar product, MPT Metall. Plant Technol. 12 (6) (1989) 14–19.
[5] C. Recalcati, C. Ventura, W. Rensch, HRM high-reduction rolling machine, Wire Ind. 57 (673) (1990) 31–34.
[6] K. Aoyagi, K. Ohta, Material deformation, rolling load and torque in 3-roll planetary mill, J. Jpn. Soc. Technol. Plast. 24 (273) (1983) 1039–1047.
[7] T. Nishio, T. Noma, S. Karashige, H. Hino, T. Tsuta, K. Kadota, Development of three-roll planetary mill (PSW), Kawasaki Steel Tech. Rep. 84 (1995) 81–90.
[8] T.Y. Chen, The design and production of the planetary three-roll experimental machine, Master Thesis, National Sun Yat-sen University, China, 2000.
[9] C.K. Shih, C. Hung, R.Q. Hsu, The finite element analysis on planetary rolling process, J. Mater. Process. Technol. 113 (2001) 115–123.
[10] E.M. Mielnik, Metalworking Science and Engineering, McGraw-Hill, 1993, p. 493.
[11] A. Segawa, T. Kawanami, Rolling-deformation characteristics of clad materials determined by model experiment and numerical simulation: experiment rolling tests using plasticine, J. Mater. Process. Technol. 47 (1995) 375–384.
[12] H. Sofuoglu, J. Rasty, Flow behavior of plasticine used in physical modeling of metal forming processes, Tribol. Int. 33 (2000) 523–529.