Study of rotating drawing process of wire rod based on slab method and FEM simulation with constant shear friction

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Abstract. The study based on the slab method and FEM simulation is to explore the wire rod drawing using rotating die. Constant shear friction is assumed at the interface between die and wire rod to explore different drawing conditions such as rotating angular velocity (ω), half die angle (γ), frictional factor (m) etc. on the influence of drawing forming characteristics. Besides, the die stress of rotating die occurred has been analyzed to realize whether the drawing die is failed or not. The axial stress, the radial stress, the drawing force, and the rotating torque can be obtained from the slab method to compare with the FEM, the error between the both models is around 8-10%. Moreover the realistic experiment is able to verify the acceptances of both models. Therefore through the study due to the rotation of drawing die, the drawing force can be reduced and the flowing of wire rod is increased.

1. Introduction
The drawing processing is one of the most common and important processes in the industry. It is widely used in various industries. Dixit et al. [1] performed an analysis of the steady-state wire drawing of strain-hardening materials. A comparison of the drawing parameters were made for three materials (copper, aluminum and steel). The distributions of residual stress tensor components along the wire radius were calculated for different values of reduction and die angle. The analysis of the obtained relations was carried out. The influence of the die angle on the distribution of residual stresses was most noticeable at small reductions. After the maximum values of residual stresses were reached at the reduction values of 35-40%, they noticeable decrease occurred [2]. Skołyszewski et al. [3] based on the results of extensive laboratory tests for six grades of high-alloy steels, an attempt of finding the relationship between the critical back tension value and the mechanical properties of a material was presented. Lu et al. [4] made the comparison between finite element method and analytical methods for studying wire drawing processes for aluminum alloy AA-5083. Nagashima et al. [5] used FEM analysis to carry out the shaped wire drawing, and in FEM analysis, it was possible to check the effectiveness of the die for extracting irregular shapes and the filling property of the wire. Dodyim et al. [6] used FEM simulation for drawing of magnesium fine wire and medical application of drawn wire. Consequently, they succeeded to draw the fine wires with 0.5 mm in diameter without internal cracks and good finishing surface roughness. The microtubes [7] had an outer diameter of 0.5 mm and a thickness of 0.13 mm. Dieless drawing apparatus with a chamber filled with argon gas to prevent oxidation was used in the experiments, effects of oxidation and surface roughening on drawing limit in dieless drawing process of SUS304 stainless steel microtubes. A 0.66 mm-diameter AZ31 alloy wire with ultimate tensile strength of 400 MPa and elongation of 28.5% was successfully prepared via the combination of cold-drawing and electropulsing treatment processing (EPT) [8]. Wang et al. [9] performed the experiment study on the variation of wall thickness during dieless drawing of stainless steel tube. They concluded that with the increasing of deformation in wall thickness and the derivative of wall thickness variation to the width of deformation reduces. The effect of a dieless drawing process on commercial grade Nickel–Titanium rods, of 5 mm diameter, was investigated by varying the

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established critical process parameters of temperature, cooling rate, drawing velocity, and heating/cooling velocity [10]. Liu et al. [11] used titanium wire drawing with ultrasonic vibration experimental study to reduce the drawing force. Srikanth et al. [12] focused on Co-Cr-Ni-Mo alloy fatigue wires drawn with different drawing practices fractography study. Hwang [13] used FEM simulation for fracture behavior of twinning-induced plasticity steel during wire drawing in order to understand the fracture mechanism of drawn TWIP steel wire. Hwang et al. [14] used FEM software (DEFORM) simulation for high temperature oxidation behavior in dieless drawing of titanium alloy wires. The multi-pass wire drawing could be made by passing the wire through consecutive dies, focused on die spacing in the evolution of damage in two-pass wire drawing processes incidence [15]. A modified damage work model has been implemented into a finite element analysis, by means of a developed Fortran subroutine, this has enabled the analysis of the occurrence of central burst defects in single and multi-pass wire drawing [16]. Colombo et al. [17] used a continuous press and pulling system with a track-chain. Normal force at the steel clamps could be generated independently on the axial force, avoiding slipping and local yielding at the external surface of the wire. Tang et al. [18] used FEM simulation for damage evolution in multi-pass wire drawing process. The Gurson–Tvergaard–Needleman model (GTN model) was introduced to describe damage evolution in the drawn wire. Based on a three-dimensional model of the drawn wire generated through ABAQUS, the numerical analyses on damage behavior in multi-pass wire drawing were undertaken for the purpose of investigating the damage evolution during all phases of the process. The wire drawing process using a web camera based vision system process monitoring [19]. The purpose of the monitoring was to detect if the process was about to fail. In this work the failure of the process was initiated by removal of the lubricant, causing galling between the wire and the die. This work proposed two methods for reducing the residual stresses during wire drawing, namely applying an advanced die geometry and performing an inexpensive post-drawing treatment based on targeted bending operations [20].

2. Slab method
Figure 1 shows Schematic diagram of wire rod drawing process using the rotating die. From this figure, the die with a rotating velocity (ω) and the half die angle (α), the wire rod with the diameter at entrance (D1) and the diameter at exit (D2), can be seen. Cross head will clamp the wire rod to forwardly occur a pull velocity (V0). Due to the rotation of die, the frictional shear stress (τ) no longer acts to the axial direction (z direction), it will act on the certain direction (β) away from the axial direction, as shown in Figure 2. Therefore, the frictional shear stress can be resolved two components, the first one is τ cos β which acts on the interface along the half die angle direction, the second one is τ sin β which is vertical to the radial direction. Then taking the small stress element from Figure 1, Figure 3, stress state for elements in z and r directions, can be seen. The force balance equations along the z and r directions can be derived, then combing the constant shear friction (τ = mk) and the yield criterion to obtain the governing equations. Moreover, the boundary conditions at the entrance are used to get a lot of formula shown in Table 1. Figure 4 shows the flow stress of workpiece material. The compression of cylinder has been done to get the engineering stress and strain, then using the formula between true stress-strain and engineering stress-strain to obtain the true stress and strain. Furthermore the power law can be used to do the curve fitting to get the strength coefficient C, 832.233 MPa, and the strain hardening index n, 0.382.
Figure 1. Schematic diagram of wire rod drawing process using the rotating die.

Figure 2. Frictional shear stress orientation on the wire rod.

Figure 3. Stress state for elements in z and r directions.
Table 1. Forming characteristics derived from the slab method.

| Forming property                  | Formula                                                                 |
|-----------------------------------|--------------------------------------------------------------------------|
| Axial stress                       | $\sigma_z = [Y + mk \cos \beta (\tan \alpha + \cot \alpha) \left( \ln \frac{A_1}{A_2} \right) ]$ |
| Radial stress                      | $\sigma_r = \sigma_z - Y$                                                |
| Die pressure                       | $p = Y - \sigma_z + mk \cos \beta \tan \alpha$                          |
| Drawing force (without shear stress) | $P = A_1[Y + mk \cos \beta (\tan \alpha + \cot \alpha) \left( \ln \frac{A_1}{A_2} \right) ]$ |
| Drawing force (Considering shear stress) | $P_r = P + P_s = P + \frac{4\alpha}{3\sqrt{3}} YA_z$                   |
| Drawing torque                     | $M_f = \frac{2\pi mk \sin \beta}{3\tan \cdot \sin \alpha (r_1^3 - r_2^3)}$ |

(b)

| Remarks | Remarks |
|---------|---------|
| $\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0$ | $\bar{\varepsilon} = \frac{2}{\sqrt{9}} (9\varepsilon_1^2 + 9\varepsilon_2^2) = 2\varepsilon_2 = -2\varepsilon_2$ |
| $\varepsilon_2 = \varepsilon_3$, $\varepsilon_r = \varepsilon_0$ | $\bar{\sigma} = C\bar{\varepsilon}^n$ |
| $\varepsilon_1 + 2\varepsilon_2 = 0$ | $\sigma_{yp} = \frac{\bar{\sigma}}{n+1} = Y$ |
| $\varepsilon_2 = -\ln \left( \frac{D_1}{D} \right)^2 = \varepsilon_r$ | $k = \frac{1}{\sqrt{3}} \sigma_{yp}$ |
| $\bar{\varepsilon} = \frac{2}{\sqrt{9}} \left[ (\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_1)^2 + (\varepsilon_3 - \varepsilon_1)^2 \right]$ | |

Figure 4. Flow stress of workpiece material.
Figure 5. Effect of half die angle on drawing force for various frictional factors under $\beta=0^\circ$ and $\beta=35^\circ$.

Figure 5 shows effect of half die angle on drawing force for various frictional factors under $\beta=0^\circ$ and $\beta=35^\circ$. $\beta=0^\circ$ stands for the die without rotation, $\beta=35^\circ$ indicates the die with rotation. As the frictional factor is high (e.g. $m=0.3$), the drawing force is reduced under the die with rotation. And the inverse point can be shown at $\alpha=8^\circ$, this half die angle has the smallest drawing force, that is to say it is an optimum angle. As the die is rotating, the optimum angle will be getting smaller.

Figure 6. Effect of half die angle on drawing torque for various frictional factors.

As the die is rotating, the drawing torque is occurred. As the half die angle is smaller, the drawing torque is higher especially under the high frictional factor. The drawing torque decreases with increasing the half die angle, finally approaches to stable.

3. FEM simulation analysis

In this paper, the commercial software DEFORM is used to simulate the on the rotating drawing with constant shear friction. This software can provide the elastic-plastic and rigid-plastic simulation of the metal forming in large deformation. The DEFORM enables to do the tool design and product design. The DEFORM provides 3D analysis with hexagonal and the tetrahedron elements for meshing the workpiece of bulk forming and the auto re-mesh step is enveloped in the software package. Using the DEFORM, it can significantly reduce the cost and time consumption of tool and die design. The flow pattern, effective stress distribution, effective strain distribution, velocity field of workpiece and load stoke can be simulated by FEM. These simulation results can be used to obtain the product geometric profile and material properties required. In the pre-process of modeling, the geometric profile of rotating
drawing can be constructed. The rigid-plastic analysis in rotating drawing process is chosen and the material properties such as Young’s modulus, Poisson’s ratio, are needed. For the first stage of exploring the rotating drawing, the isotropic work-hardening rule is assumed in flow rule due to plastic strain hardening. The von Mises yield criterion is used. The initial conditions of workpiece are set up, and the contact along workpiece and dies are defined. The wire rod with a forward speed is 33.5 mm/sec, all rigid contact bodies are assumed as insulation, and the heat conduction phenomenon during the wire rod is neglected. In the rotating drawing with constant shear friction, the relationship between strain and stress is nonlinear. The DEFORM has been developed to resolve the nonlinear problem. The conventional von Mises yield surfaces is available in DEFORM. The contact bodies are regarded as rigid surface. With a view to simulating the rotating drawing, the forming conditions, the geometry conditions, and material conditions are shown in Table 3. The schematic diagram of FEM simulation on rotating drawing is illustrated in Figure 7.

![Figure 7. Schematic diagram of FEM simulation.](image)

The drawing die is composed of entrance, approach angle, reduction area, half die angle, bearing area, back relief angle, and exit, as shown in Figure 8.

![Figure 8. Parameters definition of cross section of drawing die.](image)

Table 2 shows the FEM simulation conditions. Since the initial diameter of the wire rod is 6.4mm, the diameter of die diameter (D₁ mm) at entrance is 6.4mm, and the die diameter (D₂ mm) at exit is 5.6mm, there are three conditions of rotating angular velocity (ω rad/sec): 0, 2.5, and 4.5, where ω =0 rad/sec means that the die does not rotate, the half die angle (α°) also has three angles 10°, 14°, 18°, and there are three frictional factor (m):0.1, 0.2, 0.3.

| Table 2. FEM simulation conditions. |
Die Conditions

| Parameter                                  | Value       |
|--------------------------------------------|-------------|
| Die Diameter (D₁ mm) at Entrance           | 6.4         |
| Die Diameter (D₂ mm) at Exit               | 5.6         |
| Rotating Angular Velocity (ω rad/sec)      | 0, 2.5, 4.5 |
| Half Die Angle (α°)                        | 10°, 14°, 18°|
| Frictional Factor (m)                      | 0.1, 0.2, 0.3|

Figure 9 shows effects of half die angle on drawing force under various frictional factors. As the frictional factor (m) is relatively small (m=0.1), the half die angle increases and the drawing force increases, but as the frictional factor (m) increases to m=0.2 or m=0.3, the drawing force produces a reverse point at 14° of the half die angle. That means the drawing force firstly decreases with an increase of half die angle before the inverse point, then after the inverse point the drawing force increases with increasing the half die angle.

![Figure 9](image.png)

**Figure 9.** Effects of half die angle on drawing force under various frictional factors.

As the frictional factor (m) increases, the torque increases, and the torque decreases with increasing the half die, as shown in Figure 10.

![Figure 10](image.png)

**Figure 10.** Effects of half die angle on drawing torque under various frictional factors.
As shown in Figure 11, the forming conditions under $m=0.3$ (no rotation, $\alpha=18^\circ$, $\omega=0$rad/sec), the maximum effective stress is 615MPa, the maximum effective strain is 0.454, mainly occurs at the reduction area of the die, and the maximum velocity is 33.5mm/sec, the velocity forwards straight along the axial direction due to no rotation.

![Figure 11. The effective stress, effective strain, velocity field under m=0.3 (no rotation, $\alpha=18^\circ$, $\omega=0$rad/sec).](image)

As shown in Figure 12, the forming conditions under $m=0.3$ (with rotation, $\alpha=18^\circ$, $\omega=2.5$rad/sec), the maximum effective stress is 571MPa, the maximum effective strain is 0.372, mainly occurs at the reduction area of the die, and the maximum velocity is 33.50mm/sec, the velocity is along the frictional angle direction.

![Figure 12. The effective stress, effective strain, velocity field under m=0.3 (with rotation, $\alpha=18^\circ$, $\omega=2.5$rad/sec).](image)

As shown in Figure 13, the forming conditions under $m=0.3$ (with rotation, $\alpha=18^\circ$, $\omega=4.5$rad/sec), the maximum effective stress is 480MPa, the maximum effective strain is 0.246, mainly occurs at the reduction area of the die and the maximum velocity is 34.5mm/sec, the velocity is along the larger frictional angle direction, the velocity is more uniform and faster that no rotation.

![Figure 13. The effective stress, effective strain, velocity field under m=0.3 (with rotation, $\alpha=18^\circ$, $\omega=4.5$rad/sec).](image)
4. Die stress analysis

Figure 14 shows the die stress under no rotation (no rotation, $\alpha=18^\circ$, $\omega=0$ rad/sec, $m=0.3$). It appears that the maximum die stress is 813 MPa, mainly occurs at reduction area of the die.

![Figure 14](image)

**Figure 14.** The die stress under no rotation (no rotation, $\alpha=18^\circ$, $\omega=0$ rad/sec, $m=0.3$).

Figure 15 shows the die stress under rotation (with rotation, $\alpha=18^\circ$, $\omega=4.5$ rad/sec, $m=0.3$). The maximum die stress with rotation is 705 MPa, it is smaller than no rotation. The position of the maximum die stress is the same as no rotation.

![Figure 15](image)

**Figure 15.** The die stress under rotation (with rotation, $\alpha=18^\circ$, $\omega=4.5$ rad/sec, $m=0.3$).

5. Comparisons of slab method and FEM simulation

As shown in Figure 16, when the half die angle is relatively small, the error between the slab method and the FEM is smaller. As the half die angle increases, the error increases, and the trends produced by the both models are similar. The drawing force obtained from the slab method is slightly higher than FEM simulation. Under $m=0.3$, the optimum half die angle (i.e. the inverse point) is around $14^\circ$, as the frictional factor is getting smaller (e.g. $m=0.1$), the optimum half die angle (i.e. the inverse point) is smaller than the high friction, around $8^\circ$. 

![Figure 16](image)
Figure 16. Drawing force comparison between slab method and FEM simulation (no rotation, \(\omega=0\) rad/sec).

Figure 17 shows drawing force comparison between slab method and FEM simulation (with rotation, \(\omega=2.5\) rad/sec). From this figure, it reveals the trends between slab method and FEM simulation, are similar, as the half die angle increases. At the inverse point (the optimum angle), 14\(^\circ\), they show the smallest drawing force, and the drawing force obtained from the slab method is higher than that obtained from the FEM simulation.

Figure 17. Drawing force comparison between slab method and FEM simulation (with rotation, \(\omega=2.5\) rad/sec).

Figure 18 illustrates drawing torque comparison between slab method and FEM simulation (with rotation, \(\omega=2.5\) rad/sec). From this figure, it reveals the trends between slab method and FEM simulation, are similar, the drawing torques decrease with increasing the half die angle. And the drawing torque obtained from the slab method is higher than that obtained from the FEM simulation.
Figure 18. Drawing torque comparison between slab method and FEM simulation (with rotation, \( \omega=2.5\text{rad/sec} \)).

6. Experiment verification

Figure 19. The wire rod shape dimension comparisons between FEM and experiment. From this figure, it reveals that the wire rod shape of FEM is an agreement with the experiment. Thus the FEM simulation can be acceptable.

Figure 19. The wire rod shape dimension comparisons between FEM and experiment.

7. Conclusions

This study proposes the slab method, FEM simulation, and experiment to successfully perform the rotating drawing of wire rod. The axial stress, the radial stress, the drawing force, and the rotating torque can be obtained from the slab method to compare with the FEM, the error between the both models is around 8-10\%. Furthermore, the realistic experiment is able to verify the acceptances of both models. Therefore, through the study due to the rotation of drawing die, the drawing force can be reduced and the flowing of wire rod is increased.

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