Process design and finite element analysis of multi-station two-roller cassette hot rolling for aluminum alloy 6061 wire

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Abstract. In this paper, a round-oval-round roller cassette wire rolling process of the aluminum alloy 6061 was studied for the process and the roller design evaluation. The elliptic groove of roller was designed for the stand of oval cross-sectional profiles. The billet diameter for this 10-stand rolling process simulation is 20mm. The diameters for the round cross-sectional profile stands are 16mm, 12.8mm, 10.2mm, 8.2mm, and 6mm, respectively. The forming conditions for the CAE simulation is 400 °C for billet temperature, 0.45 for the constant shear friction factor, 20mm/s for the initial rolling speed. The CAE (Computer Aided Engineering, CAE) results had shown the maximum dimension deviation of the billet is less than 0.25 mm at the location of the roller gap and almost perfect match at the other locations. The maximum principal stress distribution on the cross section had shown a two third area was deformed under the rolling process. The CAE results had demonstrated the proposed process and die design was able to make the smaller wire with good geometrical accuracy without breaking the wire during the rolling process because of the more uniform stress distribution at the cross section of wire.

1. Introduction
The wire drawing process uses multi-pass of drawing dies to reduce the wire diameter to a required dimension continuously. The shape of the wire cross-section is kept round for each pass. This process conducts high compression and friction stress on the wire surface, which results in a severe uneven strain distribution from the wire surface to the wire centre. The cassette wire rolling uses rollers with round or oval grooves on the circumference of roller, and two or three rollers were arranged in a cassette to reduce the wire diameter gradually. The rolling contact on the wire surface results in smaller friction stress than the wire drawing process. Kim and Im [1] had proposed an expert system for wire rolling process with five roller groove designs (round, ellipse, square, star, and trapezoid). The empirical rolling force model was used to avoid high forming load and prevent fin defects at the gap areas. Behzadipour et al. [2] proposed a shape factor and a thickness parameter to predict the power consumption of the flat and shape plates rolling. The flat rolling data were adopted to train the ANN (Artificial Neural Network, ANN) system for power consumption. The shape and the thickness parameters were added to the ANN model for shape rolling process. Bontcheva and Petzov [3] used FEM simulation to study multi-pass rolling of the square and the round rods. The different designs of the grooves geometry were adopted for the rough rolling and the finishing rolling stands. The distributions of the temperature, effective stress, and the elongation strain were examined and compared with the micro structure of the final product. Sakhaei et al. [4] used constant area reduction design for the U channel rod rolling process. The material of the bar centre was compressed to the ribs of the U shape. FEM simulations were carried out for the prediction of the spread...
out capability and compared with the experimental results. Francesco [5] had applied an expert system for the rolling process of the square and the round wires. FEM results were adopted to select and adjust the rolling process in order to reduce the pass number required. Kuroda et al. [6] had designed a prototype machine equipped with two, three, and four rollers to do the cassette rolling experiments. FEM simulations were carried out for the comparison of the final cross section precision. Fu and Yu [7] had carried out the compression and tension experiments to find the recrystallization temperature of the specimen. The rolling process was designed to avoid the occurrence of the recrystallization phenomenon and obtain more fine grain for the rolled parts. Tomba et al. [8] used gear chain to replace the universal joint of the rolling mill to avoid the joint wearing in order to reduce the requirement of constant change of joint and the preparation of spare parts. Hwang [9] had studied the heat treatment of spheroidized middle carbon steel for shaped wire rolling process. The results had prevailed the more uniform spheroidized grain could achieve higher area reduction compared with the normalized heat treatment. Milenin et al. [10] had studied the material flow characteristic of the wire rolling via the FEM simulations. The distributions of the strain and the temperature were examined for multi-pass groove rolling. Lee et al. [11] had established a shape rolling process design method based on the backward tracing step and the FEM simulation. The backward tracing step was carried with the 2D FEM simulation and the final process design was adjusted with 3D FEM simulation. The profile accuracy is able to improve to the 0.3 mm level. Laila [12] had studied forming load and the torque requirement for the different groove size and the roll gap designs. The results had shown the friction had more significant effect than the roll gap. The rolling process could be simulated via the slab method, the 2D and the 3D FEM simulations [13-15]. Different material models, heat conduction boundary conditions, the tendency of the material spread on the longitudinal and radial directions [16-18]. The distributions of the stress and the strain were evaluated to predict the defects of the forming process. The force and the torque requirement were important for the formability of the wire rolling process. Ali et al. [19] proposed 3D analytical prediction of forming roll for asymmetrical wire rolling. The diameter reduction rate and the rolling speed were taken into consideration. Aksenov et al. [20] had proposed two types of roll design, the elliptical groove and the round groove, to reduce the forming loads. The FEM simulations were carried out to obtain the suitable roll gap to improve the geometry accuracy of the rod and more uniform loads for each stand. Jin et al. [21] used 3D FEM simulation for the cassette wire rolling process design. The longitudinal strains were in the range of 0.79 to 2.38 for successful forming. The different area reduction designs affected the strain distribution and the torque requirement dramatically.

According to the above references, the wire rolling process conducts high compression and friction stress on the wire surface, that we need to design a suitable process design and roll profile design, in this paper, a two-roller cassette rolling process was investigated, which includes the roll rotational speed, area reduction ratio design of each stand for reducing the highly compression stress. The finite element analysis was adopted to evaluate the proposed process parameter and process design.

2. Cassette wire rolling process and roll designs

2.1. Rolling process design

The rolling process was carried out used an aluminum wire with 20mm in diameter to obtain the final product with 6mm in diameter. The pass number was 10 under the constant area reduction ratio 20% assumption. The wire geometry was designed with oval-round-oval profile as shown in Figure 1.

The area reduction ratio (m) and the rotation speed calculation were calculated to avoid wire broken issue and material jam from stand to stand. The cross section areas of the wire billet and the final wire product were given, say $A_0$ and $A_f$ respectively. The final area ratio, $m$, of the product to the wire billet was calculated in equation (1). Assume the area reduction ratios for each stand for were the same, $m_i$, the pass number $n$ required was calculated in equation (2).

$$m = A_f/A_0$$

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\[ m_i = \sqrt[\nu]{m} = \sqrt[\nu]{\frac{A_i}{A_0}} \quad (2) \]

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\[ V_i = 2 \cdot \pi \cdot D \cdot \text{RPM} / 60 \quad (3) \]

\[ A_i V_i = A_{i+1} V_{i+1} \quad (4) \]

2.2. Cassette roller design with two-roll arrangement

The groove shapes on the roll surface were designed with a semi-circle or a semi-ellipse according to the requirement of area reduction and the wire geometry control purpose. The dimension of the short axis (L_i) of the ellipse groove was designed to be the same of the diameter (D_{i+1}) of the next stand round groove. The diameters of the round groove were calculated according to the area reduction and the product dimension requirement (the wire diameter larger than the final dimension 6mm could be obtained if necessary). The round groove diameter of the next stand was adopted for the short axis of the elliptic groove (as shown in Figure 2) in front of the round groove stand. The long axis of the elliptic groove was calculated according to the area reduction calculation.

The rotation speed of rolls for each stand should be setup according to the area reduction ratio in order to give the wire proper dragging force and prevent the buckling of wire if the front tension of the wire is not enough and the wire was compressed in the longitudinal direction. The rolling speed \( V_i \) for the \( i^{th} \) stand with the same roll diameter \( D \), which was calculated in equation 3. The volume constancy (equation 4) should be satisfied for each stand, where \( V_i, V_{i+1}, A_i, \) and \( A_{i+1} \) are the tangent speeds and the area of the roller groove of the \( i^{th} \) and the \( i+1^{th} \) stands, respectively. The roller groove dimensions, the area ratio, and the rotation speed of the rolling process were shown in Table 1.
### Table 1. The rolling process and the roller design of the AL6061 wire rolling.

| Station Number | Long axis A (mm) | Short axis B (mm) | Area reduction ratio | Rotation speed (rpm) |
|----------------|-----------------|------------------|----------------------|----------------------|
| 0              | 20              | 20               | -                    | 12.8                 |
| 1              | 20              | 16               | 80%                  | 16.0                 |
| 2              | 16              | 16               | 80%                  | 20.0                 |
| 3              | 16              | 12.8             | 80%                  | 25.0                 |
| 4              | 12.8            | 12.8             | 80%                  | 31.4                 |
| 5              | 12.8            | 10.2             | 80%                  | 39.4                 |
| 6              | 10.2            | 8.2              | 80%                  | 49.0                 |
| 7              | 8.2             | 8.2              | 80%                  | 61.0                 |
| 8              | 8.2             | 6.2              | 73%                  | 83.2                 |
| 9              | 6.2             | 6.2              | 73%                  | 113.8                |
| 10             | 6               | 6                |                      |                      |

3. Cassette wire rolling process simulation

#### 3.1. CAE simulation model

The FEM software SIMUFACT was adopted for the forming process simulation. The billet temperature was 400°C and the flow stress model at this temperature was shown in Figure 3. The constant shear friction factor was set 0.45. The tool temperature was 20°C initial. The rotation speeds for each stand were set according to table 1 design. The CAE model shown in Figure 4 used hexagonal mesh with the mesh size 2mm in the rolling (z-) direction and 0.8 mm in the cross section (x- and y-) directions. The initial mesh number is 13,442.

![AA6061 - Flow Stress Curve (temperature 400°C)](image)

**Figure 3.** The flow stress model for AA 6061 in 400°C.

![The FEM model for the cassette wire rolling.](image)

**Figure 4.** The FEM model for the cassette wire rolling.

4. Results and discussions

#### 4.1. The maximum principal stress distribution

According to the analysis results, the proposed wire rolling process and roller design resulted in the
maximum principal stress of the wire rolling process should be in the radial (r-) direction. The maximum principal stress distribution should be able to indicate the major deformation area and the rigid areas. The maximum principal stress distributions of the section cuts in the vertical and the horizontal parallel plan with respect to the rolling direction were shown in Figure 5. In the first to the fifth stands, lower stress having an area in one third of total area. The rolling stand of the sixth to the tenth stands could deform the wire in a more uniform way. A small area of low stress remained in the center area of wire but the outer ring area is under a uniform stress distribution.

4.2. The effective strain distribution
The effective strain distributions as shown in Figure 6 could indicate the hardening area of wire after rolling process. The round-oval-round process changes the strain distribution in the vertical and the horizontal directions alternatively. The highest strain only occurs at the very small area of the relief design of the roller groove to avoid the damage of the wire surface. The strain distribution had shown the dramatic change at the entrance and the exit area of the wire. The smaller the wire diameter, the effective strain increases dramatically. The strain distribution is quite uniform on the cross-section vertical to the rolling direction, this is different to the traditional wire drawing process, which has the severe strain occurred in the wire central area.
4.3. The rolling (z-direction) stress distribution

The z-direction stress of the wire rolling process is crucial for the occurrence of the wire broken issue. The next rolling stand provides a front tension to pull the wire in the rolling direction. If the pulling force is too large due to the improper velocity setup or the area reduction design, the wire diameter might be decreased further and results in a higher tensile stress which could break the wire. The z-direction stress distributions shown in Figure 7 indicate the roller contact areas could give pulling force (positive) stress, but the center areas give negative stress and slow down the material flow at this region. The wire surface at the entrance of the roll also gives negative z-direction stress because the tangent velocity of the roller is smaller than the wire rolling velocity and the wire was pushed away from roller at this area. The maximum z-stress is less than the yield stress of the wire and no broken issue occurred.

Figure 6a. The effective plastic strain distribution of stand 1-5.

Figure 6b. The effective plastic strain distribution of stand 6-10.
Figure 7a. The rolling (z-) direction stress distribution of stand 1-5.

Figure 7b. The rolling (z-) direction stress distribution of stand 6-10.

4.4. Torque and pulling force
The torque required for each stand should be considered to guarantee the driving power of the rolling mill is enough to pull the wire through the rollers. The wire length of the simulation is equal to double of the stand distance. The torque of the first stand was shown in Figure 8 which gives a maximum value of 128 N-m. The other stands show the similar torque tendency but different maximum torque value. The required maximum torques of stand 1 to 10 were shown in Table 2. The highest torque of the rolling mill is at the first stand which plays the main role of pulling wire into the mill. The resistance force of the wire for the first stand was shown in Figure 9. The maximum back force of the wire is less than 1kN. The mean tensile stress of the wire is less than 10 MPa which is not possible to cause wire broken issue.
Figure 8. The torque history of the first stand.

Table 2. The rolling torque required for the ten-stand rolling mill.

| Stand | Torque (N·m) |
|-------|-------------|
| 1     | 128         |
| 2     | 116         |
| 3     | 108         |
| 4     | 96          |
| 5     | 72          |
| 6     | 70          |
| 7     | 60          |
| 8     | 58          |
| 9     | 43          |
| 10    | 31          |

Figure 9. The z-direction force of the first stand.

4.5. Product geometry inspection
After completing the CAE simulation, the deformed wire piece was exported as a STL model, then the STL file was imported into the GOM Inspect Suite for geometrical inspection. The deformed wire was compared with the desired wire geometry, and the deviation was illustrated in Figure 10. The maximum deviation of the wire is 0.25mm at the roller relief area. The profile of the wire surface should be good enough for the wire rolling surface descaling process which could of more than 0.3mm of the hot rolled wire. The wire drawing pass could be used to resize the wire and obtain sound roundness of wire for the following forming applications.
5. Conclusions
The process and roll design for the round-oval-round roller cassette wire rolling process of the aluminum alloy 6061 was proposed. The maximum stress distribution had shown the forming process is able to obtain a uniform stress distribution at the exit of the final stand. The effective plastic strain distribution is quite uniform on the cross-section vertical to the rolling direction, this is different to the traditional wire drawing process. The maximum deviation of the wire diameter is 0.25mm which occurs at the roller relief area. The wire drawing might be required to obtain an acceptable roundness wire.

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