Analysis of Surface Roughness of Cold Roll-Beating Tooth

Limu Cui*, Yan Li, Xuefeng Wang, Xuedong Chen, Mingshun Yang
Xi’an University of Technology, Xi’an, 710048, China

*Corresponding author e-mail: cuilimu@163.com

Abstract. Surface roughness is a key measurement index of the surface quality of the cold roll-beating forming rack, which directly affects the contact conditions, fatigue strength, wear resistance and corrosion resistance of the gear parts when engaging. In view of the surface quality problem of cold roll-beating forming rack, the influence of the process parameters on the surface roughness of the tooth wall is analyzed, and the mathematical calculation model of surface roughness is established. The forming test is carried out on the self-designed cold roll-beating equipment to measure the roughness of the sidewall of the forming rack, and the correctness of the calculation model is verified.

1. Introduction
The high-speed cold roll-beating technology is a partial loaded precision plastic forming method that utilizes the characteristics of metal plastic forming, which uses a rolling wheel to roll and hit the workpiece, forcing the metal to flow to form a part profile. Compared with traditional plastic processing, cold roll-beating has the advantages of small load, low energy consumption and good flexibility, and it has broad application in the field of plastic chipless processing [1-3]. The surface formed by the cold roll-beating technology not only makes the workpiece have a flow line distribution, at the same time, the strengthened surface layer can be retained, but also improves the utilization of the workpiece material and the mechanical properties of the functional surface, also improves processing efficiency, high processing precision and high material utilization [4-10].

During the research, there were some unavoidable defects in the cold roll-beating forming process, such as folding wrinkles, insufficient forming, flanging, scratches, etc., which had a certain influence on the surface of the forming part [11-13]. The tooth wall is the main functional surface for the bonding of the tooth parts. The surface quality determines the performance. The residual height of the tooth surface after rolling is the main geometric factor in the surface quality, which is directly related to the friction, vibration, noise, fatigue, sealing, mating properties, corrosion resistance, electrical conductivity, thermal conductivity and reflective properties and wear of the tooth surface [14]. However, the current research on cold roll-beating mainly focuses on the rolling force, motion analysis and simulation of the forming process. The research on the surface quality of cold rolling is limited to the experimental stage, and the mathematical geometry analytical and microscopic analysis on the cold rolling surface quality are also not deeply involved. In order to improve the surface quality of cold roll-beating forming technology, based on the basic principle of cold roll-beating technology, the cause of the residual height of the side of the tooth rolled is researched, and mathematical modeling to
calculate the surface of the cold rolled forming part is established. It has guiding significance for improving the surface quality of cold roll forming parts and for practical engineering applications.

2. High-speed cold-roll beating technology principle
Cold roll-beating is a new near forming method, the use of metal in the cold state has a certain plastic deformation ability, using a certain shape of the rolling wheel to continuously rotate and roll the surface of the workpiece, thereby forcing the surface metal to flow locally, resulting in plastic deformation, the relative motion relationship between the rolling wheel and the workpiece, the local motions that accumulate local deformation into the final desired functional surface. Since the rolling wheel is eccentrically mounted on the rolling shaft, the rolling wheel is not always in contact with the workpiece, and the time of rolling the workpiece only accounts for a small portion of the rotation of the rolling wheel around the high-speed rotating shaft, the rest of the time, the rolling wheel rotates around the rotating shaft free rotating.

Since the cold roll-beating is a gap motion, the residual height Δh occurs at the intersection of the rolling deformation, and the z′o′y′ coordinate system is established. The geometric center of the rolling wheel is the origin of the coordinate system, and the rolling wheel is shown in the figure. A rolling wheel formed by a linear segment line connecting the straight-line AB, the circular arc BC, and the straight-line CD around the y-axis. The coordinates of each point in the figure: A(19.53,2.99), B(23.54,0.83), C(24,0.17), D(24,0), P(23.3,0.17).

The equation for line AB is:

\[ 2.16z′ + 4.01y′ = 54.1747 \quad z′ ∈ [19.53,23.54] \] (1)

Since the straight line AB of the rolling wheel rotates around the y′ axis and forms a tooth wall with the workpiece, and the rolling depth is 0.5 mm or more, in order to simplify the calculation model, the straight-line AB segment is taken as the research focus. The space coordinate system is established,
the rolling depth direction is the \( z' \) axis positive direction, and the workpiece feed direction to the right is the \( x' \) axis positive direction. According to the right hand Cartesian criterion, the \( y' \) axis positive direction is the tooth wall direction, as shown in Fig.3.

![Figure 3. Rolling coordinate system](image)

The equation for the rotation of the straight-line \( AB \) around the axis \( y' \) is:

\[
2.16\sqrt{x'^2 + z'^2} + 4.01y' = 54.1747
\]  

(2)

The center of revolution is fixed when it is rolling, and the coordinate position of the geometric center of the rolling wheel relative to the center of the common rotation is used for \( \alpha \) description. The position of the rotation center is used \( \theta \) at any time. The angle is starting line with the side of the point of entry and the final position. The radius of the rolling wheel is \( r=24 \), the radius of gyration of the center of rotation is \( R=49 \), the revolution speed of the rolling is \( \omega \) (r/min), the feed speed of the workpiece is \( v_f \) (mm/s), and the depth of the rolling is \( h \) (mm). Shift the origin \( O' \) of the axis to the point \( O \), as shown in Fig. 4.

![Figure 4. Coordinate transformation of cold-roll beating](image)

When the rolling wheel rotates to a certain position, the angle is \( \theta \) (\( \theta \in (0, \pi) \)), and the coordinate conversion formula of the coordinate system \( O' \) and the coordinate system \( O \) is:

\[
\begin{align*}
  x' &= x + R \cos \theta \\
  z' &= z - R \sin \theta \\
  y' &= y
\end{align*}
\]  

(3)

The side rotation equation of the rolling wheel based on the coordinate system \( O \) is:
During the cold rolling-beating forming process, the rolling wheel rotates at a high speed $\omega$, and the workpiece moves horizontally at a uniform speed $v_f$. After the rolling wheel contacting the workpiece, the deformation trajectory can be regarded as the rotation of the rolling wheel, and the edge moves in the opposite direction of the feeding direction of the workpiece. The positional relationship between the wheel and the workpiece is shown in Fig. 5.

\[
2.16\sqrt{(x+R \cos \theta)^2 + (z-R \sin \theta)^2} + 4.01y = 54.1747
\]  

\[ (4) \]

In the above formula, $n$ is the number of rolling wheels, and $n=3$.

The angle formed by the rolling wheel when it first contacts the workpiece is:

\[
\theta = \arcsin \frac{R + r - h}{R + r}
\]

\[ (6) \]

### 3. Residual height calculation with down beating

Since the contact between the rolling wheel and the workpiece is discontinuous, the mutual position changes momentarily, and the contact trajectory is an arc. During the period of time when the rolling wheel leaves the workpiece firstly, the workpiece continues to move forward. The rolling wheel rotates counterclockwise at the revolution speed of $\omega$, and the horizontal feed speed $v_f$ of the workpiece moves to the right. Assuming that the workpiece does not move, the rolling wheel is rotated counterclockwise while it is moving at a speed $v_f$. Regardless of the influence of the strain rate, and the trajectory formed by the two hitting workpieces intersects. Because the projection point of the trajectory intersection point of the side track on the $xoz$ plane and the trajectory of the bottom track are on a same projection line. For the convenience of calculation, set the angle of the first rolling to be $\theta_1$, and the angle of the second roll to $\theta_2$, as shown in Fig. 6.
Figure 6. The process of down-beating

\[ y' = \frac{54.1747 - 2.16 \times (r - h)}{4.01} \]  

(7)

The curved surface of the first rolling contact formed on the contour surface increases \( y' \cdot t1 \) in the \( x \)-axis direction, and

\[ t1 = \frac{\theta - \theta1}{2 \pi \omega} = \frac{30 \times (\theta - \theta1)}{\pi \omega} \]  

(8)

Substituting equation (2)

\[ 2.16 \sqrt{(x + R \cos \theta1 + v_y \cdot t1) + (R + r - h - R \sin \theta1)} + 4.01y = 54.1747 \]  

(9)

The second beating process of the rolling wheel is relative to the first time, the main change is that the workpiece rotates to the right at the \( y' \) level. If the workpiece is not moved, the rotation center coordinate of the rolling wheel has a left lateral movement. The change of distance is \( y' \cdot \Delta t \) in the direction of \( x \). Therefore, the coordinate change of the revolution center of the rolling wheel is \( (y' \cdot \Delta t, 0, 0) \), and it is substituted into equation (4)

\[ t2 = \frac{\theta - \theta1}{2 \pi \omega} = \frac{30 \times (\theta - \theta1)}{\pi \omega} \]  

(10)

\[ 2.16 \sqrt{(x + R \cos \theta + v_y \cdot t2 + v_y \times \Delta t) + (R + r - h - R \sin \theta)} + 4.01y = 54.1747 \]  

(11)

The curve which the equation (9) and (11) cut by equation \( z=R+r-h \) which is the projection of the two rolling trajectories on the \( xoy \) plane, and \( z=R+r-h \) is substituted into the equation (9). Equation (11) and parallel solution.

\[
\begin{aligned}
&2.16 \sqrt{(x + R \cos \theta1 + v_y \cdot t1) + (R + r - h - R \sin \theta1)} + 4.01y = 54.1747 \\
&2.16 \sqrt{(x + R \cos \theta + v_y \cdot t2 + v_y \times \Delta t) + (R + r - h - R \sin \theta)} + 4.01y = 54.1747
\end{aligned}
\]  

(12)
In Fig. 6, $E$ is the intersection of the two rolling trajectories at the bottom, and in the isosceles triangle, $\theta_1 + \theta_2 = \pi$, $\theta_2 > \theta_1$, so.

$$\cos \theta = \frac{v \Delta M/2}{R + r} = \frac{30v}{(R + r)\omega}$$  \hspace{1cm} (13)

$$\cos \theta = \frac{v \Delta M/2}{R + r} = -\frac{30v}{(R + r)\omega}$$  \hspace{1cm} (14)

The simultaneous (5) to (12), using MATLAB programming, the equation $y$ value. Solve the equation of the straight-line AB when $z = r - h$. Then the residual height $\Delta h \text{ (\mu m)}$ of the tooth wall is.

$$\Delta h = 1000 \times \left[ \frac{5.1747 - 2.16 \times (r - h)}{4.01} \right]$$  \hspace{1cm} (15)

The equation solves with MATLAB, and the roller wheel parameters $R=49 \text{ mm}$, $r=24 \text{ mm}$ are substituted, then calculating the residual height $\Delta h$ of the low speed section ($0 \leq \omega \leq 1000$) when $h=2 \text{ mm}$. The influence of the rotation and feed speed on the surface roughness of the contour, as shown in Fig. 7, and using MATLAB software to fit the factors affecting surface roughness, the degree of influence of the rotation and the feed speed on the surface roughness is obtained. Fitting curve and simulation for $h=3$ as shown in Fig. 8.

![Figure 7](image-url)  
**Figure 7.** Fitting curve and simulation for $h=2$

![Figure 8](image-url)  
**Figure 8.** Fitting curve and simulation for $h=3$

4. Test verification

In order to verify the correctness of the geometric analysis, the workpiece copper was rolled on the self-developed equipment. The material of the rolling wheel was 40Cr, the rolling equipment, the rolling wheel and the test piece are shown in Fig. 9. After the rolling test under different parameters, the test piece is cleaned by a wire cutting length 10 mm, width 6 mm, and height 10 mm, shown in Fig.
10. The side of the rolling block is measured with a TR200 roughness meter, and the maximum height $R_z$ of the contour is selected. Evaluation parameters, sampling length 0.08 mm, test parameters and measurement results are shown in Tab. 1.

![Rolling equipment](image1)
(a) Rolling equipment

![Rolling wheel](image2)
(b) Rolling wheel

![Rolling forming parts](image3)
(c) Rolling forming parts

**Figure 9.** Rolling equipment and forming parts

![Test piece](image4)

**Figure 10.** Test piece

| Serial number | Rolling depth /mm | Rotating speed /(r/min) | Feed rate /(mm/min) | Test value /(HV) | Calculated /(HV) | Error ratio |
|---------------|-------------------|-------------------------|---------------------|------------------|------------------|-------------|
| 1             | 2                 | 500                     | 4                   | 0.027            | 0.024371911     | 10.8%       |
| 2             | 2                 | 1500                    | 4                   | 0.003            | 0.002703989     | 11.1%       |
| 3             | 2                 | 1500                    | 8                   | 0.011            | 0.010823955     | 10%         |
| 4             | 3                 | 500                     | 4                   | 0.028            | 0.024777749     | 13.4%       |

5. Conclusion

(1) When the rolling depth and feed speed are given, the residual height becomes smaller as the rotation speed increases, and the geometric quality of the tooth wall surface increases; when the rolling depth and the rotation speed are given, the residual height increases with the feed speed. When it becomes larger, the surface geometry quality decreases; when the feed speed and the rotation speed are given, as the rolling depth increases, the residual height becomes larger and the surface geometric quality decreases.

(2) Relevant parameter tests are carried out on the self-developed equipment and measured. The difference between the test value and the calculated value does not exceed 15%, which verifies the correctness of the geometric analysis and the accuracy and reliability of the high-speed cold roll-beating technology.

Acknowledgements

The authors would like to acknowledge the National Natural Science Foundation of China [Grant No. 51475366, 51475146], Science & Technology Planning Project of Shaanxi Province [Grant No. 2016JM5074].

References

[1] Hongyu XU, Yanyi HUANG, Yuhui LIU, et al. Experimental study on hardening of high speed cold roll-beating formation, 2017 5th International Conference on Machinery, Materials and Computing Technology, vol.6, 2017.

[2] Fengkui CUI, Xiaqiang WANG, Fengshou ZHANG, et al. Metal flowing of involute spline cold roll-beating forming, Chinese Journal of Mechanical Engineering, vol.26, no. 5, pp.
[3] Mingshun YANG, Qilong YUAN, Yan LI, et al. Deformation Force Simulation of Lead Screw Cold Roll-beating. Procedia Engineering, vol.15, 2011.

[4] Fengshou ZHANG, Zhen FENG, Fengkui CUI. Study on residual stress generated during high-speed cold-rolling beat. Mining & Processing Equipment, vol. 42, no. 6, pp.111-115, 2014.

[5] S Y HAN, K B SONG. Development of a High-Speed Cold Rolling Oil with Mill Cleanness Property. Isij International, vol.38, no.4, pp.366-370, 2007.

[6] Fengkui CUI, Su Y, Xie Kege, et al. Analysis of Metal Flow Behavior and Residual Stress Formation of Complex Functional Profiles under High-Speed Cold Roll-Beating. Advances in Materials Science & Engineering, vol.28, pp. 1-10, 2018.

[7] Jiang ZHANG, Lin ZHU, Xiangyu GAO, et al. Residual stress analysis on bonding interface for cold-rolled copper / aluminum composite plate. Forging & Stamping Technology, vol.41, no.2, pp. 30-34, 2016.

[8] Shangsheng WU, Zhongming YU. Cold Rolling Process and Numerical Simulation of Residual Stress for Flexspline of Harmonic Reducer. Journal of South China University of Technology, vol.45, no.2, pp. 52-58, 2017.

[9] ZH DING, FK CUI, YB LIU, et al. A Model of Surface Residual Stress Distribution of Cold Rolling Spline. Mathematical Problems in Engineering, vol.4, pp. 1-21, 2017.

[10] Lu ZHANG, Yan LI, Mingshun YANG, et al. Study on metal flowing of lead screw cold roll-beating forming. China Mechanical Engineering, vol.23, no.13, pp. 1623-1628, 2012.

[11] Mehner T, Bauer A, Härtel S, et al. Residual-stress evolution of cold-rolled DC04 steel sheets for different initial stress states. Finite Elements in Analysis & Design, vol.144, pp.76-83, 2018.

[12] Guiyun JIANG, Yongqin WANG, Xinchun YAN. Analysis on solution of residual stress for cold rolling strip. Journal of Iron & Steel Research, vol. 22, no. 3, pp. 16-18, 2010.

[13] Xueqi HUANG, Haiwei XU, Peng LIU, et al. Cause Analysis of Residual Iron Oxide Scale on Cold Rolled Strip Surface. Hot Working Technology, vol. 44, no. 1, pp. 241-244, 2015.

[14] Mingshun YANG, Yan LI, Qinglong YUAN, et al. Theoretical analysis and experimental study on stripe of slab cold roll-beating. Mechanical Science and Technology for Aerospace Engineering, vol.32, no. 9, pp. 1363-1367, 2013.