ELSEVIER

Journal of Materials Processing Technology 187–188 (2007) 743–746

Journal of Materials Processing Technology

www.elsevier.com/locate/jmatprotec

Research on following motion rule of guide roller in cold rolling groove ball ring

L. Hua[a,b,*], Z.J. Zuo[a], J. Lan[b], D.S. Qian[b]

[a] *School of Automobile Engineering, Wuhan University of Technology, Wuhan 430070, China*
[b] *School of Materials Science and Engineering, Wuhan University of Technology, Wuhan 430070, China*

Abstract

Based on the actual working condition of a vertical cold ring-rolling mill rolling a groove ball ring, a mathematical model for the following guide roller motion is established. The variation of growth of the ring outer radius is analyzed and the guide roller motion is investigated. A system for guide roller motion design is obtained, on which a Matlab program is coded to get the required system parameters. Accurately controlling the guide roller motion may improve the precision of cold ring-rolling components. The model can be also used to guide the design of cold ring-rolling mill.

Keywords: Cold ring-rolling; Guide roller; Motion rule

1. Introduction

Because of the economic advantages of cold ring-rolling, it is a preferred manufacturing technology for many types of seamless rings [1]. The widest application of cold ring-rolling is the manufacture of inner and outer bearing races. In the past study, most of research attention was paid to feed speed, tooling design and ingot layout of ring-rolling process, and much less was paid to the research of movement of guide roller. Refs. [2–5] researched two guide rollers with following movement by FEM simulation. Refs. [6] investigated the role of a fixed guide roller in hot ring-rolling. On author's knowledge, there are no relevant published reports researching cold ring-rolling machines with a single guide roller with following motion. In this paper, taking cold ring-rolling of groove ball ring as an example, the following motion of single guide roller of a cold ring-rolling mill is researched. Variation of rotation speed and rotation acceleration of guide roller is deduced, providing a theoretic foundation for the design of guide roller and its motion for a ring-rolling machine in the future.

2. Following motion rule of guide roller

2.1. The motion track of guide roller center

As shown in Fig. 1, the ring was amounted between the active rotating driving roller and the mandrel. The rotation of the mandrel is passive but its feed motion is active. The guide roller, fixed on a frame the center of which coincides with that of the driving roller, can rotate either around the driving roller center or around the axis of its own. At the one end of frame, a hydraulic cylinder produces a pressure P that makes the guide roller to keep contact with the ring.

For the convenience of analysis, a coordination system, taking the center of driver roller as the coordinate center, is established as shown in Fig. 2. The initial position and the final position of the guide roller center is point O_1 and O_{1e}, respectively. The motion track of the guide roller center is an arc of O_1O_{1e} with a fixed radius of R_m. Therefore, the motion track can be expressed by the following equation:

$$x^2 + y^2 = R_m^2 \qquad (1)$$

Initial and final positions of guide roller center and the motion track radius R_m are to be deduced in the following.

Referring to Fig. 2, the coordination of (X_{o1}, Y_{o1}) can be expressed as

$$X_{o1} = -(R_g + R_{oi})\sin\theta + (R_d + R_{oi}) \qquad (2)$$

---

[*] Corresponding author at: School of Materials Science and Engineering, Wuhan University of Technology, Wuhan 430070, China.
Tel.: +86 27 87168391; fax: +86 27 87168391.
E-mail address: lhuasvs@yahoo.com.cn (L. Hua).

0924-0136/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmatprotec.2006.11.044

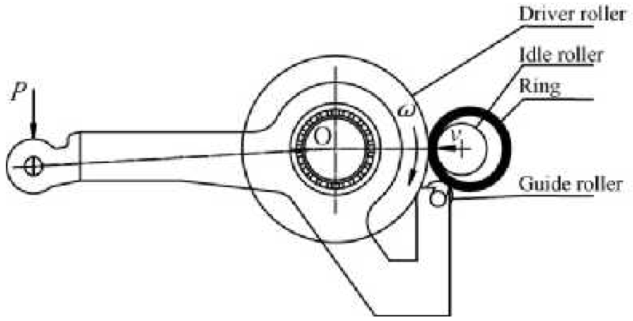

Fig. 1. Schematic diagram of cold ring-rolling mill with single following guide roller.

$$Y_{o1} = (R_g + R_{oi})\cos\theta \tag{3}$$

From Eqs. (2) and (3), the radius of motion track of guide roller center is

$$R_m = \sqrt{X_{o1}^2 + Y_{o1}^2} \tag{4}$$

The coordination of final position of the guide roller center can be defined as following:

$$Y_{o1e} = \frac{2\sqrt{p(p-a)(p-b)(p-c)}}{a} \tag{5}$$

$$X_{o1e} = \sqrt{R_m^2 - X_{o1e}^2} \tag{6}$$

where $a = R_d + R_{oe}$, $b = R_g + R_{oe}$, $c = R_m$, $p = (a + b + c)/2$. Thus, the motion track of the guide roller center is an arc with radius R_m, started from point (X_{o1}, Y_{o1}) and ended at point (X_{ole}, Y_{ole}), centered at point O (refer to Fig. 2).

2.2. Rotation of guide roller center

In actual rolling process, the guide roller is required keeping contact with the outer surface of the ring. This is realized through the pressure P applied on guide roller frame (refer to Fig. 1). Therefore, the motion of the center of guide roller is required to be consistent with the growth speed of ring outer radius. If the ring ingot has initial width T_i and radial thickness $H_i = R_{oi} - R_{ii}$, its volume V_0 is

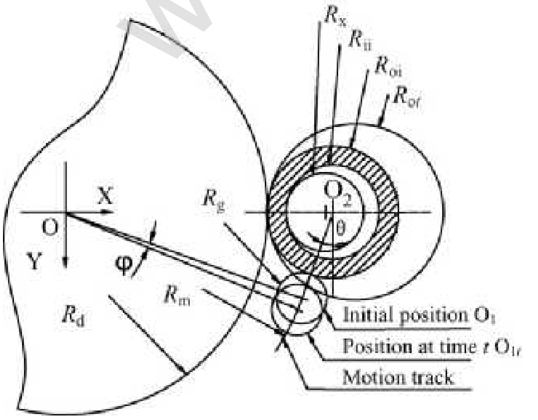

Fig. 2. Geometry relationship of cold ring-rolling at time t.

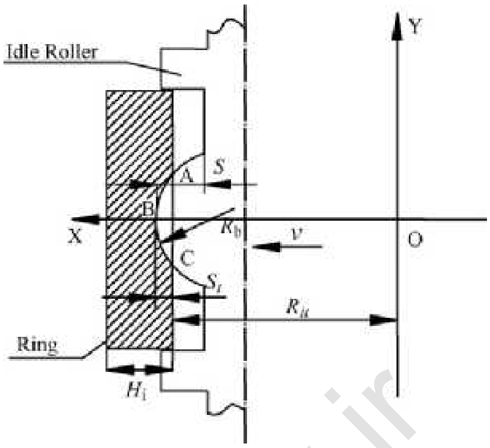

Fig. 3. Cross-section variation in ball ring-rolling.

$$V_0 = \pi(R_{oi}^2 - R_{ii}^2)T_i \tag{7}$$

2.2.1. Radius variation of groove ball ring

It assumes that there is no width spread, the volume is invariable and the ring always keeps being circular during rolling process. When rolling a groove ball ring, the ball part of the mandrel contacts ring inner surface first, and then the groove ball is pressed into the ring (shown in Fig. 3). After the groove ball is pressed into the ring completely, the groove bottom of the mandrel roller begins to contact ring inner radial surface till the end of the rolling. Therefore, the analysis of the ring radius variation should be divided into two steps.

(1) When the groove ball does not press into the ring completely, the feed stroke of the mandrel S_t is less than the height of the ball S (refer to Fig. 3). It is assumed that the radial thickness of the ring keeps constant during this stage. When the feed speed of mandrel roller is v, the feed stroke at time t is $S_t = vt$. The feed makes the ball groove to be formed and ring to be enlarged. The volume of the ball groove can be obtained by turning the section, composed of arc ABC and line segment AC, around the ring axis.

Taking the ring center as a sub-coordination center, the curve equation of arc ABC is

$$(x - A_1)^2 + y^2 = R_b^2 \tag{8}$$

where $A_1 = R_{it} + S_t - R_b$, R_{it} is the ring inner radius at time t and R_b is the Groove ball radius. Thus, the volume of the section turning around Y-axis is

$$V_{1t} = 2\pi((2C_1B_1 + Q_1)R_{it} + B_1C_1^2 + Q_1C_1 + P_1) \tag{9}$$

where

$$B_1 = \sqrt{2R_bS_t - S_t^2}, \quad Q_1 = B_1\sqrt{R_b^2 - B_1^2} + R_b^2\,\mathrm{arctg}(B_1/\sqrt{R_b^2 - B_1^2}), \quad P_1 = R_b^2B_1 - B_1^3/3$$

and $C_1 = S_i - R_b$.

By following equations, the ring inner radius R_{it} and outer radius R_{ot} at time t can be known, respectively:

$$R_{it} = \frac{V_0 + N_1}{M_1} \tag{10}$$

$$R_{ot} = \frac{V_0 + N_1}{M_1} + H_{it} \tag{11}$$

where $M_1 = 2\pi(T_i H_{it} - (2C_1B_1 + Q_1))$ and $N_1 = B_1C_1^2 + Q_1C_1 + P_1 - \pi T_i H_{it}^2$.

(2) When the groove ball presses into the ring completely, the feed stroke of the mandrel roller S_t is larger than the height of the ball S. The ring thickness reduces with the feed of the mandrel roller. Therefore, the ring thickness H_{it} at this stage is

$$H_{it} = H_i - vt + S \tag{12}$$

Let

$$A_2 = R_{it} + S - R_b$$

then the volume of groove ball section at time t is

$$V_{2t} = 2\pi((2C_2B_2 + Q_2)R_{it} + B_2C_2^2 + Q_2C_2 + P_2) \tag{13}$$

where

$$B_2 = \sqrt{2R_bS - S^2}, \quad Q_2 = B_2\sqrt{R_b^2 - B_2^2} + R_b^2 \,\mathrm{arctg}(B_2/\sqrt{R_b^2 - B_2^2}), \quad P_2 = R_b^2B_2 - B_2^3/3 \quad \text{and} \quad C_2 = S - R_b.$$

The inner radius R_{it} and outer radius R_{ot} of the ring at this stage can be obtained, respectively, by following equations:

$$R_{it} = \frac{V_0 + N_2}{M_2} \tag{14}$$

$$R_{ot} = \frac{V_0 + N_2}{M_2} + H_{it} \tag{15}$$

where $M_2 = 2\pi(T_i H_{it} - (2C_2B_2 + Q_2))$ and $N_2 = B_2C_2^2 + Q_2C_2 + P_2 - \pi T_i H_{it}^2$.

2.2.2. *Rotation speed and rotation acceleration of guide roller center*

The ring outer radius R_{ot} at time t can be derived from Eqs. (11) and (15). According to the geometric relationship in Fig. 2, the coordination of guide roller center at time t (X_{o1t}, Y_{o1t}) can be got by Helen formula:

$$Y_{o1t} = \frac{2\sqrt{p(p-a)(p-b)(p-c)}}{a} \tag{16}$$

$$X_{o1t} = \sqrt{R_m^2 - Y_{o1t}^2} \tag{17}$$

where $a = R_d + R_{ot}$, $b = R_g + R_{ot}$, $c = R_m$ and $p = (a + b + c)/2$. By using the obtained the coordination of guide roller center, the length L of arc OO_{1t} can be obtained by the following equation:

$$L = \varphi R_m \tag{18}$$

where $\varphi = 2\arcsin(\sqrt{(X_{o1} - X_{o1t})^2 + (Y_{o1} - Y_{o1t})^2}/(2R_m))$.

The rotation speed of guide roller center can be got from the first-order differential of φ with respect time t. The rotation acceleration of guide roller center can be computed by the second-order differential of φ with respect time t:

$$\omega = \frac{d\varphi}{dt} \tag{19}$$

$$\varepsilon = \frac{d^2\varphi}{dt^2} \tag{20}$$

It is too difficult to express both rotation speed and acceleration of guide roller center as a function of time and geometric parameters analytically; numerical analysis method should be used. A Matlab code is programmed based on above analysis. By using the program, a relationship between rotation speed (or rotation acceleration) and other process parameters during the process of ring-rolling can be obtained easily. It is significant for the design of cold ring-rolling machines and the control of process parameters.

3. Calculation, results and discussions

Take the cold ring-rolling of a specific bear outer race as an example. The involved rolling parameters are as follows: $R_d = 103.61$ mm, $R_{oi} = 33.75$ mm, $R_b = 9.00$ mm, $S = 2.70$ mm, $R_{ii} = 24.00$ mm, $R_g = 13.00$ mm, $\theta = 20°$, $T_i = 23.10$ mm, $v = 0.45$ mm/s and $t = 10.25$ s. Inputting above data into the self-coded program by Matlab, the rotation speed and acceleration of guide roller center are shown in Fig. 4. Relationship between rotation speed and acceleration of guide roller and its radius are shown in Fig. 5.

From Fig. 4, the rotation speed and acceleration of the guide roller center increase with time t. Attention should be paid to the fact that if rotation speed and acceleration are too large, the impact of the guide roller to the ring may occur during rolling process due to inertia force. Impacts can cause vibration of the ring, decreasing the stability of the rolling process, and in some serious condition it may crush the process, leading to failure of the process. Therefore, in the allowable range of feed speed and capability of equipment, decreasing feed speed is beneficial for the stability of rolling process because it can decrease the rotation speed and acceleration of the guide roller center, and thus decrease the impact on the ring and enhance circularity of the ring product. At the same time, after the groove ball entered into the ring completely, there is an interruption in both the rotation speed and the acceleration. When the groove bottom of mandrel roller contacts the ring inner surface, the deformation of the ring and the growth velocity of the ring outer radius increase suddenly because of the increase of the contact area, resulting in the interruption of both the rotation speed and acceleration. In this condition, decreasing feed speed is useful to decrease the interruption. From Fig. 5, at fixed time ($t = 8$ s), if the guide roller radius increases from 10 to 20 mm, although the rotation speed

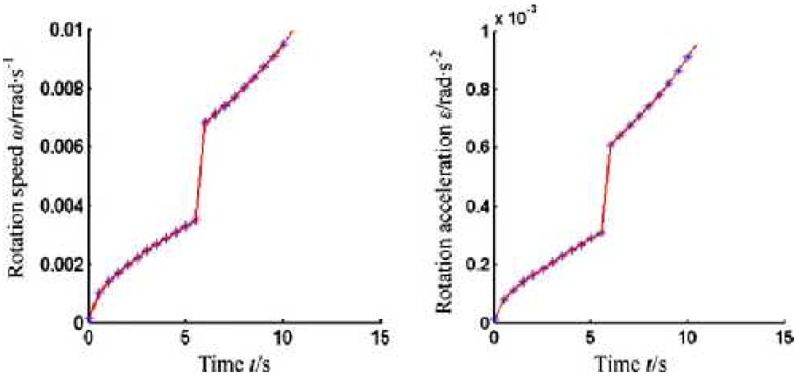

Fig. 4. Rotation speed and acceleration of guide roller center when rolling groove ball ring.

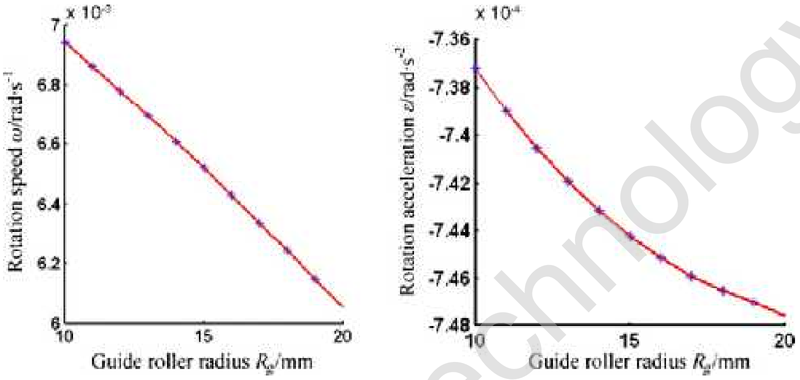

Fig. 5. Relationship between rotation speed and acceleration of guide roller center and its radius when rolling groove ball ring.

of guide roller center decreases from 6.95 to 6.04 rad/s, and the absolute value of the rotation acceleration of the guide roller center increases. Therefore, decreasing the guide roller radius is advantage to smooth the ring-rolling process and enhance the quality of ring product.

4. Conclusion

1. An analytic solution of ring outer radius growth rate is obtained for cold rolling groove ball ring product. The result can be used to predict the ring out radius and provide a theoretic foundation for on-line product measurement and inspection of ring product quality.
2. Formulations for rotation speed and acceleration of guide roller center are analyzed for rolling groove ball ring products. Based on this main factors that affect the speed and acceleration of guide roller center are discussed; these include feed speed and the geometry of the guide roller. This analysis provides a foundation for controlling the motion of guide roller, enhancing the stability of ring-rolling process and improving the ring product quality.
3. In the allowed range of feed speed and capability of equipment, decreasing feed speed is an advantage for the stability of ring-rolling process.
4. At constant feed speed, decreasing the guide roller radius is an advantage to decrease rotation acceleration of guide roller center so that inertia impact of the guide roller on the ring during rolling process can be decreased.

Acknowledgement

The authors would like to thank the support of National Natural Science Foundation of China Key Project (No. 50335060).

References

[1] L. Hua, X.G. Huang, C.D. Zhu, Ring Rolling Theory and Technology, Mechanical Industry Press, Beijing, 2001.
[2] S.G. Xu, J.C. Lian, Simulation of ring rolling using a coupled thermal rigid-plastic finite element model, Chin. J. Mech. Eng. 30 (1994) 87–92.
[3] M.R. Forouzan, M. Salimi, M.S. Gadala, A.A. Aljawi, Guide roll simulation in FE analysis of ring rolling, J. Mater. Process. Technol. 142 (2003) 213–223.
[4] U. Hiroshi, S. Yoshihiro, S. Tomoaki, T. Ichiro, Elastic–plastic finite element analysis of cold ring rolling process, J. Mater. Process. Technol. 125/126 (2002) 613–618.
[5] L.G. Guo, H. Yang, M. Zhan, Simulation for guide roll in 3D-FE analysis of cold ring rolling, Mater. Sci. Forum 471/472 (2004) 760–764.
[6] L. Zhou, Simulation and control of ring rolling, Master Thesis, Wuhan University of Technology, Wuhan, Hubei, China, 2004.