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Analysis of plastic penetration in process of groove ball-section ring rolling

L. Hua*, D. S. Qian and L. B. Pan

School of Materials Science and Engineering, Wuhan University of Technology, No.122 Luo Shi Road, Wuhan, 430070, China

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Abstract

Plastic penetration is a necessary condition of ring rolling forming. In this paper, based on the principle of groove ball-section ring rolling and characteristics of plastic penetration, a three dimensional (3D) finite element (FE) analysis model for the plastic penetration of ball groove-section ring is established under the ABAQUS software environment. A decisive factor for plastic penetration behavior, namely the penetration speed of plastic zone, has firstly been ascertained. The distribution pattern of the plastic zone in the process of plastic penetration is revealed by 3D simulation. By researching the diffusion rules of the plastic zone under the conditions of different ring radial thickness and feed speed, the influences of ring radial thickness and feed speed on plastic penetration are obtained. Lastly, the necessary condition for the plastic penetration of groove ball-section ring rolling is summarized, and is validated by experiment and simulation. The achievements of this study expressly reveal the plastic penetration rules of groove ball-section ring rolling, and it's useful for technology design and production.

Keywords: Ring rolling; Groove ball-section; Plastic penetration; FE; Simulation

1. Introduction

Plastic penetration of ring rolling means plastic zone penetrating the ring wall during the process of rolling, and thus causing some series of local plastic deformation such as thinning the radial thickness and enlarging the diameter. Which is thought as a necessary condition for ring rolling forming [1]. The plastic penetration of rectangle section ring was researched based on static theory and slip-line theory, plastic penetration condition and influencing factors were obtained [2]. Also researched based on FEM, a 3D FE model of plastic penetration was established, the distribution pattern of plastic zone in plastic penetration process of rectangle section ring and the influence of feed amount on plastic penetration were obtained [3].

Deformation of plastic penetration was simplified as plane deformation but it is three-dimensional deformation in fact, and accomplished by the alternant diffusing of plastic zone in both ring radial and axial directions [3] has researched the diffusing of plastic zone along the axial direction can influence the plastic zone penetrating along radial direction. Moreover, the researches on plastic penetration are all based on the rectangle section ring rolling. However, the contact and deformation characteristic of groove ball-section ring rolling is different from rectangle section ring rolling. In recent years, with the increased application of deep groove ball bearings in industry, the technology of groove ball-section ring rolling has gained more and more attention. But the research on ring rolling has been mostly directed to rectangle-section ring [4-8]. The lack of research on groove ball-section ring rolling has seriously prevented its development.

Therefore, in this paper, the plastic penetration of groove ball-section ring is studied based on FEM. A 3D FE model for plastic penetration is established. A decisive factor on plastic penetration behavior, namely the penetration speed of plastic zone v_p , has

*Corresponding author. Tel.: +86 27 8716 8391, Fax.: +86 27 8716 8391
E-mail address: unique_zl@sina.com
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been ascertained. Through 3D numerical simulation, the distribution pattern of plastic zone and the rules of plastic penetration are revealed, and the influence of ring radial thickness and feed speed on plastic penetration of groove ball-section ring rolling are researched. The plastic penetration conditions of groove ball-section ring rolling are summarized at last, and are validated by experiment and simulation.

2. Establishing 3D FE model

Fig. 1 shows the principle of groove ball-section ring rolling. The closed rolling gap is adopted. The driving roll makes active rotation movement. The mandrel roll is a pressure roll making feed movement and passive rotation movement. The guide roll makes translation movement following the ring. In the rolling process, the groove ball of mandrel roll contacts the ring first, and the ring groove begins to be formed at the middle width of ring under the feed movement of mandrel roll. The ring is in status of local plastic deformation. With the increase of feed amount, the groove ball is pressed into the ring gradually, and when the groove is formed completely, the mandrel roll contacts with the whole ring width, while the ring is in status of unitary plastic deformation. So, the contact and deformation characteristic of groove ball-section ring rolling is different from rectangle-section ring rolling that has been described by [1].

In the initial stage of ring rolling, the plastic zone penetrates the ring wall along feed direction with a certain feed amount, as seen in Fig. 2(a). And the plastic zone diffuses along ring radial and axial directions under the rotational movement of the ring and feed movement of the mandrel roll, as seen in Fig. 2(b). The ring then produces series of plastic deformation through thinning the radial thickness, enlarging the diameter, and figuring the section finally, as seen in Fig. 2(c). The ring plastic penetration is an instantaneous process, it is occurs before the stage of ring biting company with rotation movement, and can be thought as an extrusion process similar to a forging process.

According to the above, in modeling of plastic penetration, the rotation movement of the ring in the rolling process can be neglected. The plastic deformation of ring under the feed role of mandrel roll is mainly analyzed. Based on ABAQUS software, a 3D FE model is established first by this paper for simulation of the plastic penetration process of groove ball-section ring, as shown in Fig. 3. The model consults the actual technology parameters and boundary conditions of groove ball-section ring rolling on D56G90 CNC ring rolling mill. Based on the validated FE model of plastic penetration, the numerical simulation results of this paper can considered to be valid. The main features of the model are as follows:

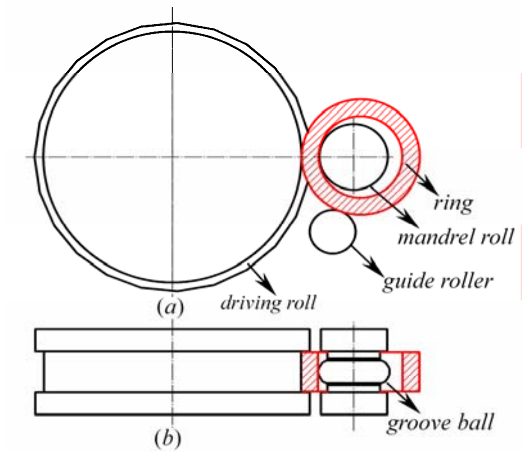


Fig. 1. Conceptual drawing of groove ball-section ring rolling: (a) Main drawing views; (b) Planform.

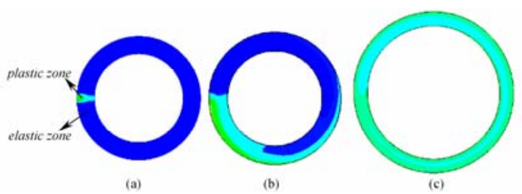


Fig. 2. Plastic deformation behavior of ring in the process of cold ring rolling.

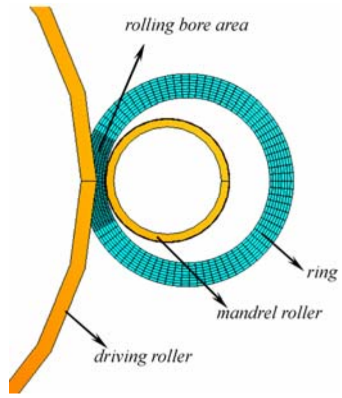


Fig. 3. 3D FE analysis model for plastic penetration of groove ball-section ring.

(1) The driving roll is constrained in six freedom degrees. The mandrel roll only makes line movement along feed direction, and guide roll is neglected.

(2) The elastic-plastic FEM is adopted to improve the computational accuracy.

(3) The Plastic penetration is considered as a quasi-static state program without considering of inertia effect, so the dynamic explicit FE procedure is used to avoid the huge computation time and convergence problem of the implicit procedure [9, 10].

(4) The 8-noded first-order reduction integration continuum elements type is used. Since the plastic deformation is only occurs in the rolling bore area, in order to improve the precision and ensure the computational efficiency a region mesh partition method is used in modeling [11]. The mesh in rolling bore area is partitioned thick, and the elastic zones of ring are partitioned thin.

All parts of the model are showed separately in Fig. 4, the geometrical parameters needed for the model are listed in Table 1, the material used in the model is bear steel Gcr15. Its density, Young's modulus and Poisson's ratio respectively are 7850kg/m^3, 209GPa and 0.3. And its constitutive equation is as follows [12]:

$$\sigma = 219.1\times10^3\varepsilon^e \ (\text{MPa}),\ \ \varepsilon \le 0.001856$$
$$\sigma = [847(\varepsilon^p)^{0.129} + 30.37] \ (\text{MPa}),\ \ \varepsilon > 0.001856$$

where σ is the true stress, ε^e and ε^p are respectively the true plastic and elastic strain, and ε is the true total stain.

Table 1. Part parameters needed for the model.

Outer diameter of ring	D	78mm
Thickness of ring	h	9.75mm
Width of ring	B	23.1mm
Outer diameter of driving roll	D_{d0}	217.04mm
Groove diameter of driving roll	D_{di}	207.22mm
Groove width of driving roll	B_d	23.4mm
Outer diameter of mandrel roll	D_{x0}	39.28mm
Ball diameter of mandrel roll	D_{xb}	39.9mm
Groove diameter of mandrel roll	D_{xi}	34.28mm
Groove width of mandrel roll	B_x	23.4mm
Ball width of mandrel roll	B_b	11.07mm

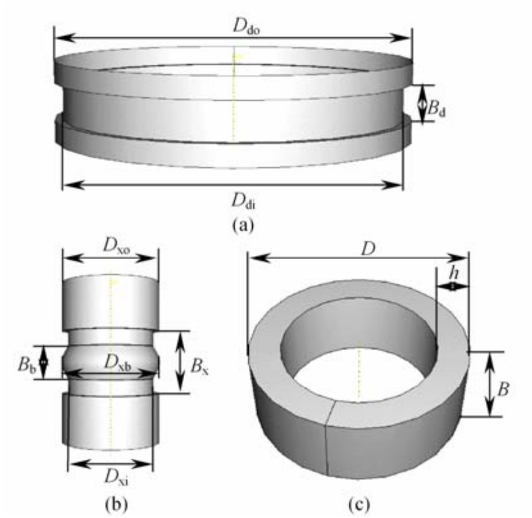


Fig. 4. Geometry model of ring and rolls: (a) Driving roll; (b) Mandrel roll; (c) Ring.

3. Research methods

In ABAQUS, PEEQ is a parameter to present equivalent pure plastic strain of an element, and the value of PEEQ is used to judge the plastic status of an element. When the PEEQ value of an element is greater than zero, it means a certain value of plastic strain occurred for the element at the moment, and therefore the element in plastic status. So the area where PEEQ value is above zero can be thought of as the actual plastic zone. As shown in Fig. 5(the axial section of ring in the rolling bore area is intercepted in the figure), at the middle width of ring, when the area where PEEQ value is above zero distributed along radial direction, it means the ring wall at middle width is penetrated by the plastic zone.

Fig. 6 shows the interception drawing of the radial and axial section of ring, $\Delta B/B$ means the relative width, different values of $\Delta B/B$ present the different axial locations of ring. In analysis, under a same

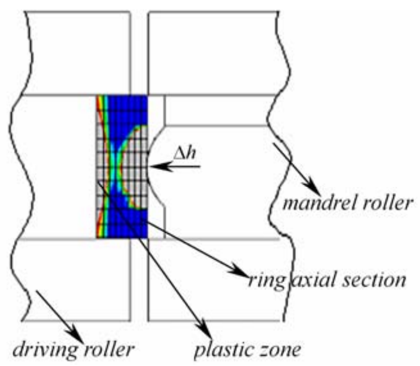


Fig. .5. Distribution of PEEQ in the axial section of ring.

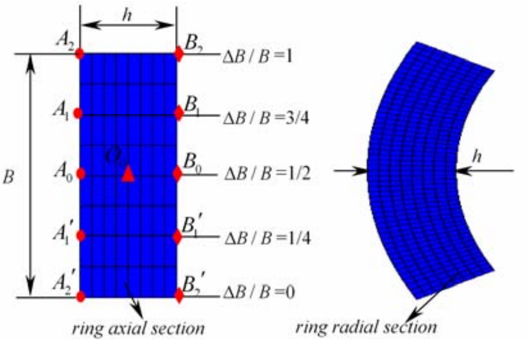


Fig. 6. Interception drawing of the ring radial and axial section in the rolling bore area.

feed amount, five axial locations of ring are selected to compare the differences of plastic zone distribution among them. The plastic zone distribution in both ring radial and axial sections at different times in the simulation process are selected to reveal the distribution rules of plastic zone in the plastic penetration process of groove ball-section ring.

[3] reported that in the process of plastic penetration, plastic zones develop from outer radial surface of the ring and inner radial surface of the ring respectively, to the middle radial surface along radial direction. Then, in this paper, we suppose that at a random axial location, the two plastic zones diffuse along opposite direction and meet at the middle radial surface exactly. As Fig. 6 shown, at middle width ($\Delta B/B=1/2$), the two plastic zones diffuse from A_0 node and B_0 node along thickness direction, and meet at O_0 node lastly. And this rule is applied at other axial locations.

By FE simulation, the times when A_0, B_0 and O_0 are yielded (nodes A_0, B_0 and O_0 begin in plastic status) can be obtained respectively, and were marked as T_A, T_B and T_O. The distances between A_0 and O_0, B_0 and O_0 were marked as S_{AO} and S_{BO}, they satisfied

$$S_{AO}=S_{BO}=h/2 \tag{1}$$

As the S_{AO}, T_A and T_O were known, so the diffusing speed of plastic zone from A_0 to O_0 can be calculated as

$$v_{pA}=\frac{S_{AO}}{T_O-T_A} \tag{2}$$

where v_{pA} means the diffusing speed of plastic zone from the outer radial surface to the middle radial surface at the middle width of ring, namely the penetration speed of outer plastic zone. v_p was named as penetration speed of plastic zone in this paper. It reflects the speed of plastic zone penetrating the ring wall, the larger value means the ring was penetrated quicker. As the same, the penetration speed of inner plastic zone v_{pB}, and v_{pA}, v_{pB} at others relative width of the ring can also be obtained. In this paper, we can explicitly reveal the plastic penetration rules and the influence factors of it in groove ball-section ring rolling by analyzing the changing of v_p under the various conditions.

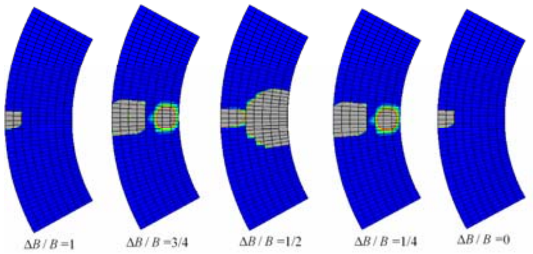


Fig. 7. Plastic zone distribution of the radial section at different ring axial locations.

4. Result and analysis

The model which is established based on the parameters of Table 1 is simulated, the plastic zone distribution in the ring radial section at five axial locations are shown in Fig. 7.

In Fig. 7, it can be seen that the plastic zone distributions of radial section are not same for the different ring axial locations. When Δh equals to 0.12mm, at relative width $\Delta B/B=1/2$, the plastic areas met at the middle radial surface of the ring and penetrated the ring wall exactly, while at $\Delta B/B=1/3$ and 1, plastic areas have not met and the ring wall is not penetrated. The areas of plastic zone in radial section are not similar to and the distributions of plastic zone are symmetric about the middle width of ring.

As shown in Fig. 8, it can be seen that plastic zone is formed first at the radial surface of ring, and distributed at the middle areas. Another plastic zone is occurs later at the inner radial surface of ring. With the increase of time, the feed amount also increased and the two plastic zones diffuse along axial direction towards the end surface of ring. The plastic zone at the outer radial surface of ring (outer plastic zone) penetrated the ring width first, and the plastic zone at the inner radial surface of ring (inner plastic zone) last. At the same time, the two plastic zones diffuse along a radial direction towards the middle radial surface of

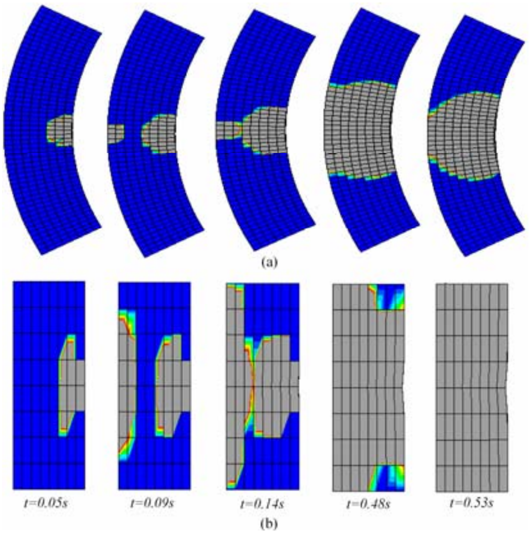


Fig. 8. Distributions of plastic zone in the ring radial and axial section at different times: (a) Distributions of plastic zone in the ring radial section; (b) Distributions of plastic zone in the ring axial section.

ring. They penetrated the ring wall at the middle width of the ring first, and then penetrated the ring wall at the axial end surface of ring later.

In Fig. 9, the penetration speeds of outer and inner plastic zone at the five ring axial locations are compared. It can be seen that the penetration speeds of outer and inner plastic zone are all symmetric about the middle width of ring. Penetration speeds of the outer and inner plastic zone decrease from axial end surface of ring to the middle width of ring. At the axial end surface of ring, the penetration speed of inner plastic zone is negative. This means that the plastic zone diffuses from the outer radial surface to the inner radial surface of ring directly. The axial end surface at the inner radial surface of the ring occurred plastic zone last, this phenomenon can be reflected by the picture of Fig. 8(b), t=0.48s. At relative width $\Delta B/B=1/2$, the penetration speed of outer plastic zone is bigger than the inner plastic zone. At $\Delta B/B=1/4$ and 3/4, the penetration speed of outer plastic zone is close to inner plastic zone. At $\Delta B/B=0$ and 1, the penetration speed of plastic zone from the outer radial surface to the middle radial surface is less than that from the middle radial surface to the inner radial surface.

It can be concluded from the above comparison and analysis that the diffusing patterns of plastic zone are not same for different ring axial locations. In the middle width of ring, inner plastic zone occurs first, and outer plastic zone occurs later. The two plastic zones diffuse along opposite direction towards the middle radial surface. But in the axial end surface of ring, outer plastic zone occurs first, and diffuse along radial direction towards the inner radial surface. Penetration speed of plastic zone increases from the axial end surface of ring to the middle width of ring. Plastic penetration always occurs first at the middle width of ring and last at the axial end surface of ring. This is the penetration rule of plastic zone in the plastic penetration process of groove ball-section ring. It is first revealed by 3D FEM in this paper.

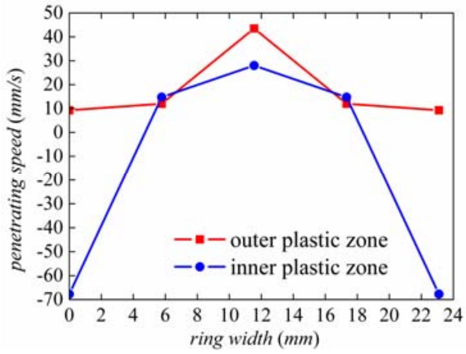


Fig. 9. Penetrating speed of plastic zone at different ring axial locations.

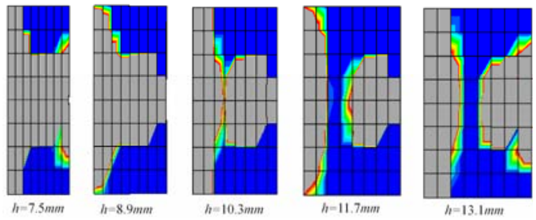


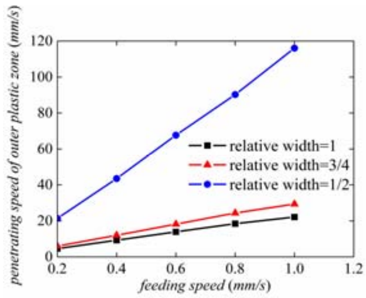
Fig. 10. Distributions of plastic zone in the ring axial section with different ring thicknesses.

Since ring plastic penetration means the ring wall is penetrated by plastic zone under the feed role of mandrel roll, the thickness of ring wall and the feed speed of mandrel roll are the two main influencing factors for plastic penetration. They can influence the diffusing of plastic zone directly. In this paper, different ring thicknesses and feed speeds are selected respectively for FE simulation. The influences of two factors on plastic penetration are researched as follow.

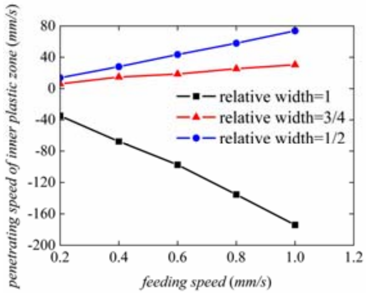
From Fig. 10, it can be seen that the plastic zone distributions are not same for different ring thicknesses under the same feed amount. At h=10.3mm, the plastic zone penetrated ring wall exactly, at h=7.5mm and 8.9mm, the plastic zone has already penetrated ring wall, while at h=11.7mm and 13.7mm, the plastic zone has not penetrated ring wall.

Fig. 11 shows the changes of penetration speed of plastic zone at three axial locations, under five ring thicknesses. As known from the above research, the plastic zone distribution are symmetric about the middle width of ring, so, half of the ring is selected for analysis. As seen in Fig. 11, at the three axial locations of half ring, penetration speeds of outer and inner plastic zone decrease with the increase of ring thickness. So, it can be deduced that the penetration speed of plastic zone decreases with the increase of ring thickness, and increase of ring thickness is harmful to the plastic penetration of groove ball-section ring rolling.

Fig. 12 shows the changes of penetration speed of plastic zone at three axial locations under five feed speeds. As seen in Fig. 12, at the three axial locations of half ring, penetration speeds of outer and inner plastic zone increases with the increase of feed speed. In Fig. 13, x-axis means the increase ratio of feed speed, and y-axis means the increase ratio of penetra-

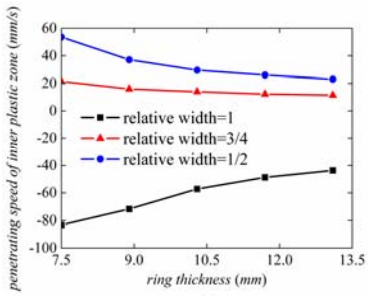


(a)



(b)

Fig. 12. Penetrating speed of plastic zone at different axial locations with different feeding speeds: (a) penetrating speed of outer plastic zone; (b) penetrating speed of inner plastic zone.



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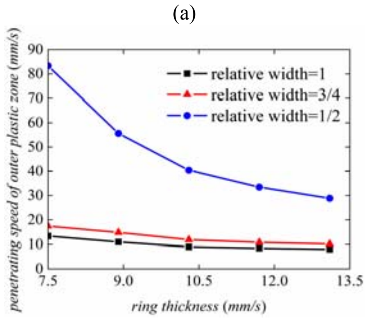
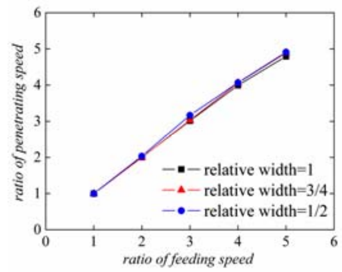
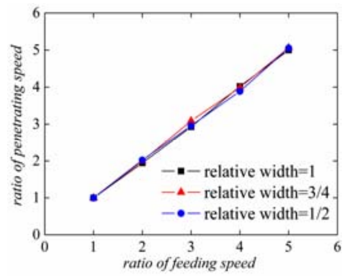


(b)

Fig. 11. Penetrating speed of plastic zone at different axial locations with different ring thicknesses: (a) penetrating speed of outer plastic zone; (b) penetrating speed of inner plastic zone.



(a)



(b)

Fig. 13. Ratios of penetrating speeds at different axial locations with different feeding speed ratios: (a) penetrating speed ratio of outer plastic zone; (b) penetrating speed ratio of inner plastic zone.

tion speed corresponding to the increased ratio of feed speed. It can be seen that at the three axial locations, the increase ratios of penetration speed are nearly same for the five feed speeds, and the slopes of lines are nearly equal to 1. It can be found that the relation between penetration speed of plastic zone and feed speed is linear. The increased ratio of penetration speed is nearly equal to the increased ratio of feed speed, and the increase of feed speed is advantaged to the plastic penetration of groove-ball section ring rolling.

Based on the diffusion rule of plastic zone in the plastic penetration process which is revealed above, it can be concluded that in the process of groove ball-section ring rolling, when plastic penetration occurs at the middle width of ring, axial location plastic penetration occurs later. Ring wall at the central width is penetrated by plastic zone can be thought as the necessary condition for plastic penetration of groove ball-section ring rolling, as shown in the picture of Fig. 8 (b), at t=0.14s. Furthermore, the feed amount at this time can obtained, and the value of it can be thought as the minimal feed amount per revolution required for the plastic penetration. Therefore, for a groove ball-section ring rolling with certain technology parameters, by using the FEM of this paper, the reasonable feed amount per revolution for ring plastic penetration can be obtained to ensure the plastic deformation of ring in rolling process.

In this paper, the driven roll, mandrel roll and ring blank are designed based on the geometric parameters that listed in Table 1, as seen in Fig. 14. The experiment of groove ball-section ring rolling is made on D56G90 CNC ring rolling mill, as seen in Fig. 15. The relative parameters for D56G90 are shown in Table 2. And the simulation of groove ball-section ring rolling with the same conditions is also made under the ABAQUS environment.

The feed amount per revolution Δh required for the necessary condition of plastic penetration is obtained by FE simulation using above methods, the value is 0.04mm. In the ring rolling experiment, two feed amounts per revolution are selected. Respectively one less than Δh, the value is 0.03mm, and another greater than Δh, the value is 0.05mm. The experiment and simulation results of groove ball-section ring rolling results are shown respectively in Fig. 16 and Fig. 17.

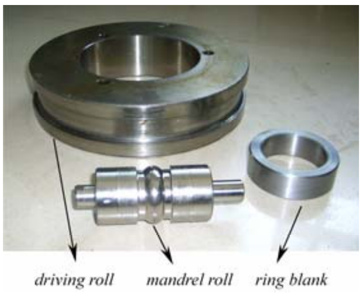


Fig. 14. Driving roll, mandrel roll and ring blank for groove-ball section ring rolling.

Table 2. Parameters for D56G90 CNC ring rolling mill.

Maximum radius of ring	90mm
Maximum width of ring	23.1mm
Radial rolling force	100KN
Maximum stroke of slide	137mm
Feeding speed of slide	0-16mm/s
Minimal closure central distance	116mm
Rotational speed	2.43rev/s
Power of motor	11KW

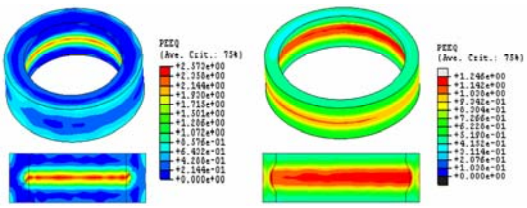
Fig. 15. D56G90 CNC ring rolling mill.

(a) (b)

Fig. 16. Experiment results of groove ball-section ring rolling under two feed amount per revolution: (a) Δh=0.03mm/rev; (b) Δh=0.05mm/rev.

Table 3. Measure results of experiment and simulation.

Feed amount per revolution	Outer diameter			Inner diameter		
	experiment	simulation	error	experiment	simulation	error
0.03mm/rev	67.62mm	67.81mm	0.28%	48.21mm	48.36mm	0.31%
0.05mm/rev	90.24mm	90.4mm	0.18%	74.34mm	74.77mm	0.58%



(a) (b)

Fig. 17. Simulation results of groove ball-section ring rolling under two feed amount per revolution: (a) Δh =0.03mm/rev; (b) Δh =0.05mm/rev.

As seen in Fig. 16 and Fig. 17, the experiment and simulation results are all show that a little plastic deformation produced at the middle with of ring when feed amount per revolution is less than Δh , the ring can not be caused series plastic deformation as thinning the thickness, enlarging the diameter and figuring the cross-section. While the ring can be penetrated by plastic zone, and produced sufficient plastic deformation when feed amount per revolution greater than Δh . The outer and inner diameters of ring in experiment are measured by Cord3 three-coordinates measuring machine. And in simulation, they are measured under the ABAQUS/View module. The comparing of measure results of experiment and simulation is shown in Table 3. From Table 3, it can be seen obviously that the outer and inner diameters of ring nearly no change when feed amount per revolution less than Δh , but they all increased when feed amount per revolution greater than Δh . And the errors of ring dimension between the experiment and simulation are very small. The agreement of experiment and simulation results shows that the necessary condition of plastic penetration is validated for groove ball-section ring rolling. The feed amount per revolution required for the condition can be obtained by FEM which is offered in this paper, and to ensure the normal process of ring rolling.

5. Conclusion

A 3D FE model is established in this study to simulate the plastic penetration process of groove ball-section ring, under the ABAQUS software environment. A decisive factor for plastic penetration behavior, namely the penetration speed of plastic zone v_p , was first ascertained. Through 3D numerical simulation, the distribution pattern of plastic zone and the rules of plastic penetration are revealed. The influences of ring radial thickness and feed speed on plastic penetration of groove ball-section ring rolling are researched. The plastic penetration conditions on groove ball-section ring rolling are also summarized. The following points summarize the main conclusions drawn from this work.

(1) Plastic zone distribution in radial sections are not the same for different ring axial locations, and they are symmetric about the middle width of ring. Penetration speed of plastic zone decrease from middle width of ring to axial end surfaces of ring.

(2) In the process of plastic penetration, inner plastic zone occurs first at the middle width of ring, and outer plastic zone occurs later. The two plastic zones diffuse along opposite directions towards the middle radial surface. But in the axial end surface of ring, outer plastic zone occurs first, and diffuses along a radial direction towards the inner radial surface. Plastic penetration always occurs first at the middle width of ring and last at the axial end surface of ring.

(3) Penetration speed of the plastic zone decreases with the increase of ring radial thickness, and increases with the feed speed increase. Increasing of ring radial thickness is harmful to plastic penetration, increasing of feed speed is useful for plastic penetration.

(4) Ring wall at the central width is penetrated by plastic zone and can be thought as the necessary condition for plastic penetration of groove ball-section ring rolling. The feed amount per revolution can be calculated by FEM, and can ensure the ring plastic penetration in rolling process.

Acknowledgments

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