Finite Element Analysis of a Non-Symmetric Ring Rolling Process of a Taper Roller Bearing Outer Race and Verification

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Summary

In this study, we conduct computer simulation of non-symmetric ring rolling of a taper roller bearing outer race. A rigid-plastic finite element method is employed. An idling disk is devised to reduce the intrinsic oscillatory motion during non-symmetric ring rolling as well as to reduce the friction between the disk and the workpiece and its applicability and effect are shown by both experiments and simulations. The formation of both under-filling defect on the outer face and tilting defect of the outer face of the taper roller bearing outer race is revealed by the ring rolling simulation.

1. Introduction

Ring rolling [1,2] has an advantage of ability to manufacture hollow axi-symmetric mechanical parts with higher accuracy. A typical example can be found from ball bearing races, which have a symmetric plane perpendicular to their axial axes. In fact, the ball bearing races are manufactured by ring rolling of machined blanks followed by grinding and/or heat or surface treatment. In manufacturing mechanical parts through a series of manufacturing processes including ring rolling, ring rolling is very important because it determines the geometrical dimensions. It is frequent that more or less dimensional tolerance made during machining can be overcome during ring rolling. One of the characteristics of ring rolling lies in that it is very pertinent to make the required accuracy or geometrical tolerance fulfilled if its process was properly designed. In addition, it is highly productive because of easy automation. It has been known that the ring rolled products also have an increased strength.

As the ball bearing race is to the typical example of the symmetric ring rolled parts, the taper roller bearing race is to that of the non-symmetric ones. Compared to the symmetric cold ring rolling, applications of the non-symmetric ring rolling have been rare in the industries. The movement of the workpiece from right to left during ring rolling has confined its wide application. Generally the movement of the workpiece results in the under-filling defect on the outer face or the tilting defect of the outer face of the taper roller bearing race with the result that it is very difficult to achieve precision ring rolling in non-symmetric ring rolling.

Therefore, compared to symmetric cold ring rolling that follows the machining of ring type forged workpiece, non-symmetric ring rolling is usually followed by the machining of the ring rolled workpiece. As a consequence, process design of the non-symmetric ring rolling is very difficult because it is highly linked with forging of the blank and the dimensional tolerance of the forged blank is generally large. This fact demands many trial-and-errors before obtaining successful process designs at the expense of much cost and time. Improper process design causes frequent costly fracture of tools including mandrel and work roll, sometimes leading to mass production of products with bad quality.

The computer simulation technology must have been very helpful to resolve the above problem. In forging industries, various forging simulators have been contributing to achieving the optimized process designs. The usage of forging simulators in forging industries is nowadays common. However, the situation in ring rolling industries is to the contrary. Although many researchers [3-23] have studied these fields, the fruits are rarely shared by the process design engineers in the ring rolling fields as yet. Of course, the major reasons have involved the theoretical complexities of the ring rolling as well as the much computational time needed. The recent advancement of personal computer technology removed one obstacle. However, mechanical complexities still remain as an obstacle. Thus the realistic way is to find acceptable engineering solutions under engineering assumptions.

In recent years, Moon et al. [21] proposed a rigid-viscoplastic finite element method of solving the ring rolling processes and applied it to predicting the polygonal shape defect formed during hot ring
rolling and the geometrical shape defect formed during ring rolling of a cage of a constant velocity joint [22]. The method was also applied to simulating a rotary forging process for making a hub bearing assembly [23], which is nearly the same as the ring rolling process.

In this paper, we simulate a non-symmetric small cold ring rolling process considering the idling plates attached in the side of support rolls, which are equipped to reduce the oscillating movement of the workpiece during non-symmetric ring rolling. The predictions are compared with the experiments for verifying the approach. The approach is tried to reveal the reason of under-filling defect on the outer face and the tilting defect of the outer face of the taper roller bearing race during non-symmetric ring rolling.

2. Equipment of reducing oscillatory motion and process design

Fig. 1 shows the taper roller bearing and its outer race selected for application. The outer radius, inner radius and width of the selected taper roller bearing are 95 mm, 60 mm, and 23 mm, respectively.

Fig. 1 Typical tapered roller bearing

The outer race of the selected bearing is non-symmetric and it has been usually manufactured by a sequence of manufacturing processes including forging, machining and grinding. It is usual that ring rolling might enhance product quality and lower product cost. However, the difficulty caused from the non-symmetry has prohibited ring rolling from being applied to manufacturing the part. The non-symmetry incurs the oscillatory motion of workpiece during ring rolling which results in the poor product quality and the frequent fracture of tools, leading to lowering the competitiveness. Thus non-symmetric cold ring rolling of small parts has been rarely applied. The axle rolls used in hot ring rolling of large parts to prevent the oscillatory motion of the workpiece can not be employed for non-symmetric cold ring rolling of small parts because of the narrow space of the cold ring rolling machine.

Because the oscillatory motion is inevitable during non-symmetric ring rolling, the precision ring rolling is inherently impossible in the case of non-symmetric ring rolling. Thus, the non-symmetric ring rolled parts have been traditionally manufactured by a sequence of forging, ring rolling, machining and grinding. In this study, we followed this tradition in non-symmetric ring rolling to develop a new non-symmetric ring rolling process for the taper roller bearing outer race shown in Fig. 1.

Fig. 2 shows a conceptual drawing of the devised equipment and the non-symmetric ring rolling process. As shown in Fig. 2, the equipment is composed of work roll, mandrel, two support rolls and two idling disks. The mandrel is supported by two support rolls which rotate opposite to the mandrel due to the friction between the mandrel and the support rolls. The work roll not only transmits power to the workpiece to be formed but it also feeds, that is, it moves towards the mandrel while rotating to make the workpiece plastically formed. In general, the smaller the distance of the two support rolls, the better the structural rigidity of the mandrel. Thus the distance of the two support rolls would rather be controlled as small as possible. In particular for non-symmetric ring rolling, two support rolls with proper distance can be used for preventing the workpiece from moving excessively towards right or left during ring rolling. A problem rises from the fact that the support roll scratches the workpiece owing to the friction between the support rolls and the workpiece which rotate opposite. To cope with
this problem, idling disks were attached in the inner side of the two supports rolls by friction reducing bearings.

Experience says that the major design parameter in non-symmetric ring rolling is the optimized initial shape of workpiece corresponding to the final ring rolled part. In the non-symmetric ring rolling of taper roller bearing outer race, shape defects shown in Fig. 4(b) and Fig. 5(b) may take place, that is, under-filling defect on the outer face and tilting defect of the outer face. The goal of our process design is to enhance the ability of the process to reflect geometrical dimension variation of the initial, usually forged, workpiece within the allowed tolerance under the condition that the shape defects are acceptable. Of course, the ultimate goal is to reduce the production cost and to enhance the product quality at the same time.

3. Simulation of non-symmetric ring rolling processes
Fig. 3 shows the geometries of workpiece, work roll, mandrel and support rolls for simulating the non-symmetric ring rolling process of the taper roller bearing outer race shown in Fig. 1. Two different shapes of workpiece were considered as shown in Fig. 4.

In general, cold ring rolling is carried out in lubricant environments and thus we assumed the mandrel was frictionless. Without this assumption, the rotating velocity of the mandrel should be considered as an unknown, which increases the degree of difficulty very much. In addition, the friction between the workpiece and the idling disks attached to the sides of the support rolls was also neglected because the idling disks rotate to minimize the frictional force and the plastic deformation of the workpiece does not take place near the idling disks.

On the contrary, the workpiece should move at the same velocity with the work roll at a certain point or region, called neutral point. It is unfortunate that it is not easy to find the neutral point especially in ring rolling simulation. One of the reasons comes from the very small contact region compared with the whole surface of the workpiece with the result that the contact region has very few nodal points, which increases numerical uncertainty and difficulty. Considering the computer limitation, we determined the neutral point at the current solution step as the maximum normal stress point at the previous solution step. The neutral point was considered as velocity prescribed. At the neutral point, its nodal velocity was calculated from the velocity of the corresponding point on the work roll. At the other nodal points the frictional forces were considered and calculated by the constant shear frictional law. The above approach were applied successfully to predicting the polygonal shape defect in hot ring rolling [21] and the edge shape defect in cage ring rolling [22].

Ring rolling is accomplished after several dozens of rotation of the workpiece. Therefore, it is peculiar that the stroke in ring rolling is several tens and hundreds times larger than that in forging and that the computational time is as much. To reduce computational time in ring rolling simulation, Hu et al. [7] developed a hybrid mesh method and recently Moon et al. [21] improved the method to minimize the numerical volume change during ring rolling simulation. This method employs both analysis mesh system and reference mesh system. In this study, we adopted the same method that was developed for symmetric ring rolling by Moon et al. [21].

The process information necessary for the simulation of the non-symmetric ring rolling process to manufacture the taper roller bearing outer race shown in Fig. 1 is as follows:

- Initial workpiece shape and dimensions: Fig. 4
- Flow stress of workpiece: \( \sigma = 350.0(1 + \epsilon^{0.14}) \) MPa
- Friction factor between work roll and workpiece: \( m = 0.1 \)
- Friction factor between mandrel and workpiece: \( m = 0.0 \)
- Rotating velocity of work roll: \( N_0 = 120 \) rpm
- Feed rate of work roll: 1.5 mm/sec

![Fig. 5 Predictions and experiments for the first initial workpiece](image-url)
With the process information, we simulated the non-symmetric ring rolling processes for the two different initial shapes of workpiece, i.e., preforms shown in Fig. 4. For the initial shapes of workpiece in Figs. 5(a) and 5(b), the predicted results shown in Fig. 5(a) and Fig. 6(a) were obtained after 10149 and 10931 solution steps, respectively. The colored distribution means the effective strain.

As seen in Fig. 5(a), the initial shape of workpiece in Fig. 4(a) contacted the right idling disk in the early stroke and then contacted the left idling disk in the late stroke. As a consequence, excessive tilting of the outer face was predicted. The experimental similarity was also found from Fig. 5(b). The predicted tilted angle was about 2 degrees while the experimental tilted angle about 3 degrees, indicating that the results are acceptable for the sake of engineering application.

On the contrary, the predicted results in Fig. 6(a) are quite other than those in Fig. 5(a). In the early stroke, the workpiece contacted the right idling disk and the contact was maintained just before the final stroke. Thus there has been no contact of the workpiece with the left idling disk. This motion of the workpiece left the under-filling defect as shown in Fig. 6(a). It is noted that these results are in good agreement with the experiments shown in Fig. 6(b).

Consequently, the initial shapes of workpiece in Fig. 4(a) and Fig. 4(b) resulted in the tilting defect of the outer face and the under-filling defect on the outer face, respectively.

4. Conclusions

In this study, we conducted computer simulation of non-symmetric ring rolling of a taper roller bearing outer race. A rigid-plastic finite element method was employed and several useful schemes and assumptions were given. The approach was verified in the engineering sense through comparison of predictions and experiments.

An idling disk was devised to reduce the oscillatory motion during non-symmetric ring rolling as well as to reduce the friction between the disk and the workpiece and its applicability and effect were shown by both experiments and simulations.

The formation of both under-filling defect on the outer face and tilting defect of the outer face of the taper roller bearing outer race was revealed by the ring rolling simulation.

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