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A blank optimization design method for three-roll cross rolling of complex-groove and small-hole ring

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ABSTRACT

Complex-groove and small-hole rings have the common geometric characteristic of asymmetric deep-groove on the outer surface and small-hole in the center, such as duplicate gears and double-side flanges. It is difficult to get the complete section profile directly by traditional forging or special ring rolling technology. Three-roll cross rolling (TRCR) is an advanced plastic deformation to form ring parts with deep groove, which can form the complete deep groove directly by three-roll rotary rolling. As a key to the design of TRCR, the blank design influences material flow and distribution as well as final shape of deep-groove. In this paper, the material flow behavior in TRCR of complex-groove and small-hole ring with rectangular section blank is analyzed by a theoretical approach. Through analysis, forming the ring with stepped-section blank is put forward, and a theoretical method to design the blank size is established. Then the possibility and shortage of the theoretical method are discussed by FE simulation. Therefore, a volume correction coefficient is proposed to correct the blank size. Further, a prediction model of the volume correction coefficient is established by using orthogonal simulation test and back propagation (BP) neural network. Finally, the blank design method is verified by simulation and experiment. The result shows that complex-groove and small-hole rings can be formed perfectly with blanks which are designed by the theoretical formulas and the prediction model.

1. Introduction

Complex-groove and small-hole rings are a special kind of profile rings. They have the common geometric characteristic of asymmetric deep-groove on the outer surface and small-hole in the center, as shown in Fig. 1. These ring parts are widely used in automobile, engineering machinery, petrochemical industry, etc. The typical ring parts are duplicate gears, double-side flanges and high-pressure value bodies. Because of the special geometric characteristics of thick-wall, small-hole and deep-groove, it is difficult to get the complete section profile directly by traditional forging. Even adopting ring rolling which is well applicable for ring parts precise forming, it is hard to form the complete deep groove before the ring diameter growing up to the target size [1]. Ring parts formed by these two methods both need a mass of following cutting, which results in high material consumption, low production efficiency and poor mechanical property.

Three-roll cross rolling (TRCR) is an advanced plastic deformation technology to form ring parts with deep groove. The forming principle of TRCR is shown in Fig. 2. In TRCR, the axial lines of main roll and passive rolls are parallel to one another. The main roll makes active rotation and linear feed motion. The two passive rolls are idle rolls with fixed axis, which make passive rotation. Under the rotation and feed motion of main roll, the workpiece repeatedly enters rolling pass comprised by the three rolls. And the material in the outer surface of the central region produces axial flow towards the upper and lower regions with the extrusion affect of rolls. Finally, under the heap of the multi-rotary deformation, the deep groove is formed out. TRCR belongs to rotary forming, which has advantages of low energy consumption, high material utilization, high production efficiency and superior product quality. So TRCR is an advanced manufacturing method, which is suitable for precise forming of complex-groove and small-hole rings.

TRCR and ring rolling have something in common. They are both plastic rotary forming technology. At present, there are many researches on ring rolling, including rolling theory, technology and equipment, using the methods of mathematical analysis, experimental test and FE simulation. Yan et al. [2] built a mathematical model for designing the feed speed of mandrel in cold ring rolling and

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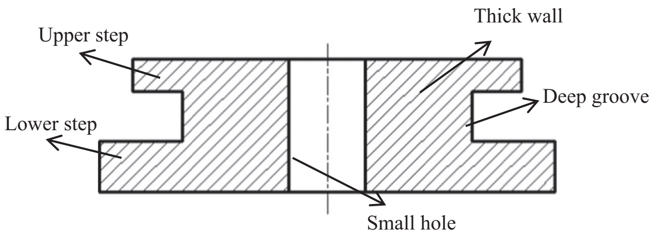

Fig. 1. Complex-groove and small-hole ring.

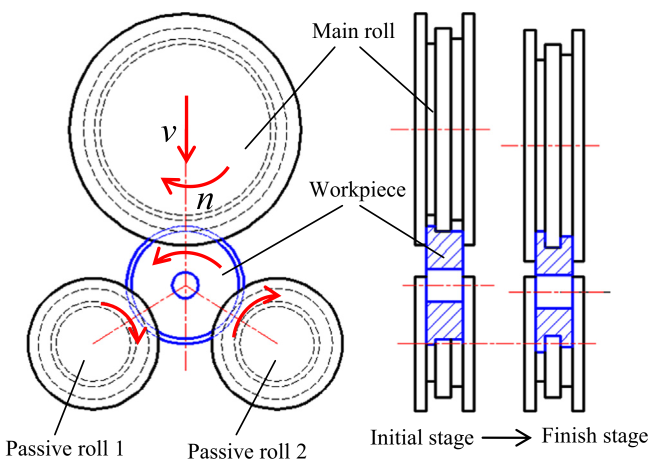

Fig. 2. TRCR forming principle.

tested it in a rolling experiment. Hua et al. [3] proposed a model of the ring stiffness in radial-axial ring rolling and derived the stiffness condition in simulative rolling experiment. Guo and Yang [4] put forward a steady forming condition for radial-axial ring rolling process and verified by FE simulation. Wang and Hua [5] presented an on-line measurement method for various guide modes of vertical ring rolling mill whose validity was evaluated by experiment. Zhou et al. [6] built a 3D coupled thermo-mechanical FE model for large-scale alloy steel ring rolling, and investigated the effects of axial rolls motions on radial-axial rolling process. Qian et al. [7] designed different blanks respectively by the ratio of radial thickness reduction to axial height reduction and the ratio of blank cross-sectional area to rolled ring cross-sectional area, and found that different blank sizes have different effects on radial-axial ring rolling of lager rectangular section ring by FE simulation. Jenkouk et al. [8] established a FE model of ring rolling process with integrated closed-loop control, which is similar to the industrial practice control system of the real rolling process. Qian and Pan [9] developed a 3D coupled macro–microscopic FE model combining blank-forging and rolling processes and revealed the evolution and distribution laws of strain, temperature, grains sizes, dynamic recrystallization during the whole process. Profile rings are a kind of special-shape ring, of which the rolling process is more complex. Complex-groove and small-hole rings belong to profile rings. Comparing to simple rectangular section ring, the rolling deformation for profile rings is more complex and the researches for them are few. Hua et al. [10,11] researched the deformation behaviors and conditions of groove ball-section ring and L-section profile ring respectively in cold ring rolling by rolling simulation and experiment. Zhao and Qian [12] established a 3-D FE model for groove-section profile ring rolling and analyzed the influence of rolling ratio on the rolling process. Davey and Ward [13] developed a FE model for profile ring rolling using a new approach based on a split-operator ALE formulation combined with a flow formulation and a novel iterative solution scheme. Qian et al. [14,15] designed blanks with different shapes and sizes for T-section ring and stepped-section profile ring respectively in cold ring rolling and obtained the optimal blank design method to determine the blank size by FE simulation and experiments.

Although TRCR is similar to ring rolling, the forming principle and the stress state of workpiece in TRCR are different, leading the rolling theory, technology and equipment are different. Up to now, the researches for TRCR are few. Zhou et al. [16,17] first proposed TRCR for forming rotary parts with surface deep-groove, and took disk rotary parts with deep-groove as research objects. A valid 3-D thermal–mechanical coupling model was established, and the distribution laws of strain, temperature and force parameters in rolling were investigated. Ma et al. [18] afterwards analyzed the evolution laws of strain, temperature and force parameters of rings with small-hole and deep-groove in TRCR process by numerical simulation. Qian et al. [19] studied on the internal surface radial spread behavior in TRCR with small-hole and deep-groove rings, the cause and main influencing factors were revealed based on FE simulation. Also, Qian et al. [1] proposed a new technology named combined ring rolling based on the TRCR, which was composed of ordinary radial ring rolling and TRCR technology. This technology could precisely form rings with thick-wall and deep-groove, and the technological possibility was verified by FE simulation and experiment. These studies provide an important support for theoretical research and technological development of TRCR.

However, neither disk rotary parts with deep-groove nor ring parts with deep-groove and small-hole in above researches, of which the groove is composed of two same size steps with symmetrical geometric features. They can be formed by simple rectangular section blank. Actual complex-groove and small-hole ring parts like duplicate gears, double-side flanges and high-pressure value bodies, the geometric shape of the groove are asymmetric. The flow and distribution of material along the roll cavities in forming process are also asymmetric. Because of the use of rectangular section blank, the volume distribution is unreasonable, leading to material filling imbalance. As a result, the groove may not be precisely formed. So it is necessary to carry out the research on blank design of complex-groove and small-hole rings formed by TRCR including establishing a reasonable blank design method to realize complex-groove and small-hole rings precise formation.

In this paper, the blank design method of TRCR to produce complex deep-groove ring is proposed through theoretical analysis. Based on establishing a reliable 3D coupled thermo-mechanical FE model, the rolling process of designed blanks are studied. The simulation result is similar to the theoretical analysis, but the forming effect needs to be improved. Then a volume correction coefficient is proposed to correct the blank size. For different rings, the volume correction coefficient is often different. It is difficult to establish a mathematical formula to calculate the volume correction coefficient. Artificial neural network (ANN) is a new modeling tools, which can get the complex relationship between input and output without giving a mathematical model. Some scholars have realized the complex nonlinear system modeling and identified by using ANN, and got accurate predicted results. Kurtaran et al. [20] realized the warpage optimization of a bus ceiling lamp using FE simulation, statistical design of experiments, artificial neural network and genetic algorithm. Kwak et al. [21] used neural network and computer simulation to improve surface profile of injection molding optic lens. Shen et al. [22] adopted artificial neural network and genetic algorithm method to optimize injection molding process parameters. Yin et al. [23] established a BP neural network modeling for warpage prediction and achieved optimization of plastic products during injection molding. Thus, we use ANN to obtain the volume correction coefficient. Finally, a reasonable blank design method is proposed and verified by experiment. This study provides some scientific guidance to technology development and application for TRCR of complex-groove and small-hole rings.