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A new cylindrical ring rolling technology for manufacturing thin-walled cylindrical ring

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ABSTRACT

Ring rolling is an advanced incremental metal forming technology used to manufacture precise seamless rings. Generally, it is classified as two types. One is pure radial ring rolling in which the ring mainly produces the deformation of thickness reduction and diameter expansion and its height basically remains unchanged. The other is radial–axial ring rolling in which the ring produces the deformation of thickness reduction, diameter expansion and height reduction. Obviously, it is difficult for the above two types of ring rolling processes to achieve a large increase in the ring height. Therefore, this paper proposes a new cylindrical ring rolling process which can achieve a large increase in both the ring diameter and height. For evaluating the proposed process, a 3D elastic–plastic FE model of cylindrical ring rolling is first established and its validity is verified by the experiment carried out on a vertical NC ring rolling machine. Then, some fundamental forming characteristics, such as the geometry evolution and strain distribution of the ring, contact characteristics between the rolls and ring and power parameters, are investigated based on this reliable 3D FE model. Finally, the effect of a critical process parameter, axial rolling ratio (circumferential rolling ratio), on the cylindrical ring rolling process is revealed numerically. Through the above analysis, three highlights of the proposed process can be summarized as follows: (1) The stability and final roundness of the deformed ring can be guaranteed easily by the inner surface of the constraint roll without the guide rolls and complicated control schedule. (2) The proposed process can achieve a large increase in both the ring diameter and height. (3) Under the constant radial deformation, different axial and circumferential deformation distribution can be achieved by changing the axial rolling ratio (circumferential rolling ratio).

1. Introduction

Ring rolling is an advanced but complicated incremental metal forming technology which is widely used to manufacture precise seamless rings, such as bearing races, ring gears, aero-engine casing, nuclear reactors parts and various connecting flanges. It has wide applications in many industrial fields such as bearing, machine, automobile, petrochemicals, aeronautics, astronautics and atomic energy due to its significant advantages including lower level of noise and vibration, uniform quality, smooth surface, close tolerance and considerable savings in energy and materials cost.

Until now, many studies have been carried out on ring rolling by experimental, analytical and simulation methods. In the aspect of experimental studies, Johnson et al. [1–3] studied the rolling force, rolling torque, pressure distribution and flow pattern by radial ring rolling experiment. Mamalis et al. [4,5] investigated the cavity formation and spread and flow pattern by radial rolling plain and profiled rings experimentally. Ryttberg et al. [6] studied the effect of cold ring rolling on the evolution of microstructure and texture experimentally. Some rolling defects in radial–axial ring rolling were investigated experimentally by Yeom et al. [7] and Kim et al. [8]. Lots of studies have also been conducted on ring rolling using analytical methods. Hawkyard et al. [9] and Mamalis et al. [10] investigated the rolling force and torque in plain and T-section ring rolling based on slip line method, respectively. Lugora and Bramley [11] studied the spread in ring rolling using Hill's general theorem. Hahn and Yang [12] used upper bound method to estimate roll torque and profile formation during profile ring-rolling. Based on the established mechanical model, the stable ring rolling conditions were calculated analytically [13–19]. Over the last decade, many attempts have sought to apply

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finite element methods to ring rolling. Kim et al. [20] reported a finite element code "RING" which was developed for the FE simulation analysis of ring rolling. Yang et al. [21] simulated the T-section ring rolling process using three-dimensional rigid-plastic FE method. Shivpuri and Eruc [22] presented a computer aided program, ERCRNGROL, for the planning and simulation of the rectangular ring rolling on a radial–axial mill to achieve a defect free ring. Xie et al. [23] developed a rigid-viscoplastic dynamic explicit FE analysis system for hot ring rolling. To reduce the run time, some efficient methods have been developed for ring rolling simulation [24–28]. Based on the finite element method, Kang and Kobayashi [29] and Joun et al. [30] carried out the studies on preform design in ring rolling using the backward tracing scheme and an axisymmetric forging approach, respectively. Casotto et al. [31] presented a thermo-mechanical–metallurgical numerical model to predict geometrical distortions of rings during cooling phase after ring rolling operations. Using the FE simulation, lots of studies have also been carried out on the deformation characteristics [32–40] and process control [41–43] in ring rolling. Sufficient information on ring rolling technology can be observed in the reviews carried out by Allwood et al. [44,45], which reviewed the contributions of 174 papers by a thorough survey of work on ring rolling published in the English and Germany languages by 2004.

The above analysis is mainly focused on the two basic types of ring rolling: pure radial ring rolling (shown in Fig. 1(a)) and radial–axial ring rolling (shown in Fig. 1(b)). In pure radial ring rolling, the ring mainly produces the deformation of thickness reduction and diameter expansion and its height basically remains unchanged. In radial–axial ring rolling, the ring produces the deformation of thickness reduction, diameter expansion and height reduction. Obviously, it is difficult for the above two types of ring rolling processes to achieve a large increase in the ring height. Therefore, this paper is aimed to propose a new cylindrical ring rolling process which can achieve a large increase in both the ring diameter and height. For evaluating the proposed process, a 3D elastic–plastic FE model of cylindrical ring rolling is developed and its validity is verified by the experiment carried out on a vertical NC ring rolling machine. Based on this reasonable 3D FE model, some fundamental forming characteristics, such as the geometry evolution and strain distribution of the ring, contact characteristics between the rolls and ring and power parameters, are investigated. Finally, the effect of a critical process parameter, axial rolling ratio (circumferential rolling ratio), on the cylindrical ring rolling process is revealed numerically.

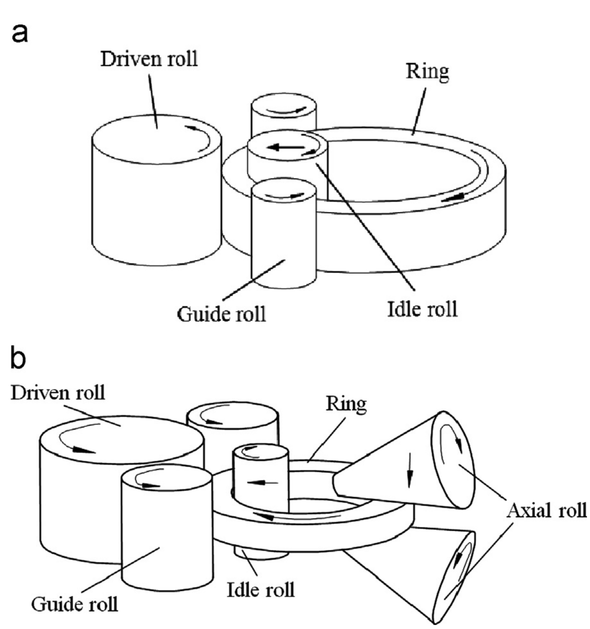

Fig. 1. Schematic diagram of the ring rolling process. (a) Pure radial ring rolling and (b) Radial-axial ring rolling.

2. Forming principle of the proposed cylindrical ring rolling process

Fig. 2 shows the schematic diagram of the proposed cylindrical ring rolling process. During the process, the constraint roll rotates actively around its axis at a constant rotational speed. Under the action of the friction force, the constraint roll takes the ring to rotate together. Simultaneously, the idle roll feeds radially towards the ring. The whole forming process includes two stages: radial ring rolling stage and axial ring rolling stage.

(1) Radial ring rolling stage. In this stage as shown in Fig. 2(a) and (b), the radial ring rolling process is established and under the actions of the constraint roll and idle roll, the ring mainly produces the deformation of thickness reduction and diameter expansion and its height basically remains constant.
(2) Axial ring rolling stage. When the outer diameter of the ring gradually increases until its outer surface completely contacts the inner surface of the constrained roll, the axial ring rolling process is established. In this stage as shown in Fig. 2(c) and (d), the outer diameter of the ring is completely constrained by the constraint roll and thus the ring produces the deformation of thickness reduction, inner diameter expansion, outer diameter constancy and height increase.

3. 3D FE modeling for cylindrical ring rolling

3.1. Establishment of 3D FE model

In this study, the FE method is adopted to evaluate the proposed cylindrical ring rolling process. Fig. 3 shows the 3D elastic–plastic dynamic explicit FE model of the process and Table 1 shows the process parameters adopted in the simulation. The FE model has the following features.

(1) The elastic–plastic formulation is adopted to improve the computational accuracy and the dynamic explicit FE procedure is used to avoid the huge computational time and convergence problem of the static implicit procedure.
(2) The two rolls are treated as the rigid bodies and the ring is treated as the deformable body. The ring is meshed by the 3D linear reduction integration continuum element with eight nodes. An adaptive mesh domain is created for the entire ring to maintain a high-quality mesh throughout the analysis. Reduced integration and hourglass control are employed to improve the computational efficiency and avoid the zero-energy mode, respectively.
(3) The loading conditions of the 3D FE model given in Fig. 3 are as follows: the constraint roll is constrained to rotate only around it own axis and its rotational speed is set to be 240 r min^{-1}. The idle roll is constrained to translate radially towards the ring and its feed rate is set to be 1 mm s^{-1}. Moreover, the rotational degree of freedom of the idle roll around its own axis is not constrained.
(4) Two contact interactions between the two rolls and ring are established: constraint roll/ring and idle roll/ring. The interactions