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Forming mechanism and characteristics of a process for equal-thickness in-plane ring roll-bending of a metal strip by twin conical rolls

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ABSTRACT

A flexible and precise forming technology for low-cost, high-efficient and high-quality manufacture of equal-thickness rings is urgently required. To this end, a novel technique for equal-thickness in-plane ring roll-bending of a metal strip (ET-IRS) by twin conical rolls is presented. In this process, the twin conical rolls are placed to form an equal-thickness roll gap. The rolls rotate in opposite directions with identical angular velocity. The strip is bitten into the roll gap by frictional force and compressed equally across its width. Under the varying boundary conditions supported by the varying tangential velocity (VTV) of the rolls and varying deformation zone (VDZ) across the strip width, monotonically varying elongation of the strip is obtained, the coordination of which creates an equal-thickness ring. The results show that the VTV of the rolls plays a major part in ring formation, whereas the VDZ has little influence. However, remarkable coupling effects of VDZ with VTV exist. In comparison with the tangential velocity of the roll, the outlet velocity at the inner half of the strip is larger, but the velocity at the outer half is smaller. As a result, the inner half and the outer half experience frictional drag and traction, respectively, which produces a bending moment acting on the strip. The deformation characteristics of ET-IRS studied by simulation and experiment demonstrate that gradients exist in the radial and hoop strain components and outlet velocity of the strip across its width. Positive radial strain at the inner rim of the strip and negative strain at the outer rim result in positive and negative spread, respectively, leading to minimal resultant spread of the formed ring. The independently adjustable parameters, such as initial position of the strip z_0, the roll gap t, the friction coefficient μ, the strip width b_0 and the cone-apex angle α, affect the deformation. The gradient of radial strain increases with decreasing z_0 and t and increasing μ and α, and the spread increases with increasing z_0 and α and decreasing t and b_0. The results indicate the forming mechanism and characteristics of ET-IRS are considerably different from existing processes.

1. Introduction

O-shape and C-shape rings are commonly used as connection or assembly gaskets to reduce unit pressure on the contacting surface or to ensure tightness and avoid leakage. They are widely used in almost all industrial fields and are generally manufactured by conventional blanking processes. However, complex production lines (e.g., aircraft production) contain increasingly more parts for connection and assembly, necessitating a large supply of gaskets of different shapes and sizes. Furthermore, conventional blanking processes are limited by their high cost, low efficiency and low quality: each type of gasket requires its own die for manufacture, the production cycle for the die is lengthy, the quality of the die determines the quality of the gasket, and the texture and streamline of the rolled blank are destroyed in the process. One proposed replacement process is the in-plane bending of metal strips through three-roll bending. Zeng et al. (2008) studied the process of plate roll bending for forming a conical tube. In this process, tensile and compressive stresses arise at the outer rim and inner rim of the plate, respectively, which can lead to wrinkling at the inner rim and fracture at the outer rim. Additionally, the process cannot produce a ring with a small radius, especially when the strip is thin. New versatile technologies are required to address these issues.

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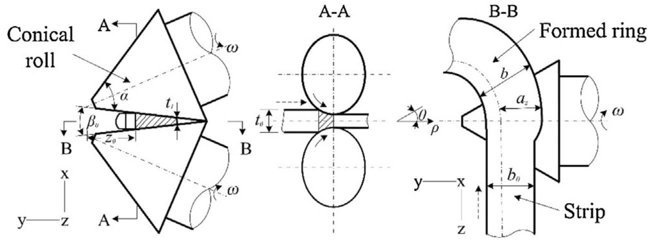

Fig. 1. Illustrated process of wedge-shaped in-plane ring roll-bending of a metal strip.

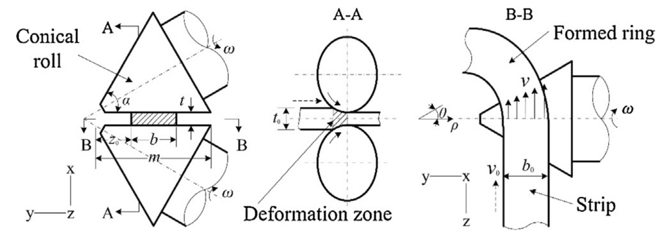

Fig. 2. The principle of equal-thickness in-plane ring roll-bending of a metal strip.

Yang et al. (2000) proposed in-plane roll-bending of the strip (IRS) through the use of two conical rolls, as illustrated in Fig. 1, and concluded that this forming process is a flexible one capable of producing ring parts with the advantages of good flexibility, high precision, high efficiency and high quality. Similar flexible rolling processes implemented in Japan were reviewed by Allwood and Utsunomiya (2006). The IRS process has been studied by Li et al. (2010) by means of 3D finite element modeling and simulation with experimental verification. In this process, twin conical rolls are positioned symmetrically in a coplanar configuration to form a wedge-shaped gap (The process is thus termed WS-IRS). The rolls rotate synchronously in opposite directions, and the metal strip enters the roll gap under the action of frictional force. The strip undergoes uneven compression across the strip width (heavy compression at the outer rim but minimal or no compression at the inner rim). As a result, the strip elongates unequally across its width. The coordination of the uneven elongation shapes the strip into a ring. As noted by Yang et al. (2004), the key factor enabling ring formation in WS-IRS is the uneven compression across the strip width. As a result, the produced ring is with thick inner and thin outer rims (i.e., an unequal-thickness ring), which limits industrial implementation of the WS-IRS process.

In addition, the uneven deformation of the strip in the WS-IRS process is controlled by the wedge angle β_0 of the roll gap, the initial position z_0 of the strip, and the minimal roll gap t_1. Here, β_0 and z_0, besides t_1, are necessarily interdependent during the adjustment process to achieve the desired thickness reduction. As a result, the uneven compression on the strip is affected by the interaction of β_0 and z_0, leading Li et al. (2011) to study the combined influence of β_0 and z_0 on ring formation. Their results showed that the bending radius decreases considerably with increasing β_0 at fixed z_0 and decreases with increasing z_0 at a fixed β_0. It is therefore challenging to adjust z_0 and β_0 appropriately to produce the desired ring. Additionally, the heavy compression at the outer rim leads to considerable spread, which increases difficulty for accurate prediction. Therefore, Li et al. (2010) established a 3D finite element model to consider the effects of spread on ring formation. Their results improved the prediction precision of the bending radius by 56.2% by compared to the results obtained by Feijun et al. (2000) with the use of the rigid-plastic finite element model. It can be concluded that precise formation control is impracticable with WS-IRS because of the difficulties both in parameter adjustment and in accurate prediction.

Table 1
ET-IRS parameters.

Description	Parameters	Meanings
Related to rolls	ω	Angular velocity
	α	Cone-apex angle
	m	Generatrix length
Related to strip	b_0	Strip width
	b	Width of the formed ring
	t_0	Strip thickness
	v_0	Inlet velocity
	v	Outlet velocity
Related to processing	t	Roll gap, i.e., thickness of the formed ring
	z_0	Initial position of the strip

Furthermore, Liu et al. (2014) noted that there exist four instability modes with WS-IRS: external wrinkling, internal wrinkling, and two types of spatial turning. Halvorsen and Aukrust (2006) showed that the probability of buckling is related to the magnitude of the compressive stresses. They confirmed that the magnitude of the compressive stress distribution controls whether buckling occurs or not. In addition, buckling is also influenced by the constraints applied on the material. In WS-IRS, the risk of buckling is increased by the larger hoop compressive stress at the outer rim of the strip and by the smaller stress at the inner rim from the bending moment. Moreover, the inner rim of the strip is subjected to weak or no constraints by the rolls as a result of little or no compression. Thus, the WS-IRS process can be applied with either full compression or partial compression, as discussed by Li et al. (2010). Therefore, both uneven compression and different constraints across the strip width can lead to the occurrence of one or more of the four forming defects.

In view of the disadvantages of WS-IRS (e.g., unequal thickness, difficulty in parameter adjustment, large spread and forming defects, as mentioned above) a revised technique for in-plane roll-bending of strips is needed. Our goal is to develop an industrial process to form an equal-thickness ring. Based on this motivation, it is natural to consider a parallel roll gap for the purpose of producing equal-thickness rings. However, a parallel roll gap implies equal thickness reduction (i.e., equal compression), which precludes ring formation because the mechanism is similar to plate rolling, e.g., in the work by Abdelkhalek et al. (2011). In their work, an initially straight flat strip passes through the equal-thickness roll gap and then elongates uniformly across the strip width as well as exhibiting identical spread at both rims. The difference between such plate rolling processes and our proposed process lies in the shape of the rolls. The rolls are cylindrical in plate rolling, but conical in our process. These conical rolls maintain varying tangential velocity and varying deformation zone on the strip across its width. This difference is the key to producing the desired ring configuration. In comparison with WS-IRS, the roll gap is different: it is wedge-shaped in WS-IRS but parallel in the new process. The one difference totally alters the mechanism for ring formation as unequal compression dominates ring formation in WS-IRS, but the new process employs equal compression. Therefore, it is necessary to determine the exact mechanism of ring formation and the characteristics of this new process.

This study combines elasto-plastic finite element analysis with experimental verification. A novel equal-thickness in-plane ring roll-bending of strip (ET-IRS) process is proposed in Section 2 for the purpose of forming an equal-thickness ring, and the corresponding mechanism of ring formation is studied in Section 3. The characteristics of ET-IRS are investigated in several aspects in Section 4. The benefits and limitations of this process are discussed in Section 5. Finally, several conclusions are drawn.