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A hybrid method for accurate prediction of multiple instability modes in in-plane roll-bending of strip

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ABSTRACT

The in-plane roll-bending of strip (IRS) is a flexible forming process to produce ring parts with advantages of low forming forces, low material waste and good flexibility. However, if deformation condition is inappropriate, it results in several instability modes including external wrinkling, internal wrinkling, turning-I and turning-II. Solely using pure analytical solution, implicit finite element method (FEM) or explicit FEM cannot predict all these instability modes of the strip. In this study, a new hybrid method is proposed to accurately predict all these instability modes in IRS. First, using two analytical models with two simple support conditions to simplify the actual roll-bending conditions, the eigenvalue buckling analysis and the analytical solution analysis are conducted to generate four kinds of buckling modes, respectively, and a series of imperfections are defined in the shapes of these buckling modes. Second, assigning these geometrical imperfections into the perfect geometry of strip, a series of hybrid FE models for IRS are established. Four specific case studies of external wrinkling, internal wrinkling, turning-I and turning-II are carried out. By comparing with corresponding experimental results, an appropriate imperfection and an optimal scaling factor A_i are obtained. Third, to validate our proposed method, the hybrid method is applied to five cases of arbitrary experimental condition. The comparisons between the predicted results and experiments show that the proposed method is reliable to accurately predict all instability modes in IRS.

1. Introduction

Lightweight thin-walled parts have attracted more and more applications in various industrial sectors such as aviation, aerospace and automobile. Wrinkling is one of the major defects in thin-walled parts metal forming processes along with tearing, springback and other geometric and surface defects (Kim et al., 2000). Wrinkling may be a serious obstacle to implementing the forming process and assembling the parts, and may also play a significant role in the wear of the tool. Most thin-walled parts forming processes have complicated boundary conditions (CBC), such as IRS, thin-walled tube NC bending, thin-walled part spinning, etc. (Li et al., 2009). The CBC is defined as: complex loading paths and history, complicated contact conditions caused by dynamic die constraints and complicated friction and clearance between workpiece and dies. While it is known that the boundary conditions play vital roles in restraining wrinkling in current CBC forming processes. For square plate with compression in one direction, it is found that the critical stress $\sigma_{cr} = KE(t/b)^2$ differs greatly with different coefficient K subjected to different constraints (Liang and Hu, 1983). Cao et al. (2002) emphasized that the wrinkling initiation depends heavily on boundary conditions and part geometry by analyzing the onset and post-buckling behavior of a wedge strip under various boundary constraints. Cao et al. (2007) carried out "Contact Buckling Test" on characters of contact of tooling to buckling with or without one-side contact, and four different buckling phenomena were obtained. They concluded that the contact obviously delays the initiation of buckling Yang et al. (2010) investigated the effect of different friction conditions on wrinkling occurring in thin-walled tube rotary-draw-bending process, they concluded that the larger friction on tube–wiper die helps decrease the wrinkling tendency. And for this reason, instabilities in these thin-wall parts forming processes are much sensitive to the above CBC, and show multiple wrinkling modes for a small deviation of these conditions.

In-plane roll-bending of strip (IRS) shown in Fig. 1, constrained by two symmetrical conical rollers rotating in the opposite direction, is a typical CBC process (Yang et al., 2004). The formed rings of various in-plane processes for different unequal deformation conditions and materials have been achieved (as shown in Fig. 2(a)), and high forming limits of up to 91.6% for AA-3003O (the equivalent percentage elongation for a ring) have been obtained in the authors' laboratory compared with conventional process. However,

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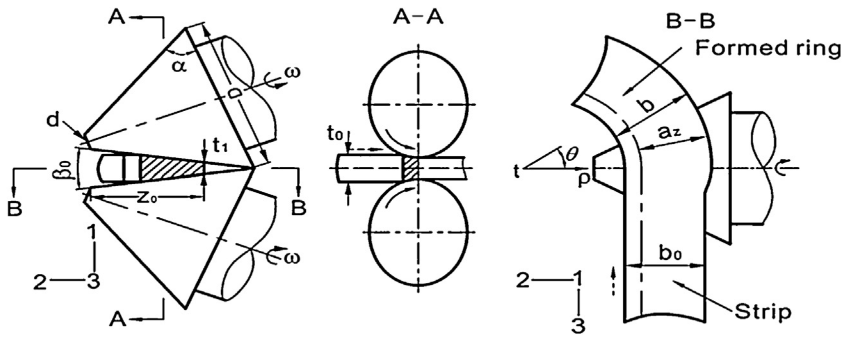

Fig. 1. Schematic diagram of the IRS process, in which two coordinate systems are used: for the strip, 1, 2 and 3 denote the thickness, transverse and longitudinal directions, respectively.

a workpiece of strip metal, monotonically unequally compressed over the width direction, has two obvious compressive stress areas on the inner and outer edges of the strip (shown in Fig. 2(b)). Halvorsen and Aukrust (2006) pointed that the probability of buckling is related to the magnitude of the compressive stresses; they confirmed that the magnitude of the compressive stresses distribution influenced whether buckling occurs or not. Therefore, the two unique longitudinal compressive stress distributions are the cause of the workpiece suffering multiple instabilities. The greater is the longitudinal compressive stress, the more likely it is that the workpiece will suffer instability. It is also seen from Fig. 2(b) that the thickness continually decreases from inner to outer edges. Thereby, wrinkling instability may occur in either inner (i.e., internal wrinkling) or outer edge (i.e., external wrinkling). And on certain conditions, it simultaneously occurs in both of edges (i.e., turning-I and turning-II). These multiple wrinkling modes are shown in Fig. 3. Therefore, how to predict these multiple instability modes accurately has become one of the key problems urgently to be solved for the development of this advanced IRS process at present.

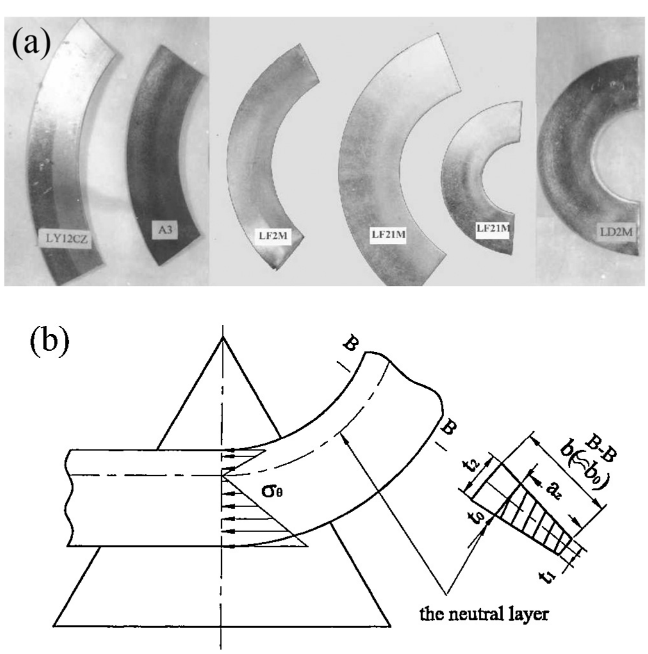

Fig. 2. A typical CBC process of IRS: (a) photograph of the formed rings of different deformation conditions and materials; (b) schematic view of the compressive longitudinal stress areas in the deformation region of the loaded workpiece (Yang et al., 2000).

Up to now, much effort has been devoted to studying the wrinkling from both experimental and theoretical (i.e., analytical solution and numerical simulation). But accurate prediction of wrinkling instability is still one challenge and a focused issue, especially for thin-walled part plastic forming process with CBC.

It is known that the analytical bifurcation theory is mostly used to solve the instability problems of simple boundary conditions (SBC). Paquette and Kyriakides (2006) investigated the plastic buckling and collapse of long cylinders under internal pressure and axial compression. Bardi et al. (2006) investigated the plastic buckling and collapse of circular tubes under pure axial compression. Peek (2002) solved the problem of a tube under pure bending as a generalized plane strain problem, and the onset of wrinkling is predicted by introducing buckling modes involving a sinusoidal variation of the displacements along the length of the tube. Cao and Wang (2000) developed an analytical model for the onset of the sheet wrinkling under normal constraints and transverse tension. Kadkhodayan and Moayyedian (2011) studied the elastic and plastic wrinkling of flanges in deep drawing using a bifurcation functional and Tresca yield criterion. Wang and Cao (2000a) proposed an analytical model for the onset of plate wrinkling under normal constraint, and it works well to predict the onset of wrinkling in a square cup forming. Shafaat et al. (2011) developed new analytical deflection function in deep drawing process of conical cups, and investigated effects of material anisotropy on the onset of wrinkling using Hosford and Hill-1948 yield criteria. Referring to the above cited literatures, they are all typical examples of SBC, such as the buckling of a column under pure axial loading or pure bending, the buckling of a compressed plate and the wrinkling of a deep-drawing process. Due to the absence of dynamic die-contact, clearance and friction, the SBC can be easily analytically formulated. Therefore, an analytical solution is suitable only for solving some simple forming problems without CBC.

Riks (1979) proposed a continuation implicit method by which the post-bifurcation analysis can be carried out along the secondary solution path. As a static implicit algorithm, this solving method not only considers the singular point (singular of tangent stiffness matrix) of the equilibrium at each step of the deformation, but also tracks the actual load and displacement to obtain all the state information of the structural instability during the entire forming process. Kim et al. (2000) introduced a continuation method to analyze the puckering initiation and growth in the spherical cup deep drawing process. However, thin-walled parts forming process with CBC always possesses their own various complicated contact and friction boundary conditions, and these methods cannot be used to solve large complex contact problem (deteriorated convergence). Therefore, they concluded that the implicit algorithm is usually avoided in CBC finite element codes.

By using a combination of finite element analysis and energy conservation, Cao and Boyce (1997) proposed a new criterion for