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An imperfection-based perturbation method for plastic wrinkling prediction in tube bending under multi-die constraints

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ABSTRACT

The prediction of plastic wrinkling in sheet metal forming process with multi-die constraints is difficult. In this paper, taking rotary draw bending of large diameter thin-walled Al-alloy tube bending as research objective, combined with initial imperfection and finite element (FE) method, an imperfection-based perturbation method is proposed to accurately predict wrinkling in tube bending process under multi-die constraints. Considering the distribution of compressive stress in the tube bending process, two simplified models, i.e., tube under pure bending and tube under axial compression, are employed to obtain the buckling modes of a tube in rotary draw bending. By using the eigenvalue buckling analysis and Timoshenko's energy method, two kinds of geometrical imperfection are generated based on the above simplified models, respectively; These geometrical imperfections are embedded into a series of explicit FE models to induce wrinkling in tube bending under multi-die constraints; By updating the wavelength and the magnitude of the imperfection, the imperfection leading to the lowest deformation energy is chosen as the appropriate imperfection; The predictive capability of the imperfection-based perturbation method is validated by using two types of bending experiments, viz., bending with wrinkling and wrinkling-free bending. It is shown that the proposed predictor is more sensitive to the wrinkling compared with the pure explicit FE results with perfect geometry. By providing an over prediction of wrinkling, a "lower bound" forming conditions are obtained, which ensures a reliable wrinkling-based process design for complicated forming process under multi-die constraints.

1. Introduction

Lightweight thin-walled parts have attracted more and more applications in various industrial sectors such as aviation, aerospace and automobile. This kind of thin-walled structure usually has a very small diameter thickness ratio (thin wall pipe $\Phi/t>20$) or width thickness ratio (thin plate $80>W/t>8$), thus, the bending stiffness of such structure is small. Furthermore, thin-walled parts forming process always possesses their own various complicated contact and friction boundary conditions, thus unequal compression stress inevitably occurs in the thin-walled structure. Small bending stiffness and large local distributed compressive stress will increase the likelihood of wrinkling during thin-walled part forming production. 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 [15].

The tube bending process, based on a rotary draw bending (RDB) method, is a typical thin-walled part forming process with complicated boundary conditions. Under multi-die constraints as shown in Fig. 1(a), the wiper die are designed for eliminating the wrinkling on intrados of the tube; the mandrel and balls are also both inserted into the hollow tube to prevent wrinkling and cross-section distortion. As a result, there are five complicated contact interfaces (multi-dies) altogether in the tube bending progress: tube-wiper die, tube-mandrel, tube-bend die, tube-pressure die and tube-clamp die. In practice, if deformation condition is inappropriate, it results in severe wrinkles on the intrados of the tube. Especially, with an increase in diameter and a decrease in thickness, the thin-walled tube cannot ever support biggish compressive stress because of their small bending rigidity. The result of compressive stress is that buckling occurs and wrinkles are formed easily (shown in Fig. 1(b)). Meanwhile, manufacturing experience suggests that the wrinkling during tube bending is strongly affected by process conditions and can be dramatically induced by a small deviation of the process conditions such as the contact condition, the original position of the blank and the perturbation of clearances between tube and dies [20,35].

Motivated by this challenge, much effort has been undertaken by industrial and academic researchers aimed at accurately predicting the wrinkling in tube bending process. It is known that the analytical solution and experiment method are mostly used to serve for some simple compressive instability problems with less

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Nomenclature

ΔU	external work done by membrane forces
ΔT	bending energy
Φ	the diameter of the tube
W	the width of the plate
p	load
u	displacements
λ_i	the eigenvalues
ϕ_i	the ith buckling mode shape
A_i	the scale factor in eigenvalue buckling analysis
Δx_i	geometrical imperfection
a	the radius of the cylindrical shell
l	the length of the cylindrical shell
h	the thickness of the cylindrical shell
m	wave number
w	normal deflection
λ	half-wavelength in imperfection
λ_{cr}	critical half-wavelength
σ_{cr}	critical value of the compressive stress
D	bending rigidity
N_{cr}	critical value of the compressive load
E	elastic modulus
δ	elongation
$\sigma_{0.2}$	yield strength
σ_b	tensile strength
ν	Poisson's ratio
r	normal anisotropy coefficient
n	hardening exponent
k	strength coefficient
u_x	x-direction displacement of nodes along the monitoring path
u_y	y-direction displacement of nodes along the monitoring path
x_i	experimental measured value in the X axis direction,
y_i	experimental measured value in the Y axis direction
E_e	recoverable elastic strain energy
E_p	plastic dissipation energy
t_0	original thickness of tube
t	the thickness after bending
R_d	bending radius
d	diameter of the mandrel
e	extension length of the mandrel

complex geometry and boundary conditions such as the buckling of a tube under axial compression [39] or pure bending [36], tube under radial external pressure [26], a rod under compressive load [4], etc. But both the analytical and experimental methods have their own intrinsic limitation. For experiment, the wrinkling is difficult to detect by monitoring equipment due to multi-die constraints, and only the finally wrinkled parts can be observed after forming process [18]. In an analytical approach, simplifications are made in the material model, geometry and boundary conditions, and therefore it is quite limited in terms of applicability [25]. The lack of accuracy and reliable of plastic wrinkling prediction in sheet metal forming simulation is so far widely known, especially involving multi-die constraints conditions [24]. Therefore, how to predict the wrinkling instability more robustly and accurately has become one of the key problems urgently to be solved for the development of this advanced RDB process. The present effort is mainly aimed at establishing an accurate and robust simulation tool.

The increased computation capability makes numerical *method* a prime tool to solve the wrinkling instability problems. There are three types of numerical procedures that can be used to solve bifurcation problems (1) an energy method combined with finite element method; (2) a bifurcation analysis of perfect structure; and (3) a non-bifurcation analysis employing initial imperfection.

By using a combination of finite element analysis and energy conservation, Cao and Boyce [5] proposed a new criterion for wrinkling in sheet metal forming process. Then, Wang and Cao [32] further developed this method. In their energy approach, a deflection function is assumed for the plate and the critical buckling condition can be assessed by equating the internal energy of the buckled plate, ΔU, and the work done by the in-plane membrane forces, ΔT. If the internal energy for every possible assumed deflection is larger than the work produced by membrane forces, the sheet is under a stable equilibrium condition. Hence, the stability condition is expressed as $\Delta T \leq \Delta U$. The energy method combined with explicit algorithm is first proposed by Li et al. to predict wrinkling instability occurring in RDB process [18,22]. From the global viewpoint, the effects of the basic parameters including the geometrical, material and clearance and friction on the onset of wrinkling are clarified in the terms of energy, and each parameter has their own specific physical meanings.

However, the works of Li and Cao are both concerned about the bifurcation point of wrinkling, the solution after the bifurcation point cannot be further carried out. Furthermore, the energy method may not suitable to the forming process with complicated boundary condition, many assumptions are made and several vital parameters such as the friction and lubrication and variation of

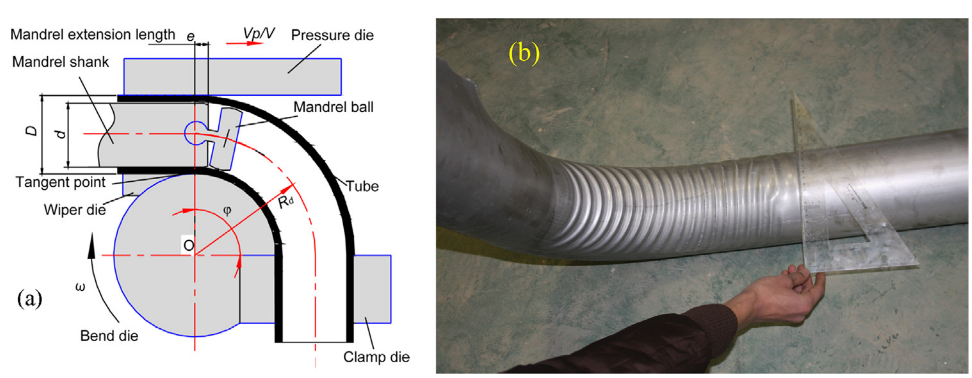

Fig. 1. Large diameters thin-walled tube under rotary draw bending: (a) with multi-die constraints; and (b) photographs of wrinkled tube (150 mm (Φ) × 1.5 mm (t_0) × 1.75 Φmm).