



11th International Conference on Technology of Plasticity, ICTP 2014, 19-24 October 2014,  
Nagoya Congress Center, Nagoya, Japan

## Modelling of wrinkling in NC bending of thin-walled tubes with large diameters under multi-die constraints using hybrid method

Nan Liu, He Yang\*, Heng Li, M. Zhan, Zhijun Tao, Xiao Hu

*State Key Laboratory of Solidification Processing, School of Materials Science and Engineering, Northwestern Polytechnical University, P. O. Box 542, Xi'an 710072, P. R. China*

---

### Abstract

Numerical control thin-walled tube bending is an advanced technology for manufacturing precision bent tube parts in aerospace, aviation and automobiles, etc. With an increase in the diameters of thin-walled Al-alloy tubes and a decrease in bending radii, accurate prediction of wrinkling instability under multi-die constraints is still one challenge and a focused issue, especially for the thin-walled Al-alloy tubes in aviation. Solely using pure analytical solution method, energy-based analytical solution method, pure explicit algorithm or implicit algorithm cannot accurately predict the wrinkling instability. In this study, the analytical bifurcation solution, analytical-numerical energy-based model and eigenvalue buckling analysis are conducted to generate different kinds of buckling modes, respectively, and a series of imperfections are defined in the shapes of these buckling modes. Second, by assigning the geometrical imperfection into the perfect mesh of the tube, a series of hybrid explicit FE models for numerical control rotary-draw-bending is established. The numerical perturbation analyses are carried out with different bifurcation modes-shapes. Thus, based on the minimum energy principle, the shape of imperfection (bifurcation path) and the magnitude of the imperfection (scaling factors) are chosen, which is corresponded to the lowest level of energy consumption. Third, a set of bending experiments is conducted on Al-alloy tube to verify the predictive capability. The predicted results are in good agreement with the experimental results.

© 2014 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/3.0/>).

Selection and peer-review under responsibility of the Department of Materials Science and Engineering, Nagoya University

*Keywords:* Thin-walled tube bending; Implicit; Explicit; Instability; Imperfection; Hybrid method

---

\* Corresponding author. Tel.: 86-029-88495632; fax: 86-029-88495632.

*E-mail address:* yanghe@nwpu.edu.cn(He Yang), liheng@nwpu.edu.cn(Heng Li).



## 2. Implementation of hybrid method for wrinkling instability in NC bending

Three kinds of hybrid methods are proposed to accurately predict wrinkling instabilities in rotary-draw-bending of thin-walled tube. First, considering the characteristics of the distributions of tension and compression stress in the tube, the actual boundary conditions of the rotary-draw-bending of thin-walled tube is thus simplified to obtain wrinkling bifurcation solution. By using analytical bifurcation solution (Corona et al., 2006), analytical-numerical energy-based model and eigenvalue buckling analysis, three different buckling modes of tube are estimated, respectively. Second, after computing the buckling mode-shapes, three different selected buckling modes are introduced into the structure as a geometrical imperfection. On account of the principle of minimum energy consumption, the shape of imperfection (bifurcation path) and the magnitude of the imperfection (scaling factors) are obtained. Third, based on the above strategy, the appropriate imperfections are seeded into the explicit 3D-FE models for the purpose of perturbing the bending tube.

A new 3D elastic–plastic FEM model assigned the geometrical imperfection is established to predict the wrinkling instability using the FE platform ABAQUS (shown in Fig. 2(a)). Taking the tube with 150 mm ( $D$ ) $\times$ 1.5 mm( $t$ ) $\times$ 1.75 $D$  mm as the research object. Experiment of rotary-draw-bending under the multi-die constrained is shown in Fig. 2(b). The three buckling modes are used in the seeding the imperfection, with the same imperfection amplitude which discussed in next. Four separate input files, which are the same as the primary input file except for the use of the \*IMPERFECTION option, are provided, with the shape of perfect of the geometry, half-circle imperfection generated by eigenvalue buckling analysis, full-circle imperfection  $\lambda_1$  generated by analytical bifurcation analysis and full-circle imperfection  $\lambda_2$  generated by energy-based wrinkling prediction model, respectively. The strategy of application of the hybrid method for wrinkling prediction is presented in Fig. 3. The detailed strategy of application is articulated in Fig. 3.

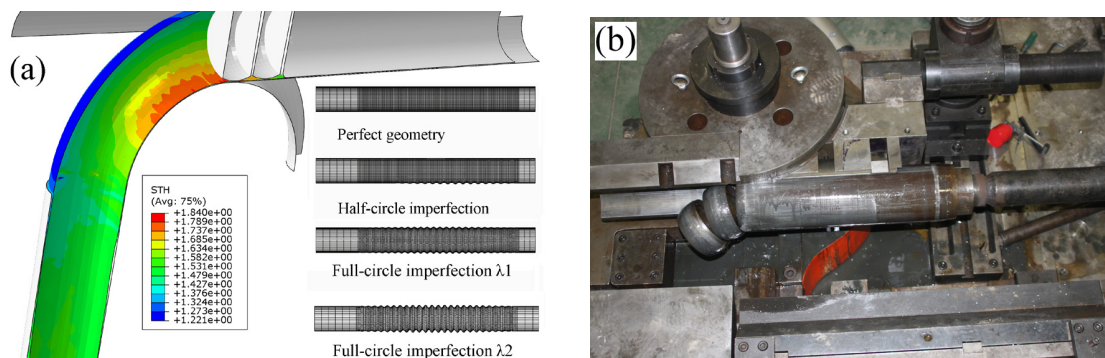


Fig. 2. The 3D elastic–plastic FEM model for rotary-draw-bending of thin-walled tube: (a) assigning three different imperfections into the 3D elastic–plastic FE model. (b) The W21YPC-159 bender machine and dies used in experiments.

## 3. Results and discussion

Recoverable elastic strain energy  $E_e$  and the plastic dissipation energy  $E_p$  which dissipated through plastic processes are the two components of the deformation energy in a bending process. Therefore, using the sum of  $E_e$  and  $E_p$ , an indicator of deformation energy is proposed as follow:  $E_{sum} = E_e + E_p$ . An investigation concerning evolution of elastic strain energy  $E_e$  and plastic dissipation energy  $E_p$  by time is carried out as shown in Fig. 4(a) and (b). It can be seen from the Fig. 4 that the order of the energy consumption of the four kinds of imperfection is: perfect of the geometry gets the largest, half-circle imperfection comes second, full-circle imperfection  $\lambda_1$  comes third and full-circle imperfection  $\lambda_2$  is the lowest one. This is due to the imperfection of analytical bifurcation analysis considers the uniform ovality in the tube pure bending, while the rotary-draw-bending has no obvious section flattening in practice (the support of mandrel and core balls). For this reason, as an imperfection for wrinkling simulation the one corresponding to the lowest level of energy consumption would be the best one. According to the minimum energy principle, the full-circle imperfection  $\lambda_2$  is chosen and employed in the following studies. The influence of the imperfection amplitude  $b$  on the calculated responses is illustrated in

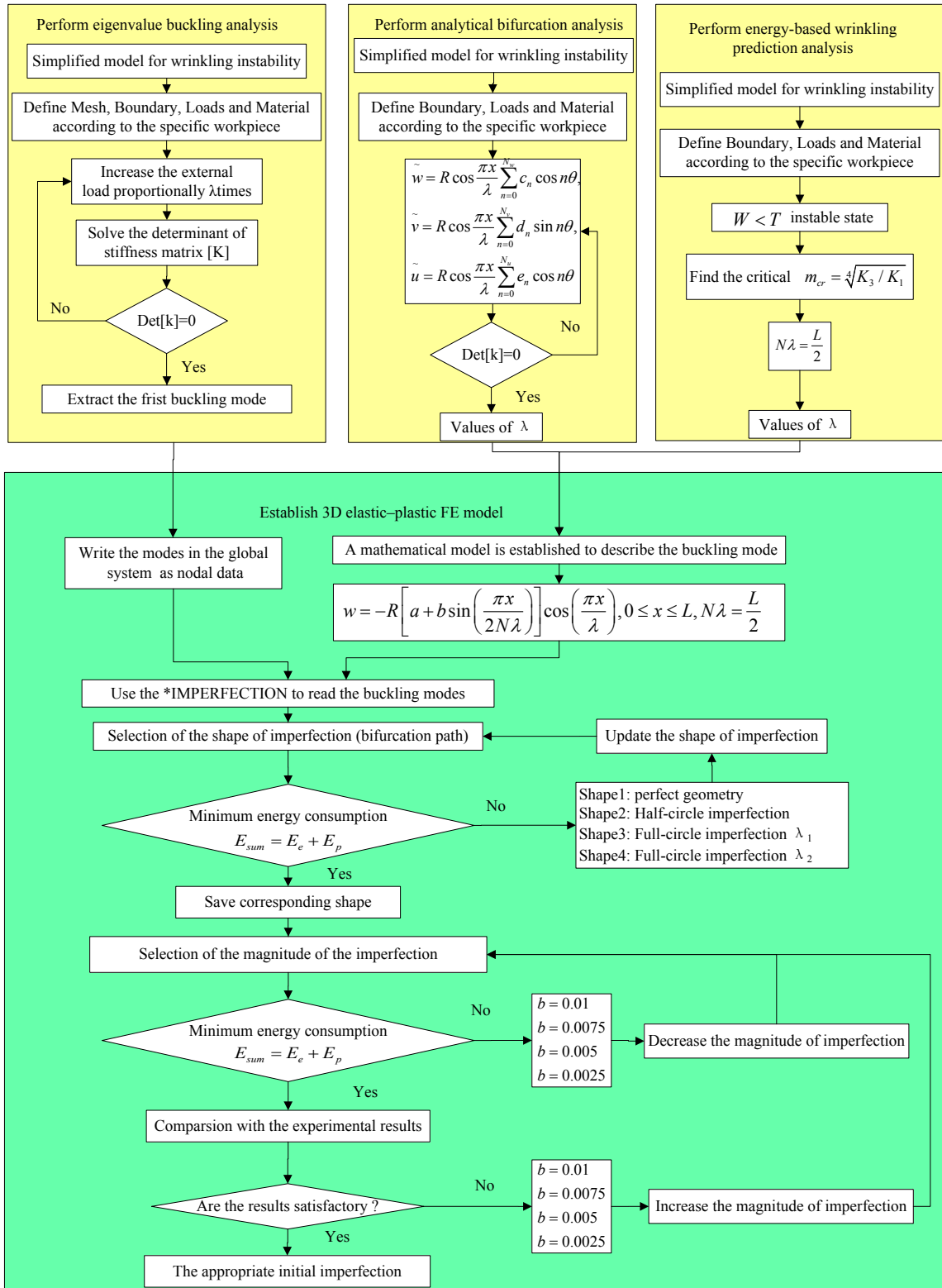


Fig. 3. The strategy of application of hybrid method for wrinkling prediction in tube bending.

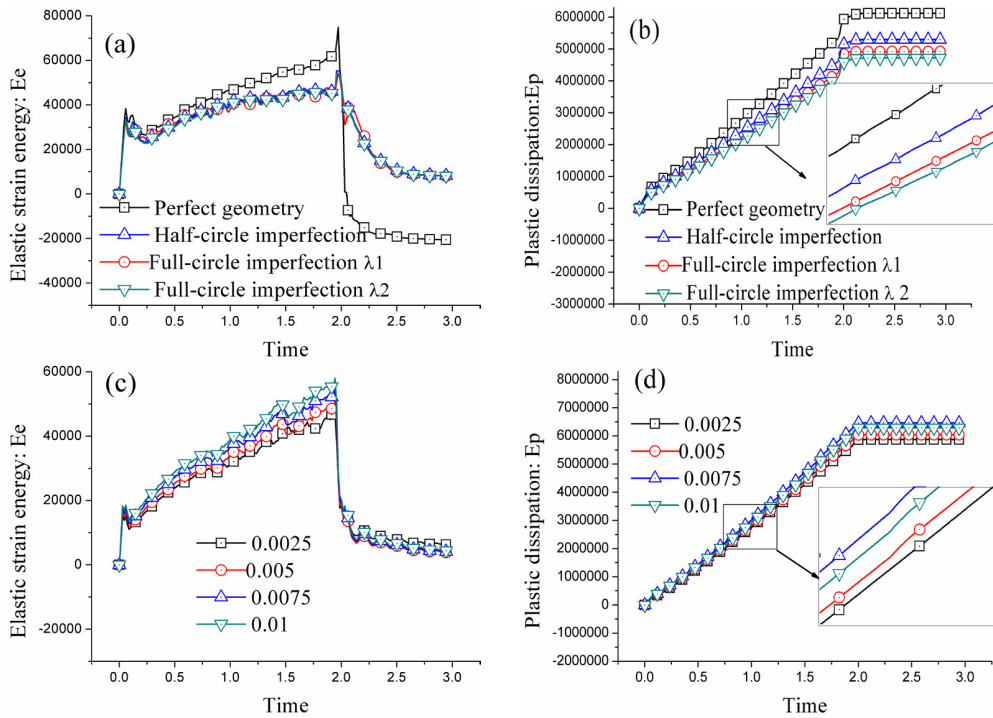


Fig.4. Selection of imperfection on wrinkling in perturbation analysis: (a) and (b) are the recoverable elastic strain energy and plastic dissipation energy for different imperfection shapes; (c) and (d) are recoverable elastic strain energy and plastic dissipation energy for different imperfection amplitude.

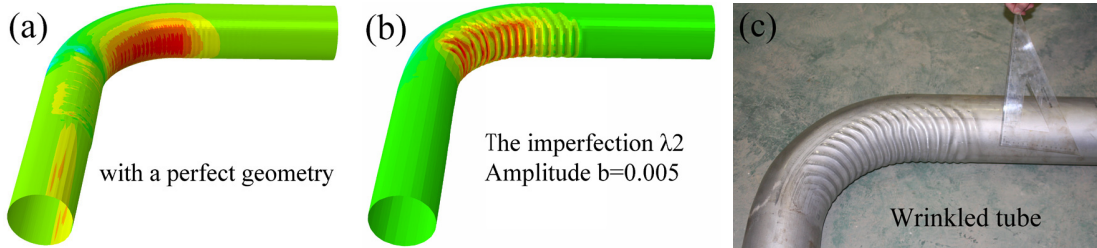


Fig. 5. Simulation results of the perturbation method: (a) with a perfect geometry, (b) with the imperfection  $\lambda_2$  and amplitude  $b=0.005$  and (c) photograph of the corresponding wrinkled tube.

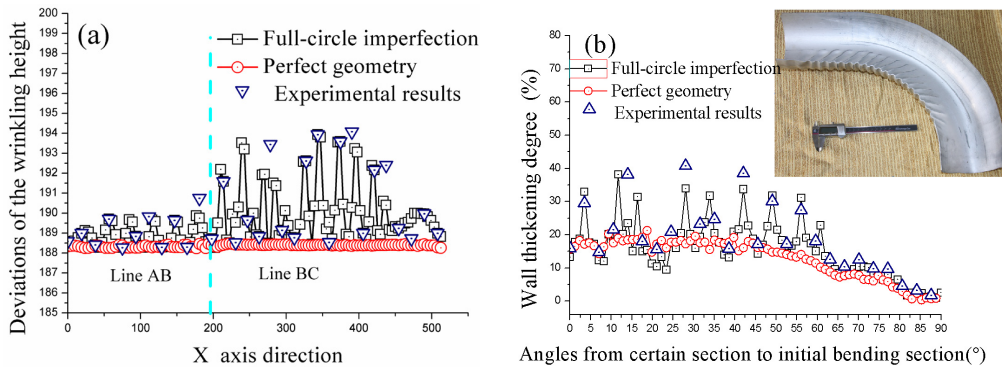


Fig. 6. Comparison of simulation results obtained by full-circle imperfection, perfect geometry and experiment result: (a) wrinkling profiles; (b) wall thickening degree.



Fig. 4(c) and (d). Based on experimental measurements the value  $b=0.005$  used in the rest of the study was selected as the most representative for the tubes tested. The results presented and discussed from now on are all based on this imperfection (full-circle imperfection  $\lambda_2$  and amplitude  $b=0.005$ ).

Fig.5 shows the wrinkling profiles obtained by full-circle imperfection  $\lambda_2$  and amplitude  $b=0.005$ , perfect geometry and the experiment result, respectively. In order to show the difference in detail, the deviations of the wrinkling height of the nodes along the intrados of the tube are shown in Fig. 6(a). It is found obviously that a perfect geometry cannot induce the instability of the wrinkling, and the hybrid method gets the best results compared with the experimental ones. This phenomenon is also accordant with the wall thickening degree in Fig. 6(b). So this study proves the conclusion that the pure explicit algorithm with perfect geometry is unreliable and inaccurate for wrinkling prediction in the tube bending, and the full-circle imperfection generated by analytical-numerical energy-based model does better than the perfect geometry model on the wrinkling detection, which is realized by perturbing the mesh of the structure with tiny imperfection.

#### 4. Conclusions

A hybrid method is proposed to accurately predict wrinkling instability in the rotary draw bending of thin-walled Al-alloy tube. Taking a large diameter thin-walled Al-alloy tube (diameter  $D=150$  mm, thickness  $t=1.5$  mm and bending radius  $1.175D$ ) as research objective, the effectiveness of the proposed procedure is validated by comparing the tube bending experimental results. The main conclusions are as follows:

Duo to multi-die constraints, the wrinkling in the NC bending process are usually can't be simulated by an implicit solver. Therefore, based on the analytical bifurcation solution, analytical-numerical energy-based model and eigenvalue buckling analysis, three buckling modes of tube are generated and embedded into the explicit FE model for NC bending. On account of the minimum energy principle, the shape of imperfection (bifurcation path) and the magnitude of the imperfection (scaling factors) are chosen. As a result, the optimal appropriate imperfection shape (full-circle imperfection  $\lambda_2$ ) generated by energy-based wrinkling prediction model and the magnitude of the imperfection (amplitude= $0.005$ ) are obtained.

Using the above optimal appropriate imperfection, a series of 3D elastic-plastic FE models assigned the initial imperfection are established. Meanwhile, the bending experiment is carried out, which is used to verify the predictive capability of the hybrid method. The hybrid method is more accurate and robust in plastic wrinkling prediction than the pure explicit finite element method (with perfect mesh), especially for the issues with complex multi-die constraints. It also provides instructive understanding of the plastic wrinkling in thin-walled part forming.

#### Acknowledgements

The authors would like to thank the National Natural Science Foundation of China (No. 50905144 and 51275415), the Program for New Century Excellent Talents in University, National Basic Research Program of China (No. 2010CB731701) and the 111 Project (B08040).

#### References

- Li, H., Yang, H., Zhang, Z.Y., Li, G.J., Liu, N., Welo, T., 2014. Multiple instability-constrained tube bending limits. *J Mater Process Tech*214,445-455.
- Kim, J., Yang, D., Yoon, J., Barlat, F., 2000. The effect of plastic anisotropy on compressive instability in sheet metal forming. *Int J Plasticity*16,649-676.
- Li, H., Yang, H., Zhan, M., 2009. A study on plastic wrinkling in thin-walled tube bending via an energy-based wrinkling prediction model. *Modelling Simul. Mater. Sci. Eng.*1-33.
- Halvorsen, F., Aukrust, T., 2006. Studies of the mechanisms for buckling and waving in aluminum extrusion by use of a Lagrangian FEM software. *Int J Plasticity*22,158-173.
- Liu, N., Yang, H., Li, H., Li, Z.J., 2014. A hybrid method for accurate prediction of multiple instability modes in in-plane roll-bending of strip. *J Mater Process Tech*214,1173-1189.
- Corona, E., Lee, L.H., Kyriakides, S., 2006. Yield anisotropy effects on buckling of circular tubes under bending. *Int J Solids Struct*43,7099-7118.