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REVIEW ARTICLE

Plastic wrinkling prediction in thin-walled part forming process: A review

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Abstract The precision forming of thin-walled components has been urgently needed in aviation and aerospace field. However, the wrinkling induced by the compressive instability is one of the major defects in thin-walled part forming. The initiation and growth of the wrinkles are interactively affected by many factors such as stress states, mechanical properties of the material, geometry of the workpiece and boundary conditions. Especially when the forming process involves complicated boundary conditions such as multi-dies constrains, the perturbation of clearances between workpiece and dies and the contact conditions changing in time and space, etc., the predication of the wrinkling is further complicated. In this paper, the current prediction methods were summarized including the static equilibrium method, the energy method, the initial imperfection method, the eigenvalue buckling analysis method, the static-implicit finite element method and the dynamic-explicit finite element method. Then, a systematical comparison and summary of these methods in terms of their advantages and limitations are presented. By using a combination of explicit FE method, initial imperfection and energy conservation, a hybrid method is recommended to predict plastic wrinkling in thin-walled part forming. Finally, considering the urgent requirements of complex thin-walled structures' part in aviation and aerospace field, the trends and challenges in wrinkling prediction under complicated boundary conditions are presented.

1. Introduction

Lightweight thin-walled parts have attracted more and more applications in various industrial sectors such as aviation, aerospace and automobile. The wrinkling induced by the compressive instability is one of the major defects in thin-walled part forming processes. 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. In order to improve the productivity and quality of products, the wrinkling problem must be solved.[1–3] However, the initiation

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of wrinkles are interactively affected by many factors such as stress state, mechanical properties of the material, geometry of the workpiece, and especially contact conditions (boundary condition). It is difficult to analyze the wrinkling initiation and growth considering all the factors because the effects of the factors are very complicated and the wrinkling behavior may show a wide scatter of data for a small deviation of factors[4,5] (see Fig. 1).

Nowadays, the trend towards designing very light-weight thin-walled structures requires that forming process involves complicated boundary conditions (CBC). The characteristics of the CBC are multiple tooling constraints, complex loading paths and history, complicated contact conditions caused by dynamic die constraints which are changing in time and space and perturbation of clearances between workpiece and dies.[1] It is known that the boundary conditions play vital roles in restraining wrinkling in thin-walled part forming processes. Consequently, the predication of wrinkling in thin-walled part forming is further complicated, which is attributed to the fact that the boundary condition during the accurate forming process is changing in time and space and the contact nonlinearities make the bifurcation check more challenging. Taking in-plane roll-bending of strip (IRS)[6,7] as an example, if deformation condition is inappropriate, it results in multiple instability modes including external wrinkling, internal wrinkling, turning-I, and turning-II.[8] The tube bending process, based on a CNC rotary draw bending (RDB) method,[9] is also a typical forming process with complicated boundary conditions. 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. If deformation condition is inappropriate, it results in multiform and asymmetric local distributed wrinkles on the surface of the tube.[10,11]

Motivated by these challenges, much effort has been undertaken by industrial and academic researchers aimed at accurately predicting the wrinkling in thin-walled parts forming processes. However, accurate prediction of wrinkling instability is still one challenge and a focused issue in thin-walled part forming processes, especially involving CBC. The prediction methods for the onset of wrinkling can be broadly divided into six categories: the static equilibrium method, the energy method, initial imperfection method, the eigenvalue buckling analysis method, the static-implicit finite element method and the dynamic-explicit finite element method. However, all the methods mentioned above have their own intrinsic limitation to predicted wrinkling under CBC.

In this paper, a review of current prediction methods is assessed in terms of their advantages and limitations. By using a combination of explicit FE method, initial imperfection and energy conservation, a hybrid method is recommended to predict plastic wrinkling in thin-walled part forming. The trend towards designing very light-weight thin-walled structures requires that forming process involves multi-dies constrains, the perturbation of clearances between workpiece and dies and the contact conditions changing in time and space. Therefore, considering urgent demands for solving the problem of plastic wrinkling prediction under complicated boundary condition, the trends and challenges of prediction methods in thin-walled part plastic forming are presented.

2. Analytical approach

Mass and great efforts have been taken in sheet metal wrinkling research using analytical approach for more than half a century. It is known that the wrinkling defects during thin-walled part forming processes can be simplified as the buckling stability of thin plate or shell under laterally constrained conditions. For example, the tube in rotary draw bending and the cylinder in spinning forming can be simplified to a shell model. Stamping of sheet and in-plane roll-bending of strip can be simplified into a thin plate model. The analytical approach is mainly based on the static equilibrium method, the energy method and initial geometric imperfection method. A comprehensive comparison of the characteristics of the above three methods are shown as follows.

2.1. Static equilibrium method

In the static equilibrium method, for a thin plate undergoing the uniform stress field of in-plane compressive loading, P_x, in the x-direction, P_y, in the y-direction and P_{xy}, in x–y plane, assuming that these stresses are parallel to the mid-plane and all the stress states that through the thickness is uniform before buckling (see Fig. 2). In Fig. 2, W is the width of the plate and L the length of the plate.

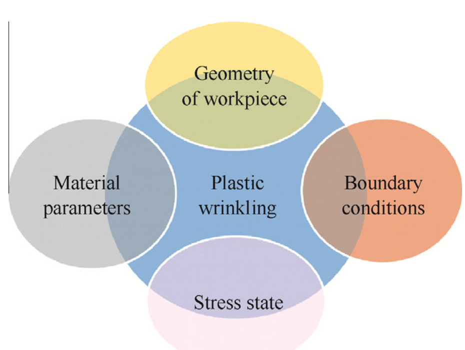

Fig. 1 Plastic wrinkling is interactively affected by stress state, material parameters, geometry of workpiece and contact conditions.

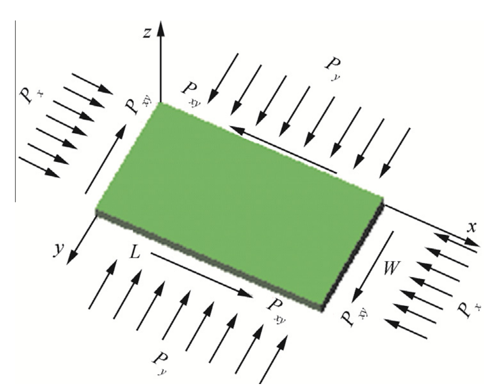

Fig. 2 A rectangular thin plate under in-plane compressive loading.