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Plastic wrinkling model and characteristics of shear enforced Ti-alloy thin-walled tubes under combination die constraints and differential temperature fields

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Abstract Plastic wrinkling predictions and shear enforced wrinkling characteristics of Ti-alloy thin-walled tubes under combination die constraints have become key problems urgently in need of solutions in order to improve forming quality in their shear bending processes under differential temperature fields. To address this, a wrinkling wave function was developed by considering their shear bend deformation characteristics. Based on this wave function and the thin shell theory, an energy prediction model for this type of wrinkling was established. This model enables consideration of the effects of shear deformation zone ranges, material parameters, loading modes, and friction coefficients between tube and dies on the minimum wrinkling energy. Tube wrinkling sensitive zones (WSZs) can be revealed by combining this wrinkling prediction model with a thermal-mechanical coupled finite element model for simulating these bending processes. The reliability of this wrinkling prediction model was verified, and an investigation into the tube wrinkling characteristics was carried out based on the experimental conditions. This found that the WSZs are located on either a single side or both sides of the maximum shear stress zone. When the friction coefficients between the tube and the various dies coincide, the WSZs are located on both sides. The larger the value of the tube inner corner radius and/or the smaller the value of the outer corner

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radius, the smaller the wrinkling probability. With an increase in the value of the moving die displacement, the wrinkling probability increases at first, and then decreases.

1. Introduction

As a compact, light-weight component with high strength and performance, Ti-alloy thin-walled tubes with ultra-small bend radii (bend radii and tube diameter ratios < 1) integrate structural and material advantages in a way that makes them be widely applicable to aerospace, aviation and related high technology industries. Tube bending is a key technology for manufacturing tube parts, and it has shown a tendency to focus its development on these Ti-alloy thin-walled tubes.[1] In contrast to the existing rotary draw bending[2–5] and push bending,[6] a shear bending process under differential temperature fields, as shown in Fig. 1, has provided an innovative solution to enable the manufacturing of these Ti-alloy thin-walled tubes while decreasing yield strength and improving formability.

In Fig. 1, a tube is bent first by shear force. After passing along die corners, its bend deformation zone transforms into a vertical segment that enables the transfer of shear force to the tube blank. This vertical segment is subjected to a shear stress where there is an evident shear deformation zone. Both sides of the shear deformation zone are subjected to a compressive stress respectively, and thus the tube can possibly wrinkle. Fig. 2 shows the tube's shear enforced wrinkling defects.[7,8] The probability of tube wrinkling grows with the increases in tube diameter and decreases in bend radius. The tube forming processes need combination dies and differential temperature fields to act in coordination. Thus, the plastic wrinkling predictions and shear enforced wrinkling characteristics of Ti-alloy thin-walled tubes have become problems that urgently need to be solved in order to improve forming quality and achieve forming limits in these shear bending processes. A great deal of research about the predictions of shear enforced wrinkling has been carried out mainly in plates or membranes under simple boundary conditions,[9–12] however, there are hardly any published studies on the plastic wrinkling predictions of shear enforced tubes under combination die constraints and differential temperature fields.

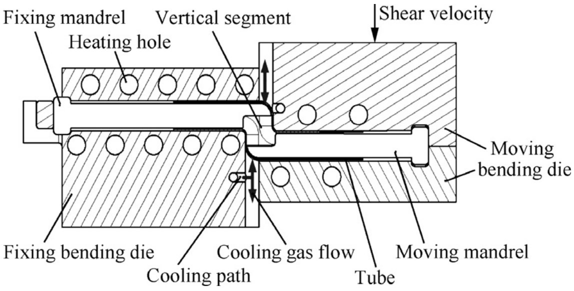

Fig. 1 Shear bending process of Ti-alloy thin-walled tube under differential temperature fields.

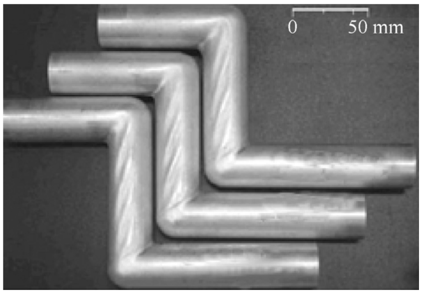

Fig. 2 Tube shear enforced wrinkling.[7,8]

Over the last several decades, three kinds of methodologies have been used for determining the critical conditions of wrinkle onset in order to predict plastic wrinkling in sheet and/or tube metal forming processes. These consist of an experimental approach, a bifurcation theory and an energy method.

(1) The experimental approach is based on critical wrinkling displacement or strain fields measured online in metal forming processes. Yoshida[13] developed a buckling test, and the critical amplitudes of buckling are measured to estimate a sheet's anti-wrinkling abilities in an unequal stretch process. Narayanasamy and Loganathan[14] studied the wrinkling in the deep drawing process of circle cup parts without blank holding pressure constraints, and the critical hoop strains and radial strains ratios of wrinkling zones had been used for estimating wrinkling.

(2) The bifurcation theory is based on the bifurcation functionals proposed by Hill[15] or Hutchinson[16]. When the solutions of their variation equations are nonzero, wrinkling occurs. Kim et al.[17–19] combined Hill's bifurcation theory and a continuation method proposed by Riks[20] for post bifurcation analysis along a secondary solution path with an implicit finite element (FE) code. The deep drawing process of a cone part and the Yoshida buckling test process were simulated by using this modified code, and the critical displacement fields in these two processes had been acquired. Chu and Xu[21] simplified the sheet deep drawing process as a two dimensional problem, and analyzed the critical wrinkling stresses by using the bifurcation theory. Based on Hutchinson's functional, Abbasi et al.[22] analyzed the flange of tailor welded sheets, and Pourmoghadam et al.[23] analyzed the critical blank holding pressures of anisotropic laminated sheets. Ravindra and Dixit[24] combined Hill's functional with the implicit FE method, and considered the determinants of the coefficient matrixes of its variation equations as the critical wrinkling conditions of the flanges of square cup parts.

The explicit FE method enables simulations of post bifurcation behaviors along a secondary solution path in forming