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Hole flanging with ironing process of two-ply thick sheet metal

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Abstract: An incremental updated Lagrangian elasto-plastic finite element method(FEM) was employed to analyze the hole-flanging with the ironing of circulate plates using a pre-determined smaller hole at the center of the two-ply sheet metals. An extended $r_{\min}$ technique was employed such that each incremental step size can be determined not only by the yielding of an element Gaussian point, but also by the change under the boundary conditions of penetration, separation, and the alternation of the sliding-sticking state of friction along the tool-sheet interface. Two-ply sheet metals are generally composed of metals that have different mechanical properties. Thus, the forming process of these materials is complicated. A number of experiments and simulations were performed using a conical punch with a cone angle of 45°. The experimental results were compared with FEM-simulated results. It is found that using the elasto-plastic FEM can effectively predict the generation process of the deformed shape until unloading. The calculated sheet geometries and the relationship between punch load and punch travel are in good agreement with the experimental data.

Key words: hole-flanging; ironing; elasto-plastic; finite element method; sliding-sticking friction

1 Introduction

Hole-flanging is one of the important techniques of sheet metal forming, and has been used widely when manufacturing industrial parts. After forming, the products are mainly offered for thread cutting to carry on with second machining and coordinated as a strut when connecting pipelines or supporting other parts[1]. One of the related studies is that of JOHNSON et al[2]. They performed an experimental study on the deformation of circular plates leading to fracture of the lip in the hole-flanging process. They applied the plastic anisotropy of the Hill onto the plane stress condition to forecast the change in thickness along the edge of expanded hole on the sheet material and to discuss the distortion pattern of the expanded hole of the curving flanged part after the sheet material was burst. They also discussed the influence of the plastic properties of the material and processing geometry on hole-flanging. TANG[3] proposed a finite element method(FEM) using the membrane shell theory while ignoring the bending effect. He used four different punch shapes, i.e. hemispherical, ellipsoid, cylindrical and conical to analyze the distribution of the sheet material's stress and strain during the hole-flanging process. The result showed that the strain path is independent of the punch shapes during the formation process, but that the maximum punch load depends on the punch shapes. TAKUDA et al[4] used pure zirconium sheet to perform the deep-drawing and bore-expanding test in order to obtain its basic formability. They also carried out a simulation using the rigid-plastic FEM and the criterion of ductile fracture to predict the forming limitation of zirconium sheet. The results showed that in the process of deep-drawing and bore-expanding, the forming limitation of zirconium sheet would decrease significantly along with the reduction in punch profile radius. The forming characteristics of hole-flanging with ironing for bimetal sheets have been studied recently using a conical punch with a cone angle of 45° by KUMAGAI et al[5]. Their experimental and simulated results demonstrate that rigid-plastic FEM can effectively simulate the forming process. YAMADA et al[6] studied the effects of initial yield stress and strain hardening on bore-expanding using the incremental theory of plasticity with a flat-headed cylindrical punch to determine the stress and strain distribution. WANG et al[7] found that the state of stress in the flanged neck is dominantly uniaxial according to a total strain membrane

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theory of rigid-plasticity for analysing the stretch flanging of a clamped sheet of anisotropic material using a spherical punch. TAKUDA et al[8] examined the formability of bore-expanding using the rigid-plastic FEM with the ductile fracture criterion to find the fracture initiation sites of sheets. JOHNSON et al[9−10] found that the lip always fractures at the outer edge owing to excessive hoop tension and tensile instability when a conical punch is used. Besides the plastic properties of material, such as strain-hardening and anisotropy, which affect the formability in the hole-flanging process[11−12], other external influencing factors include the lubrication condition, the punch shapes and the clearance between the punch and die[13−15]. The effect of cone semi-angle of a truncated conical punch on the limitation of formability in the process has not been explored.

In this study, the elasto-plastic finite-element code, developed from the updated Lagrangian formulation, was adopted to simulate the hole-flanging with ironing process under variable parameter conditions. An experiment from Ref.[5] was used to confirm the accuracy of theoretical estimation and the formula developed using the elasto-plastic FEM.

2 Description of basic theory

2.1 Variational principal

The variational principal, with respect to current deformed material on the basis of an updated Lagrangian formulation using Jaumann rate of Cauchy stress, can be expressed as[16]

$$\int_V (\tilde{\sigma}_{ij} - 2\sigma_{ik}\dot{\varepsilon}_{kj})\delta\dot{\varepsilon}_{ij}\mathrm{d}V + \int_V \sigma_{jk} L_{ik}\delta L_{ij}\mathrm{d}V = \int_{S_\mathrm{f}} \dot{t}_i \delta v_i \mathrm{d}S \tag{1}$$

where $\tilde{\sigma}_{ij} = (\dot{\sigma}_{ij} - \varpi_{jk}\sigma_{kj} + \sigma_{ik}\varpi_{kj})$ is the Jaumann rate of Chaucy stress, σ_{ij} is the Eluer stresses, $\varpi_{ij} = -\varpi_{ji} = \frac{1}{2}(\dot{u}_{i,j} - \dot{u}_{j,i})$ is the anti-symmetrical rotation rate tensor, $\dot{\varepsilon}_{ij}$ is the strain rate tensor, $L_{ij} = \dot{u}_{j,i} = \partial v_j / \partial X_i$ the velocity gradient tensor, X_i is the spatial fixed Cartesian coordinate, $v_i = \dot{u}_i$ is the velocity of node, $\dot{t}_i$ is the rate of the nominal traction, V and S_f are the material volume and surface where the traction is prescribed.

2.2 Finite element discretization

As the principle of virtual work rate equation and the constitutive relation are linear equation of rates, these can be replaced by increments defined with respect to any monotonously increasing measure, such as the tool displacement increment.

Following the standard procedure of finite elements to form the whole global stiffness matrix, we obtain

$$[\boldsymbol{K}]\{\Delta u\} = \{\Delta F\} \tag{2}$$

where

$$[\boldsymbol{K}] = \sum_e \int_{V^e} [\boldsymbol{B}]^\mathrm{T} ([\boldsymbol{D}^\mathrm{ep}] - [\boldsymbol{Q}])[\boldsymbol{B}]\mathrm{d}V + \sum_e \int_{V^e} ([\boldsymbol{E}]^\mathrm{T} - [\boldsymbol{G}])[\boldsymbol{E}]\mathrm{d}V \tag{3}$$

$$\{\Delta F\} = (\sum_{<e>} \int_{S^{<e>}} [N]^\mathrm{T} \{\dot{t}\}\mathrm{d}S)\Delta t \tag{4}$$

In these equations, $[\boldsymbol{K}]$ is the global tangent stiffness matrix, $[\boldsymbol{D}^\mathrm{ep}]$ is the elemental elasto-plastic constitutive matrix, $[\boldsymbol{N}]$ is the shape function matrix, $[\boldsymbol{B}]$ is the strain rate-velocity matrix, $[\boldsymbol{E}]$ is the velocity gradient-velocity matrix, $\{\Delta u\}$ denotes the nodal displacement increment, and $\{\Delta F\}$ denotes the prescribed nodal force increment. $[\boldsymbol{Q}]$ and $[\boldsymbol{G}]$ are defined as stress correction matrices due to the current stress states at any stage of deformation.

2.3 Treatments of elasto-plastic and contact problems

The contact condition between tools and blank on each node should remain in the same state at the moment of one incremental deformation. In order to satisfy this requirement, the r-minimum method proposed by YAMADA et al[17], is adopted and extended to treat the elasto-plastic and contact problem. The increment of each loading step is controlled by the smallest value from r_1 to r_6, i.e.

$$r_\mathrm{min} = \min\{r_1, r_2, r_3, r_4, r_5, r_6\} \tag{5}$$

where r_1 confirms that the state of the element stress is the same as that on the yielding surface when the elemental stress is greater than the yielding stress, r_2 and r_3 constrain the largest principal strain and the rotation increment, respectively, to the linear relation, r_4 causes the free nodes to contact the tools, r_5 causes the contact nodes to depart from the tool surface, and r_6 gives the alternation of a friction state from sliding to sticking for the contacted node along the tool-blank interface.

3 Numerical analysis

The experimental setup and the analytical model of hole-flanging with ironing process were developed under axisymmetric condition. Because of the symmetry of the blank, only the right-half portions of the tools and work pieces were modeled. A conical punch with a cone angle of 45° and a diameter (D_p) of 18.0 mm was used. The punch had 2.0 mm land length and 1 mm punch corner radius, whilst the dies, had 1.0 mm die profile radius. The clearance (C_r) between the punch and the dies was controlled by changing the inside diameter of the dies (D_d). Setting the ratio of clearance to thickness ($R_\mathrm{c}=C_\mathrm{r}/T$) at less than unity, ironing was applied to the blank.