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Adaptive finite element simulation of sheet forming process parameters

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Process parameters;
Adaptive mesh refinement;
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Drawing process

Abstract The forming processes are influenced by several parameters including dimensions of blank, shape of the tools, mechanical properties of the blank material and type of forming process. In the present study, the sheet metal forming process with varying process parameter is simulated using the adaptive finite element techniques. In an adaptive finite element simulation, the element mesh is automatically refined, coarsened or mesh relocated optimally in areas of insufficient accuracy and sharp strain gradients. A recovery type error estimator based on the energy norm is used for guiding the h-refinement. The simulation results of sheet forming process parameters, namely type of forming process i.e. stretching and drawing, thickness of sheet and, sheet radius and punch radius ratio, are presented and discussed. It is found that the efficiency of process simulation increases with an increase in sheet thickness and decreases with an increase in radius ratios under both stretching and drawing processes.
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1. Introduction

The finite element method has won acceptance as a tool for simulation of sheet metal forming operations. Forming operations on thin sheet cause complex deformations in the blank. The nature of deformation in different portions of the blank is generally different. It could range from pure stretching to pure bending, to combined stretching and bending. The recent trend in the simulations is the use of adaptive refined mesh to increase solution accuracy and simulation reliability. The purpose of all adaptive simulations is to obtain numerical solutions efficiently and economically, i.e. restricting the discretization error within permissible limit at minimum computational cost. Sheet forming processes are influenced by several parameters including dimensions of blank, size, and shape of the punch, mechanical properties of the blank material, and radius of the die corner. Tube hydro-forming process was investigated by Jansson et al. (2007) for process parameter estimation such as material feeding and inner pressure considering problem as deformation controlled process. Adaptive mesh free simulation of buckling in sheet metal forming was carried out by Lu et al. (2005). The formability studies of metal in deep drawing process and at elevated temperatures were carried out by Lade et al. (2014) using finite element code LS-DYNA. Kačianauskas et al. (2005) has solved the elastic–plastic problem of SENB specimens using adaptive finite element analysis technique. Adaptive remeshing technique to improve

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the simulation of metal forming processes utilizing the geometrical and physical error estimators was proposed by Labergere et al. (2008). Energy based adaptive strategy for plates and laminates was presented by Rajagopal and Sivakumar (2009). Solid element adaptive procedures with single and double layer mesh were used by Chung et al. (2014) for simulation of the sheet metal forming process. The adaptive simulation of contact conditions in sheet forming processes was presented by Ahmed et al. (2015). Suresh and Regalla (2014) studied numerical efficiency of the sheet forming process maintaining the same accuracy using shell elements with different element edge lengths and adaptive mesh. An h-type adaptivity using geometric error indicator and based on the mesh free shell formulation was developed by Guo et al. (2013) for the applications in the sheet metal forming simulations. The literature review indicates that research work related to effect of forming process parameters under adaptive environment is scarce. The objectives of the present work is to apply the velocity recovery based adaptive finite element procedures to analyze the effect of parameters, namely, forming process type (stretching and drawing), blank parameters on the deformations during the sheet metal forming process simulation. The adaptively refined mesh zones, i.e. the indicators of the localized deformation zones, and their distributions including the remeshing number required to achieve the predefined accuracy under varying process parameter are studied.

2. Finite element formulation

The basic equations for the finite element model for rigid plastic or rigid visco-plastic material can be derived with the help of the variational principle. It states that among all admissible velocity fields (u_i) that satisfy the conditions of compatibility, incompressibility and the velocity boundary conditions, the actual solution is one that makes the following functional (π) stationary (Oh and Kobayashi, 1980).

$$\pi = \int_V \bar{\sigma}\dot{\bar{\varepsilon}} dV - \int_{S_f} F_i u_i dS \tag{1}$$

where $\bar{\sigma}$, is the effective stress, $\dot{\bar{\varepsilon}}$ is the effective strain rate and F_i represents surface tractions.

In the dual variational problem, the first order variation of the functional vanishes,

$$\therefore \delta\pi = \int_V \bar{\sigma}\delta\dot{\bar{\varepsilon}} \mathrm{dV} - \int_{S_f} F_i \delta u_i \, dS = 0 \tag{2}$$

The incompressibility constraint on the admissible velocity field in Eq. (2) may be incorporated using a penalty term (Zienkiewicz and Taylor, 2000) as given below.

$$\delta\pi = \int_\Omega \overline{\sigma}\delta\dot{\bar{\varepsilon}} d\Omega + k\int_\Omega \varepsilon_v \delta\dot{\varepsilon}_v d\Omega - \int_{\Gamma_f} F_i \delta u_i d\Gamma_f = 0 \tag{3}$$

where k, a so-called penalty constant, is a large positive constant.

Eqs. (2) and (3) may now be discretized in terms of nodal point velocities $\boldsymbol{v}$ of different elements and their variation $\delta\boldsymbol{V}$. From arbitrariness of δV_i, the following set of algebraic equations (stiffness equations) are obtained.

$$\frac{\partial\pi}{\partial v_i} = \sum_J \left(\frac{\partial\pi}{\partial v_i}\right)_{(J)} = 0 \tag{4}$$

where J indicates that the quantity referred to pertains to the Jth element. The small-letter suffix signifies that it refers to the nodal point number.

Eq. (4) can be simplified and expressed in the following form.

$$\boldsymbol{K}.\delta\boldsymbol{V} \quad = \boldsymbol{f} \tag{5}$$

where $\boldsymbol{K}$ is called the stiffness matrix and **f** is the residual of the nodal point force vector.

The boundary in metal forming process at time t can be assumed to be divided into three parts, namely S1 on which velocity is prescribed, S2, which is free and S3 where frictional contact occurs. The following conditions apply on each type of boundary.

$$\text{On S1}: \quad (v - vo)\cdot n \quad = 0 \tag{6}$$

$$\text{On S2}: \quad \sigma \cdot n \quad = 0 \tag{7}$$

$$\text{On S3}: \quad \Delta vt \quad = (v - vo)\cdot t \tag{8}$$

where $\mathbf{v}$, $\mathbf{v_o}$ are the material and the die velocity, $\mathbf{n}$ & $\mathbf{t}$ are unit vectors in the normal and tangential directions with respect to the die surface respectively, and σ is the stress tensor.

The constitutive equation relating deviatoric stresses (σ'_{ij}) and strain rate (ε^*_{ij}) is given as follows,

$$\sigma'_{ij} = 2.\left(\frac{\bar{\sigma}}{3\dot{\bar{\varepsilon}}}\right)\varepsilon^*_{ij} = 2.\mu\varepsilon^*_{ij} \tag{9}$$

The interpolation equations for iso-parametric element can be written as follows.

$$x(\xi,\eta) \quad = N(\xi,\eta)\cdot x \quad \text{and} \quad v(\xi,\eta) = N(\xi,\eta)\cdot v \qquad \dot{\varepsilon} = \boldsymbol{B}\cdot\boldsymbol{v} \tag{10}$$

where ξ, η are the natural coordinates, N is the shape function matrix and B is the strain rate matrix.

The global system equations are obtained from elemental equations through an assembly procedure using the Eq. (4) and (10). A two-point reduced integration is employed for the penalty terms. The non-linear system equation is solved by Newton–Raphson algorithm. To achieve convergence, linear line search technique has been used in the code. A technique based upon the least-squares fitting of velocity field over an element patch has been used to extract derivatives and stresses. An adaptively refined mesh is generated on the basis of the computed error by uniform distribution of the square of error in the elements of the domain until the global error norm is satisfied and predefined solution accuracy is obtained. The energy norm of the error is adopted for assessing of the quality of the solution (Li and Wiberg, 1994) and h-refinement scheme is employed for improving the mesh (Zienkiewicz and Zhu, 1992).

3. Illustrative examples of forming process parameters simulations

A two-dimensional finite element code **AdSheet2**, incorporating the adaptive procedures, was specifically developed for the simulation of sheet forming operation. The validation of the developed code is demonstrated by comparing the predictions of the forming load with those due to Garino and Oliver (1992) and the results of the proposed code is in good

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