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ScienceDirect
Acta Metall. Sin.(Engl. Lett.)Vol.21 No.5 pp380-388 Oct. 2008

ACTA
METALLURGICA SINICA
(ENGLISH LETTERS)
www.ams.org.cn

AN ADAPTIVE EFG-FE COUPLING METHOD FOR THE NUMERICAL SIMULATION OF EXTRUSION PROCESSES

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Manuscript received 26 October 2007; in revised form 6 March 2008

An adaptive EFG-FE coupling method is proposed and developed for the numerical simulation of lateral extrusion and forward-backward extrusion. Initially, the simulation has been implemented by using a conventional FE model. During the deforming process, mesh quality is checked at every incremental step. Distorted elements are automatically converted to EFG nodes, whereas, the less distorted elements are reserved. A new algorithm to generate EFG nodes and interface elements is presented. This method is capable of dealing with large deformation and has higher computational efficiency than using an EFG method wholly. Numerical results demonstrate that the adaptive EFG-FE coupling method has reasonable accuracy and is effective for local bulk metal forming such as extrusion processes.

KEY WORDS *Meshless method; Coupling method; Numerical simulation; Extrusion process*

1. Introduction

Large deformations often occur in the simulation of bulk metal forming. Conventional computational methods such as finite element (FE) method are not very suitable for these problems, because highly distorted elements incur computational errors and require remeshing procedures. Meshless methods eliminate the reliance on meshes and construct approximations entirely in terms of discrete nodes. This property makes them advantageous for dealing with large deformations.

The element-free Galerkin (EFG) method[1] is recognized as a representative of meshless methods. A lot of successful applications of this method to numerical simulations of bulk metal forming have been reported, proving it reasonably effective. Li *et al.*[2] presented the total Lagrangian formulation and implementation of the EFG method for the analysis of plane-strain upsetting and backward extrusion. Xiong *et al.*[3] developed the EFG method for slightly compressible rigid-plastic material models and applied it to the simulation of plane-strain rolling. Guan *et al.*[4] introduced the EFG method based on the hypothesis of the rigid/visco-plastic material and gave the numerical example of simple forging. Despite its remarkable advantages, EFG is computationally more expensive than the conventional FE method, which limits its further development.

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Regarding the maturity and comprehensive capabilities of finite element methods, it is meaningful to use meshless methods only in the subdomains where their unique advantages are beneficial. The idea of coupling EFG and FE methods came into existence. Belytschko *et al.*[5] proposed a coupled finite element-element-free Gelerkin method. A layer of interface elements is employed to blend the EFG domain and FE domain. Xiao *et al.*[6] adopted a collocation approach to couple EFG and FEM, and implemented it in some numerical examples of structural mechanics. Liu *et al.*[7] applied the EFG-FE coupling method to the analysis of elastoplastic contact problems. Rabczuk *et al.*[8] gave a general overview of the coupling of meshless methods with finite elements.

Few literatures on the coupling method for metal forming processes have been published. As severely deformed domains vary dynamically during the simulation, it is difficult to determine the specific location of the two regions, resulting in limited applications of the method. Karutz *et al.*[9] presented an adaptive FE/EFG discretization, mainly oriented for crack propagation. Nevertheless, fragmentary EFG regions may be produced in this method, making it too complicated to implement and not fit for metal forming problems.

In this article, an adaptive EFG-FE coupling method oriented for bulk metal forming is proposed. The billet is discretized with finite elements initially. During the process, the FE region where severe deformation occurs is automatically converted to an EFG region. A new algorithm is developed to generate EFG nodes and interface elements dynamically. Lateral extrusion and forward-backward extrusion are taken as numerical examples to verify the accuracy and validity of this adaptive coupling method.

2. Formulations

2.1 EFG approximations

EFG method is derived from moving least-squares approximations. The velocity field $u^{\mathrm{h}}(x)$ is written as follows

$$u^{\mathrm{h}}(x) = \boldsymbol{\Phi}(x)\boldsymbol{u} \tag{1}$$

where

$$\boldsymbol{\Phi}(x) = [\phi_1(x), \phi_2(x), \ldots, \phi_N(x)] = \boldsymbol{p}^{\mathrm{T}}(x)\boldsymbol{A}^{-1}(x)\boldsymbol{B}(x) \tag{2}$$

$$\boldsymbol{A}(x) = \boldsymbol{P}^{\mathrm{T}}\boldsymbol{W}(x)\boldsymbol{P} \tag{3}$$

$$\boldsymbol{B}(x) = \boldsymbol{P}^{\mathrm{T}}\boldsymbol{W}(x) \tag{4}$$

$$\boldsymbol{P} = [\boldsymbol{p}(x_1), \boldsymbol{p}(x_2), \ldots, \boldsymbol{p}(x_N)]^{\mathrm{T}} \tag{5}$$

$$\boldsymbol{W}(x) = \begin{bmatrix} w_1(x) & 0 & \ldots & 0 \\ 0 & w_2(x) & \ldots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \ldots & w_N(x) \end{bmatrix} \tag{6}$$

In these equations, $\phi_I(x)$ and $w_I(x)$ are the shape function and weight function associated with node I, respectively; $\boldsymbol{p}(x)$ is a complete monomial basis; N is the number of nodes whose domains of influence cover the calculating point.

As EFG approximations do not satisfy the Kronecker delta properties: $\phi_i(x_j) \neq \delta_{ij}$, essential boundary conditions cannot be directly imposed. With reference to the boundary