3D ductile crack simulation based on h-adaptive methodology

FT. YANG[a], A. RASSINEUX, C. LABERGERE[b], K. SAANOUNI

a. Laboratoire Roberval UMR CNRS/UTC 7337, Sorbonne Université, Université de Technologie de Compiègne, fangtao.yang@utc.fr
Centre de Recherche de Royallieu, BP 20529, F60205 Compiègne, France + email (12)
b. ICD/LASMIS, UMR STMR 6279, Université de Technologie de Troyes, 12 rue Marie Curie, BP2060, F10010
Troyes, France, carl.labergere@utt.fr

Abstract:

In this article, we propose a 3D h-adaptive methodology used to simulate the initiation and propagation of cracks in ductile material during metal forming process. This methodology is iterative and is performed by a loading sequence. In each loading step, the mesh is refined according to accumulation of plastic strain and damage variable. The state variable fields are transferred from coarse mesh to the fined mesh. The crack is represented by element deletion process in which the volume reduction is compensated by node relocation process. The length of each loading step is adapted in order to guarantee that the size of deleted elements is smaller than minimum size of the mesh which can be regard as a material parameter. Several numerical examples are given to show the robustness of the methodology.

Key words: 3D h-adaptive methodology, iterative loading sequence, ductile crack initiation and propagation

1 Introduction

The metal forming process is of great importance in the industry. The damage of ductile material as well as the fracture occurring during metal forming process is a great concern during metal forming processes. The 2D simulation of ductile damage [1] [2] is widely studied in the literature, however 3D simulation of ductile damage, especially the representation of the cracks based on h-adaptive methodology is still an opening problem to be discussed.

2 Damage model

The elasto-plastic model proposed by Hooputra et al. [3] is used to describe the inelastic behavior of the ductile material. The equivalent plastic strain is given by Eq.1.

$$\bar{\varepsilon}_D^{pl}\left(\eta,\dot{\bar{\varepsilon}}^{pl}\right)=\frac{\varepsilon_T^{+}\sinh\left[k_0\left(\eta^{-}-\eta\right)\right]+\varepsilon_T^{-}\sinh\left[k_0\left(\eta-\eta^{+}\right)\right]}{\sinh\left[k_0\left(\eta^{-}-\eta^{+}\right)\right]} \tag{1}$$

Where ε_T^+ and ε_T^- correspond to the equivalent plastic strain at ductile damage initiation for equibiaxial tensile and equibiaxial compressive deformation, respectively. For isotropic materials the stress triaxiality in equibiaxial tensile deformation state, η^+ , is 2/3 , and in equibiaxial compressive deformation state, η^-, is -2/3. The stress triaxiality η is defined as $\eta = -p/q$ where p is the pressure stress, q is the Mises equivalent stress and $\dot{\bar{\varepsilon}}^{pl}$ is the equivalent plastic strain rate. The damage variable D is defined in Eq. 2 which increases monotonically with plastic deformation.

$$D = \int \frac{\mathrm{d}\bar{\varepsilon}^{pl}}{\bar{\varepsilon}_D^{pl}\left(\eta, \dot{\bar{\varepsilon}}^{pl}\right)} \tag{2}$$

3 3D h-adaptive methodology

3.1 3D mesh refinement strategy

During the metal forming processes, with the plastic strain $\bar{\varepsilon}_D^{pl}$ accumulating, the damage D increases which results in a highly localized physical field. These two physical quantities are chosen as indicators to make a referenced size map. The mesh is then refined by bi-section technique [4]. This technique given by a minimum size ratio 2 between old coarse mesh and new fine mesh. This requires field transfer operator to capture the evolution of the physical field in a reliable way.

3.2 Element deletion and volume conservation

The cracks are represented by deleting totally damaged elements. The damage value ranges from 0 to 1. We define a critical damage value as $D_c = 0.99$ [5]. If all integration points in an element having the damage value bigger than this critical damage value, this element is defined as totally damaged elements. As discussed in section 3.1, the totally damaged elements located within very narrow damage bands and the size of totally damaged elements are limited to be equal or smaller than minimum mesh size. Therefore, when these elements are removed from the mesh, the volume reduction is very small. Based on this fact, the compensation of the volume can be performed by relocating the nodes on the crack surface. This process is similar to a smoothing process, however the displacements of the nodes are small. As a result, the topology of the mesh around the crack surface can be kept.

3.3 Field transfer operator

The mesh is refined according to cumulative strain and damage field. Then the nodal fields and integration fields should be transferred from old (coarse) mesh to the new (fine) mesh. Nodal fields are transferred by shape function interpolation as expressed in Eq. **:

$$S_j^{new}(x,y,z) = \sum_{i=1}^{n_{Gauss}} N_i^{old}(x,y,z) \bullet S_i^{old} \tag{3}$$

where N_i^{old} is the shape function corresponding to ith node of the containing element in old mesh which contains the node j in the new mesh. The nodal value S_i^{old} is at ith node of the containing element. The nodal value S_j^{new} is at jth node in the new mesh. Sometimes, after refinement and relocation process, a node in the new mesh may be located outside the old mesh. In order to interpolate around all boundary of the old mesh, the shape function here can be negative outside the element. In this case, we choose the element in the old mesh which is nearest to the considered node in the new mesh as the containing element. Because this node is very near to the "containing" element, the continuity of shape function is not disturbed.

Now we focus on the integration field transfer. This field transfer process is performed by Diffuse Interpolation [6]. A brief introduction of this technique is presented. This method is aimed to reconstruct the scalar field S^{new} by a local moving least square based approximation as expressed in Eq. 3 in which $\underline{P}^T$ is the basis of the approximation, $\underline{X}$ is the local coordinates centered at evaluation point $M_0\left(\underline{X}_0\right)$ and $\underline{a}$ is the unknown coefficient vector of the basis.

$$S^{new}\left(\underline{X}-\underline{X}_0\right)=\underline{P}^T\left(\underline{X}-\underline{X}_0\right)\bullet\underline{a} \tag{3}$$

In this article, we propose a linear approximation in Cartesian coordinate system to perform the field transfer process. Therefore, Eq. 3 can be developed as Eq. 4 as following:

$$S^{new}(\underline{X}_0)=\begin{bmatrix}1 & x & y & z\end{bmatrix}\begin{bmatrix}\alpha_0\\ \alpha_1\\ \alpha_2\\ \alpha_3\end{bmatrix} \tag{4}$$

The coefficient vector $\underline{a}$ is solved by minimizing the following objective function Eq. 5.

$$\text{Min}: J_\alpha\left(\underline{X}-\underline{X}_0\right)=\sum_{i=1}^{n\geq 5}\omega_i(S_i^{new}-S_i^{old})^2=\sum_{i=1}^{n\geq 5}\omega_i(\underline{P}^T(\underline{X}_i-\underline{X}_0)\bullet\underline{a}-S_i^{old})^2 \tag{5}$$

in which $\underline{X}_i$ is the coordinates of information point M_i and ω_i is the interpolating weight obtained by Eq. 6. The radius $R(\underline{X}_0)$ of a sphere which is centered at M_0, enclose all the information points $\underline{X}_i$.

$$\omega_i=\frac{W_i}{1-W_i} \quad \text{with} \quad W_i=\left(1-\frac{\left\|\underline{X}_i-\underline{X}_0\right\|}{R(\underline{X}_0)}\right)^2\bullet\left(1+\frac{\left\|\underline{X}_i-\underline{X}_0\right\|}{R(\underline{X}_0)}\right) \tag{6}$$

4 Numerical results

This adaptive methodology is used to simulate crack initiation and propagation on aluminum board under tensile test. The aluminum alloy EN AW-7108 T6 is used to run the simulation. The numerical process is carried out by ABAQUS Explicit® in a quasi-static frame. The parameters in equivalent plastic strain are listed in Tab. 1.

Table 1 Experimentally determined ductile failure parameters [3]

Parameters	ε_T^+	ε_T^-	k_0
Values	0.26	193.0	5.277

Three different shape of specimens with a uniform thickness 0.5mm are used. For each of the specimen, the initiation and propagation of the crack are displayed. The adaptive process does not influence on the evolution of the plasticity and damage field. The cracks propagate within a narrow bands. The damage field on the specimens are colored with blue equals to 0 and red equals to 1.

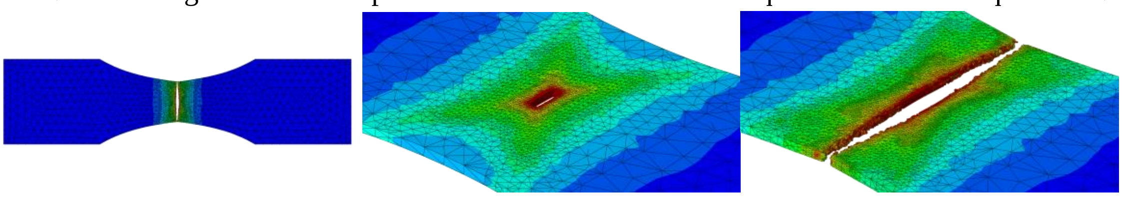

Figure 1. The crack initiation and propagation on the double arc specimen

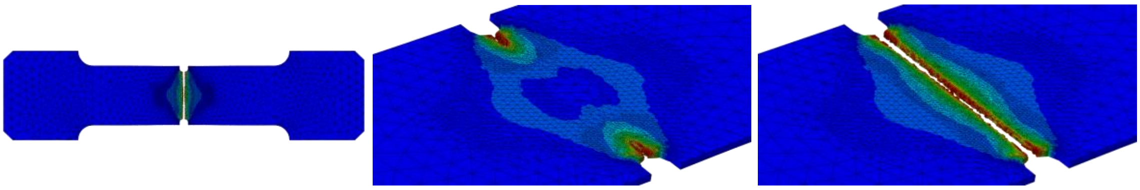

Figure 2. The crack initiation and propagation on the double notched specimen

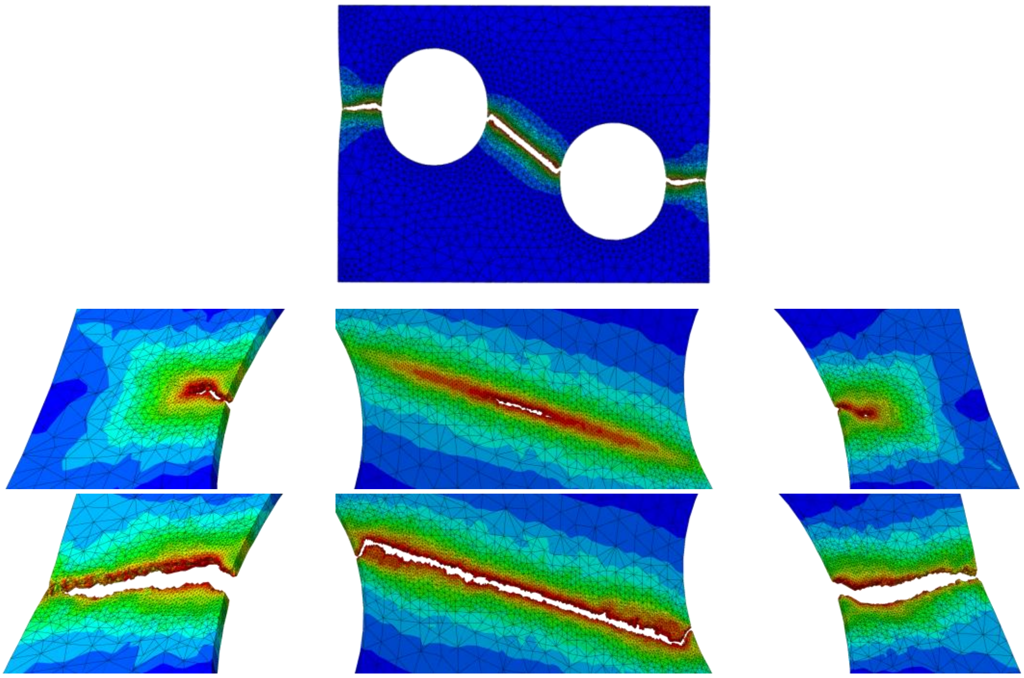

Figure 3. The crack initiation and propagation on the specimen with double holes

We can see in the Fig. 1, the double arc specimen is fixed at the left extreme and a load is added at the right extreme. The crack initiates in the middle of the specimen and propagates to the two arc boundaries. In Fig. 2, the double notched specimen is also fixed at its left extreme and a load is given at the right extreme. The crack initiates around two notches and propagates to the middle of the specimen. The specimen with two holes is fixed at the bottom and a load is given at the top. Three cracks appear on the specimen. We can see that in all numerical results the initial meshes are very coarse meshes and the meshes are refined around the cracks because of the accumulation of the plasticity and damage in these zones. The advantages of our method are that saving lots of the computational cost and no need to pre-refined mesh along the potential crack path.

References

[1] C. Labergere, A. Rassineux, K. Saanouni, Numerical simulation of continuous damage and fracture in metalforming processes with 2d mesh adaptive methodology, Finite Elements in Analysis and Design 82 (2014) 46–61.

[2] Bouchard, P. O., Bay, F., Chastel, Y., & Tovena, I. (2000). Crack propagation modelling using an advanced remeshing technique. Computer methods in applied mechanics and engineering, 189(3), 723-742.

[3] Hooputra, H., Gese, H., Dell, H., & Werner, H. (2004). A comprehensive failure model for crashworthiness simulation of aluminium extrusions. International Journal of Crashworthiness, 9(5), 449-464.
[4] A. Rassineux, 3d mesh adaptation. Optimization of tetrahedral meshes by advancing front technique, Computer Methods in Applied Mechanics and Engineering 141 (3) (1997) 335–354.
[5] K. Saanouni, Damage mechanics in metal forming: Advanced modeling and numerical simulation, John Wiley & Sons, 2013.
[6] P. Breitkopf, G. Touzot, P. Villon, Consistency approach and diffuse derivation in element free methods based 22on moving least squares approximation, Computer Assisted Mechanics and Engineering Sciences 5 (4) (1998) 479–501.