3D fracture modeling based on the coupling between damage criteria, phase field and crack propagation

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Abstract. In addition to predicting the onset of fracture, some specific material forming processes require the modeling of crack propagation and the accurate prediction of the fracture surface. In such configurations, the use of the deletion element technique is not adapted since it suffers from major mesh dependency and spurious artificial volume loss. This work introduces a new alternative in which the phase field method is coupled to a 3D automatic crack initiation and propagation technique within the Forge® finite element software.

1. Introduction

In some given metal forming processes the modeling of fracture is mandatory to get the final shape of the manufactured component. This is the case for processes such as blanking, machining or cutting. In such configurations, ductile damage can be modeled either by uncoupled or coupled damage models (the readers can refer to [1] for a review on ductile damage in metal forming). Once a given threshold is reached, fracture must be modeled. Fracture creates a discontinuity which is often modeled using the deletion element technique. This is a robust technique that consists in deleting the elements from the mesh once a damage threshold has been reached. However, this technique suffers from several drawbacks such as dependency to the mesh size and spurious volume loss. In addition, the stress field at the crack tip cannot be captured accurately since it is based on the deletion of elements.

We propose here an alternative approach that combines the phase field for ductile fracture and a 3D crack insertion and propagation technique independent from the mesh.

Initially defined for brittle fracture problems [2], the phase field method was then extended to ductile fracture [3]. This work introduces new contributions to the field so as to be applied to metal forming processes:

- a new formulation in which the phase field-damage formulation can be coupled to ductile damage models;
- adaptive remeshing followed by the identification of the crack surface intersection with arbitrary mesh topologies based on the phase field evolution [4];
- fitting the crack surface within the mesh using local mesh partitioning operations;
• A nodal duplication strategy based on the local coloring algorithm in order to open the crack faces followed by a volume remeshing step [5].

The proposed framework offers a robust numerical tool for the modeling of damage to fracture transition in complex industrial processes. Metal sheet blanking and piercing processes will be used to show the accuracy and efficiency of this new approach compared to the conventional element deletion method.

2. **The phase field method for ductile fracture**

Initially based on a formulation of the Griffith theory of brittle fracture [2], the phase field method was later on adapted to numerical computations through a regularized approximation presented in [6]. This new formulation consists in the minimization of the regularized total energy functional:

\[
E_{\text{reg}}(u, d) = \int_{\Omega_h} g_e(d) \psi_e(\varepsilon^e) d\Omega_0 + \int_{\Omega_h} G_c \gamma(d, \nabla d) d\Omega_0
\]  

(1)

Where \( u \) and \( d \) are respectively the displacement field and the phase field \((d=0\) for an intact material and \(d=1\) for a totally damaged state). \( \Psi_e \) is the elastic strain energy, \( G_c \) is the fracture toughness, \( \Omega_h \) is the volume of the domain and \( g_e(d) \) is a degradation function. The regularized fracture energy (crack surface density) is defined by:

\[
\gamma(d, \nabla d) = \frac{1}{2l_c^2} (d^2 + l_c^2|\nabla d|^2)
\]  

(2)

Where \( l_c \) is a length scale parameter.

The elastic degradation function \( g_e(d) \) is used to couple the effect of crack propagation on the bulk material. The following quadratic form is chosen \( g_e = (1 - d)^2 \) in order to satisfy the following conditions: \( g_e(0) = 1 \), \( g_e(1) = 0 \) and \( g_e'(1) = 0 \).

The minimization of the regularized energy functional with respect to the phase field parameter conducts to the following evolution of the phase field equation:

\[
d - l_c^2 \nabla^2 d = -g'_e(d) H_e
\]  

(3)

Where \( H_e \) is the local history function that is defined by:

\[
H_e = \frac{l_c}{G_c} \max_n \psi_e(\varepsilon^e(x, d_n))
\]  

(4)

Where \( n \) is a unit vector normal to the surface. As defined in [3] a plastic degradation function can be added to local history function in order to handle ductile fracture.

In the present work, it is decided to define the local history function \( H \) (replaces \( H_e \)) so as to introduce a damage variable \( D \) and its threshold \( D_{th} \):

\[
H = \eta_c (D - D_{th})
\]  

(5)

Where \( \eta_c \) is an additional material parameter used to control the post-peak stress response of the material once \( D \) has reached its threshold \( D_{th} \). And \( (x) = x \ if \ x \geq 0 \ and \ (x) = 0 \ otherwise. \) With such a formulation, it is possible to use different kinds of ductile fracture criteria such as the one presented in [1].
3. 3D modeling of fracture driven by the phase field variable

Once the damage variable has reached its threshold, the phase field variable increases leading to progressive degradation of the material’s mechanical behavior. Finally, the phase field threshold is reached leading to fracture. The idea consists in using the phase-field variable \( D \) in order to identify regions where the transition from damage to fracture should occur. It is worth mentioning here that the non-local nature of the phase-field formulation leads to a mesh independent solution, which is one of the main drawbacks of the element deletion technique.

In [5], a new methodology was implemented in Forge® in order to propagate 3D cracks. This methodology, called CIPFAR (Crack Initiation and Propagation algorithm using the phase Field model and Adaptive Remeshing), and detailed in [5] can be summarized as follows:

- The phase field is computed as described in the previous section. At this stage, an adaptive remeshing strategy is used to ensure extreme mesh refinement in the area in which fracture is expected to initiate. This strategy is detailed and validated in [4].
- The phase field solution provides a highly concentrated damage field in which the crack surface can be identified as the points that have a phase field value of 1. In order to provide a unique and accurate fracture surface localization, the phase field solution is combined with its gradient. This approach enables to deal with multiple cracks.
- The intersection of the crack surface with the mesh edges is identified and new nodes are inserted. Local remeshing operations are carried out so as to fit the crack topology with the mesh.
- The nodes lying on the crack surface are duplicated in order to open the new crack. Finally a subsequent remeshing operation is carried out to insure mesh quality and mechanical fields are transported from the old mesh to the new mesh.

The whole methodology, illustrated in Figure 1 and validated in [4, 5], provides an efficient, robust and accurate 3D initiation and propagation technique driven by the phase field computation. The CIPFAR methodology is also conservative in terms of volume, solving in this way the other drawback of the aforementioned element deletion technique.

![Figure 1: Summary of the main steps of 3D crack initiation and propagation based on the phase field computation and automatic remeshing](image)
4. Application to a multi-stage forming process

The methodology was applied to several configurations of metal forming processes such as extrusion chevrons cracking or shear cutting (see [7] for more details). The accuracy was compared to the conventional kill element technique. The CIPFAR algorithm showed very good ability to model damage to fracture transition and the failure surface quality was very convincing with particular accuracy on predicting fracture zone and burr height in shear cutting processes. In the following, the methodology is applied to a 3 stages forming process that includes blanking, piercing and finally bending.

4.1 Multi-stage process definition

The three stages of the process together with the final shape of the component are detailed in Figure 2.

![Figure 2](image_url)

Figure 2: Forming process split into a) blanking, b) piercing and c) bending. The shape of the final part is given in d) (scale not mentioned for confidentiality reasons)

4.2 Material and input process parameters

The material is a 36Mn5 steel grade with an elastic-plastic behavior with strain rate dependency. The Young modulus $E$ and Poisson ratio $\nu$ are respectively 210 000 MPa and 0.3. The yield stress $\sigma_y$ [MPa] is given by the following hardening law:

$$\sigma_y = 1.011 \varepsilon^{0.316} \varepsilon^{0.012} e^{0.018}$$

Where $\varepsilon$ and $\dot{\varepsilon}$ are respectively the equivalent strain and equivalent strain rate.

The Coulomb limited by Tresca friction law is used for the tangential contact between the different dies and the billet. The Coulomb and Tresca friction parameters are respectively equal to 0.2 and 0.4.

The normalized Latham-Cockcroft damage model is chosen to drive the phase field evolution all along the three stages (See Equation (5)):

$$D = \int_0^\varepsilon \frac{(\sigma_1)}{\bar{\sigma}} d\vec{e}$$

Where $\sigma_1$ is the maximum principal stress and $\bar{\sigma}$ is the equivalent von Mises stress. Parameter $\eta_c$ is fixed and equal to 200 whereas $D_{th}$ will be varied. The characteristic length scale $l_c$ is fixed to 1.2 mm.
An initial mesh size of 1 mm is used in the whole domain. The adaptive remeshing strategy is used to refine the mesh in the regions where the equivalent plastic strain exceeds a threshold of 0.05. Two mesh sizes are used in the numerical simulations: 0.6 mm and 0.3 mm respectively for the coarse mesh and the fine mesh. For the crack propagation simulations, the effective crack area is chosen as two times the minimum mesh size.

The accumulated plastic strain field is transferred from each step to the following one in order to reflect the effect of strain hardening on the material behavior. However, the damage field is not transferred from each stage to the next one. This assumption is necessary here in order to avoid immediate crack initiation at the very beginning of stages 2 and 3 in the immediate vicinity of the previous crack surface. This problem can be viewed as a consequence of the use of a coupled model to the material behavior at the macroscale that does not describe accurately the growth of voids near the cracked zone at the micro-scale. The size of this damaged zone should be much smaller than the characteristic length scale (and hence the smallest element size) in order to accurately capture the size of the damaged zone. However, the problem would be computationally very expensive especially in 3D calculations. It should be noted that neglecting the effect of damage might lead to inaccurate results in the cases where the damaged surface is subjected to another shearing process in the following stages. Indeed, a future investigation of this assumption is needed to have a better understanding of its limitations.

In the following, a comparison will be carried out between the conventional kill element technique and the new CIPFAR algorithm. The influences of the mesh size and of the damage threshold \( D_{th} \) are detailed in [8].

### 4.3 Results

Figure 3 shows the final shape of the part obtained after stages 1 (shear cutting) and 2 (piercing) with the new CIPFAR algorithm and with the conventional kill element technique.

At the end of stage 1, a better smoothness of the fracture surface can be observed with the CIPFAR algorithm. In addition, the formation of burrs can be accurately captured with the CIPFAR algorithm since the surface details are not eliminated during the simulation, contrary to the element deletion algorithm for which all burrs are removed from the mesh.

Regarding stage 2, two main observations can be made: (i). The discrete crack predicted by the CIPFAR algorithm leads to a better quality of the sheared surfaces as compared to the element deletion algorithm; (ii). the CIPFAR algorithm leads to an accurate prediction of the crack path which can be clearly seen in the exact contact between the punch and sheared edge. On the other hand, the deletion of elements results in a gap without any contact between the punch and the sheared edge in which the size of this gap is dependent on the mesh size.

It is interesting to notice as well that the CPU time for both methods are similar. Despite the coupling introduced by the CIPFAR algorithm, a reduced number of Newton-Raphson iterations compared to the deletion element technique conducts to a similar CPU time (see [8] for more details). In addition, the element deletion technique conducts to very rough fracture surface that can lead to degraded convergence of the mechanical resolution given the complex contact path at such rough surfaces.

Figure 4 shows the end of stage 4. In Figure 4.a two values of \( D_{th} \) are used in order to illustrate its influence on the final failure pattern. Figure 4.b shows the comparison with the experimental observation and a very good agreement both in terms of location of failure initiation and crack length.
Figure 3: Comparison between the CIPFAR algorithm (left) and the conventional element deletion technique (right) at the end of stages 1 and 2.

Figure 4: a) Influence of $D_0$ on the final fracture pattern at the end of the 3rd forming stage (bending) and b) comparison with experimental observation.
5. Conclusion

In this work, ductile fracture is addressed by enhancing the phase field approach for ductile fracture through the coupling with damage criteria. The new developed approach also deals with the transition from continuum damage to discrete fracture. A specific methodology where the crack surface is localized within the mesh based on the phase field variable and its gradient is developed. Mesh adaptation techniques are then carried out in order to incorporate 3D crack surfaces in a very robust and efficient manner to model ductile fracture propagation. The method has been successfully applied to conventional ductile fracture problems as well as to ductile fracture occurring during material forming processes.

The multi-stages process shown in this paper illustrates the accuracy of the new approach compared to the classical element deletion technique. Fracture surfaces are really smooth which makes it easier to compute further forming process stages on the result of the previous forming stage. The new method is also very efficient since the CPU time is equivalent to the one of an uncoupled failure criteria using the deletion element algorithm.

The transfer of the phase field variable from one stage to the following remains to be discussed. This phase field variable is already very close to 1 in the failed area and in a thickness layer which depends on the characteristic length scale. The transfer of this variable from one stage to the following may conduct to premature cracking in this area whereas experimentally only micro-voids would be present in this area. The same issue would arise with non-local damage approaches.

The damage criteria used here is one of the simplest dedicated to ductile fracture. However, the way damage is introduced within the phase field formulation (See equation (5)) makes it appropriate for any other kind of damage criteria as shown in [8].

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