Predicting the shape of blanked products: a finite element approach

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Abstract

Prediction of the properties of products of the blanking process is nowadays still mainly an empirical effort. The lack of fundamental knowledge of the process may cause lengthy process development, and obstructs process innovation. Consequently, a validated numerical model of the process would be of great value.

In this paper, an elasto-plastic finite element model will be introduced, in which the extremely large deformations which occur are handled by an operator split arbitrary Lagrange–Euler method combined with remeshing. Ductile fracture is incorporated by a discrete crack approach. To demonstrate the possibilities of the procedure, some simulation results are presented.

Keywords: Sheet metal blanking; Finite element method; Arbitrary Lagrange–Euler method; Remeshing; Discrete fracture approach

1. Introduction

The design and realisation of a metal blanking process (see Fig. 1) are currently mainly based on empirical knowledge of the process. Analytical models are available [1], but unable to fully capture all the phenomena involved. Numerical modelling is a possible key to gain more knowledge of the process. The objective of the current research is to generate a validated finite element model of the blanking process, able to predict product shape and residual stresses.

Blanking is one of the most widely used sheet metal operations in which a blank is separated from a sheet by a punch (see Fig. 1). The product can either be the blank or the sheet. The process itself is characterised by very large, localised deformation followed by ductile material failure. In engineering practice, the shape of the product, near the cut edge, is by far its most important property. Four characteristic zones can be distinguished (Fig. 1):

- The roll over zone. This is the part of the edge that is drawn into the sheet by the punch.
- The sheared zone. This zone is formed by the punch before the onset of ductile fracture. Generally, the surface of the sheared zone is rather smooth.
- The fracture zone. This zone has a rough surface formed by ductile material fracture as the punch progresses through the sheet.
- A burr is formed, because of the specific location of the fracture initiation.

The cut sides of blank and sheet are shaped simultaneously, and for both the areas mentioned above can be indicated. The sizes of the fracture zone and burr are items that cannot robustly be predicted by empirical models, because these sizes are mostly determined by ductile fracture. From a manufacturing point of view, however, they are often the most important quality parameters.

Recently, some finite element approaches have been presented to model the blanking process, mutually differing mainly in the way that material failure is modelled. Leem et al. [2] do not describe failure in their rigid plastic analysis of fine-blanking, which renders this model useful up to the onset of material failure. Post and Voncken [3] and Abdali et al. [4] use elasto-plastic continuum damage approaches. Although these approaches lead to more useful results, the models conceptually fail to describe the actual separation process. Furthermore, special care has to be taken to avoid...
problems concerning mesh dependence and energy dissipation with classical local continuum damage models. Another strategy presented in literature is element elimination or erosion, as used by Jeong et al. [5] and Taupin et al. [6], both employing rigid plastic material models with particular failure criteria. Although the element elimination procedure is a simple, very effective method to model failure, it is inherently mesh dependent. For the current research a discrete crack approach is used for which mesh independence has already been shown to a certain extent [7].

2. Large deformations

One of the problems in simulating forming processes with free surfaces, using the common Lagrangian finite element method, is excessive element distortion, due to finite deformations. An appropriate solution to this problem is frequent updating of the mesh, in which the element topology is either changed (remeshing) or preserved (ALE technique [8–10]). In the present strategy, both methods are combined, because the application of ALE only is not sufficient to maintain mesh quality, due to the extremely localised deformation during the blanking process.

2.1. Operator split ALE

The ALE method is implemented in an operator split way, which decouples the calculation of the deformation from the mesh adaptation. After an updated Lagrangian step, which is performed using the commercial finite element package MARC [11], the nodes are shifted to more favourable positions, to preserve mesh quality. These positions are determined by a Laplacian smoothing algorithm, which places a node at the centroid of the polygon formed by the adjacent nodes. Then the state variables are transported to this new mesh in a convective step. The problem in this convective step is that the state variables to be transported are generally discontinuous across element boundaries. By solving the convection equation based on the discontinuous Galerkin (DG) formulation from Lesaint and Raviart [12], artificial diffusion due to smoothing of the state variable fields can be limited [13].

2.2. Remeshing

As mentioned earlier, frequent remeshing is needed, nevertheless, to prevent mesh degeneration. After a number of OS-ALE steps, a full remeshing is performed. Transport of the state variables between meshes cannot be achieved using DG in space, because the mesh topology has changed. Consequently, transport is achieved by interpolation in smoothed state variable fields defined on the old mesh [14]. The algorithm can be summarised in the following steps:

- A continuous state variable field is calculated on the old mesh, by extrapolating the integration point values to the nodes at element level, and averaging the contributions of the different elements on the nodes. The extrapolation is performed using the element shape functions.
- For each integration point on the new mesh, the location on the old mesh (defined by an element number and a set of local coordinates) is determined. The old element is determined by searching for the element which forms the polygon inside which the new integration point is situated. Subsequently, the local coordinates are determined by inverse mapping, using an analytical approach suggested by Olmi et al. [15].
- Using these local coordinates, the state variable value on the new integration point can be easily interpolated between the averaged nodal values, employing the shape functions.

Remeshing is performed periodically, after a fixed number of OS-ALE steps.

3. Ductile fracture

Ductile fracture in metals is known to be caused by the growth and coalescence of voids [16–18]. These voids are holes in the material, caused by dislocation pile-ups, second-phase particles or other imperfections. Under the influence of plastic deformation, the voids can grow, until a number of voids coalesce to initiate a crack. The void growth rate is strongly influenced by the hydrostatic stress during plastic deformation, often characterised by a nondimensional parameter, the triaxiality: \( \frac{s_m}{\sigma} \) in which \( s_m \) is the hydrostatic stress, and \( \sigma \) the equivalent (von Mises) stress.

The process of coalescence is governed by localisation of deformation in a small area between two voids, often introducing local void phenomena on a smaller scale. Void link-up, caused by failure of the ligaments between the voids, allows a fracture to initiate. Fracture propagation takes place by successive coalescence of the crack with neighbouring voids.

3.1. Criteria for ductile fracture

So far, efforts to predict ductile fracture have resulted in an extensive selection of mainly local failure criteria. These
criteria predict the onset of failure at a material point by studying the stress and strain history of this point. Various criteria have been evaluated by for instance Bolt [18] and Clift et al. [19]. The Gurson model for porous plasticity [20] is one of the most applied approaches for simulation of processes involving ductile fracture. It introduces a flow rule which allows for softening due to void growth, but exhibits the same defects as local damage models if no regularisation is incorporated to avoid spurious localisation. Other classical criteria were suggested by Rice and Tracey [21], McClintock [22] and Oyane [23], all featuring an explicit dependence on the triaxiality.

The local criteria considered above are clearly distinguished from the global fracture criteria stemming from fracture mechanics, using stress intensity factors $K$, energy release rates $G$ or $J$-integrals. These criteria, based on elastic material behaviour, can generally only be applied in cases where the plastic zone is limited to a small area near the crack tip (small scale yielding). Attempts are made, however, to define fracture-mechanics based parameters for ductile fracture [24,25].

In predicting ductile fracture in metal forming processes, local criteria have been shown to be able to generate results which are reliable up to a certain extent. Since this cannot yet be established for global ductile fracture criteria, a local criterion is adopted in the present research.

### 3.2. Discrete fracture approach

Fracture can numerically be simulated either by a continuous approach as used in continuum damage mechanics, or by a discrete crack, stemming from fracture mechanics. A discrete crack model captures the actual separation process more closely than a continuum damage model. However, the localisation of deformation between voids is not adequately accounted for. Furthermore, a discrete crack approach can more easily be combined with existing FEM codes, which enhances the practical value of the model. Therefore a discrete crack approach is used for the current research.

A discrete crack approach implies that a strategy is required for adapting the mesh to accommodate cracks. In this research, a global mesh modification approach was followed which generates a completely new mesh when a crack propagates. Currently, the only elements available in MARC for robust geometrically nonlinear, two-dimensional elasto-plastic contact analysis are bilinear quadrilaterals. This complicates the execution of mesh modification, relative to triangular mesh modification, significantly.

### 3.3. Mesh modification

The main problem in implementing the mesh modification is robust quadrilateral mesh generation of a strongly nonconvex, fractured domain. It should be noted that quadrilateral mesh generation for these kinds of domains is considerably more difficult than for triangular mesh generation. The problem was solved by combining Shewchuk’s quality Delaunay triangulation mesher ‘Triangle’ [26] with a remarkably simple, but very effective, conversion algorithm by Rank et al. [27].

Given a boundary defined by a number of points, Triangle first generates a constrained Delaunay triangulation of these points, and then adds points inside the domain and on its boundary to ensure that the mesh has the prescribed quality. Subsequently, this triangulation is converted into a quadrilateral mesh, by executing the following steps:

- First a combined quad/triangle mesh is generated by merging certain couples of triangles. The couples resulting in the best quadrilaterals are merged first, while couples resulting in quads with a quality below a predefined minimum are not merged.
- Secondly, the combined mesh resulting from the previous step is smoothed.
- Next, all elements in the resulting combined mesh are split: quads are divided into four smaller quads, and triangles into three smaller quads.
- Finally, the nodal positions of the resulting quad mesh are smoothed to improve mesh quality.

In Fig. 2, three stages of the mesh conversion are visualised, for an example problem. The result is a quadrilateral mesh which is approximately twice as fine as the original triangular one. The generated quadrilateral meshes are of fair quality, and can be strongly refined, as can also be observed in the left part of Fig. 6.

### 3.4. Implementation aspects

Discrete cracks are conditionally initiated and propagated over a crack length increment $\Delta l$, controlled by evaluation of a fracture potential field calculated over the domain, using one of the many available local ductile fracture criteria. For the present research, a criterion is used based on Rice and Tracey’s void growth model [21,28] for high triaxialities $\sigma_{m}/\sigma$:

$$\frac{\Delta R}{R} = \int_0^{\gamma_p} 0.427 \exp \left( \frac{3\sigma_{m}}{2\sigma} \right) d\gamma_p > C \quad (1)$$

in which $R$ is the initial radius of the void, and $\Delta R$ the increase in radius due to deformation. The integration vari-

![Fig. 2. Mesh conversion example.](image)
able is denoted by $\hat{c}_p$, while $\hat{c}_p^2$ refers to the effective plastic strain in the current configuration. The criterion according to Eq. (1) postulates the condition for crack growth to be the excess of the critical threshold value $C$ by the void growth factor $\Delta R/R$, where $C$ should be considered as a material parameter. The fracture potential is defined as the ratio of the void growth factor and $C$, resulting in a field variable representing the locally accumulated damage in the material. It is called fracture potential rather than damage to avoid confusion with damage mechanics approaches, where damage is assumed to have a degenerating effect on the material stiffness. The fracture potential, being history dependent, is treated as an extra internal state variable during ALE or remeshing.

At the end of every load increment, the integration point based fracture potential is extrapolated to the nodes. When the fracture potential in a node reaches unity, a crack is initiated, or in the case of a crack tip propagated, in the direction of maximum fracture potential. This direction is determined by sampling a finite number $N_{\text{ang}}$ of locations, radially spaced in the vicinity of the node. For crack path stability several sampling distances are required. A set of distance factors $\rho = \{\hat{\xi}_1, \ldots, \hat{\xi}_{N_{\text{ang}}}\}$ can be defined to store the ratios of the sampling distances and $\Delta l$. An example of this approach is visualised in Fig. 3, for the case $N_{\text{ang}}=13$, $N_{\text{dis}}=4$. For every radial distance an angle (or direction) is determined for which the fracture potential reaches a maximum. The crack initiation or propagation direction is established by taking the median of these angles. In case of crack propagation the angle is limited by $\pm \pi/2$ with respect to the existing crack. The initiation angle (relative to the inward normal of the existing boundary) is limited to $\pm \pi/4$. Cracks are assumed to initiate only at the boundary of the mesh, and not within a distance of $\frac{1}{2} \Delta l$ from other existing fractures.

Implementation of a discrete crack model has to be performed striving for consistency between applied load and crack length. Generally, this load is defined in terms of applied (distributed) forces, or a prescribed displacement. In the simulations presented here, load refers to the punch displacement. In a state of equilibrium, the fracture potential in a crack tip node should always be equal to or less than unity. Starting from a situation in which the crack lengths and load are mutually consistent, the crack length increments corresponding to the applied load have to be determined. Due to the nonlinearity of the problem, this requires an iterative procedure which is computationally expensive. To reduce the computational effort, the following approach is applied, which approximates the crack length with an accuracy of $\Delta l$:

- If it is established from the converged state at the end of a load increment that a fracture should have been initiated or propagated during that increment, a new mesh is generated covering the deformed domain, with the crack extended by an appropriately prescribed crack length increment $\Delta l$. Subsequently, the state variables at the end of the previous increment are transported to this new mesh.
- Then, a null-increment is performed, in which the load is not changed, to obtain the new equilibrium state with the extended crack.
- At the end of this null-increment, the domain is again checked for possible crack extension, using the fracture potential at the end of the previous null-increment. If further crack extension is needed, the process is repeated until the fracture potential does not exceed unity anymore.

4. Results

The model introduced above has been used to simulate plane strain blanking of a fictitious material. A schematic view of the model with geometrical properties and boundary conditions is displayed in Fig. 4. Simulations were performed for different clearances $S$, in which classical von Mises plasticity with linear strain hardening was used. The flow stress is denoted by $\sigma_0$, with a subscript 0 denoting the initial value. The elastic properties are given by Young’s modulus $E$ and Poisson’s ratio $\nu$. Friction has been described by the Coulomb friction law with coefficient $\mu=0.1$. Material, geometrical and numerical parameters are displayed in Fig. 4. The tools have been modelled as rigid bodies.

Simulations have been performed for four different clearances of $S/T = 0, 0.025, 0.05$ and $0.1$. Two characteristic resulting product shapes are displayed in Fig. 5. This figure clearly shows the different fracture behaviours for the two clearances. The initiation sites for the two clearances $S/T = 0$ and $S/T = 0.05$ are on die and punch, respectively. The characteristic zones as introduced in Fig. 1, can clearly be distinguished on the cut edges of both sheet and blank. Moreover, there is a significant difference between the predicted lengths of sheared and fractured zones, as well
as the burr size. For \( S/T = 0.05 \), the predicted fracture potential field and mesh are displayed in Fig. 6.

In Fig. 7, the blanking force–displacement curves for the different clearances are presented. The predicted blank and product shapes appear to be quite realistic, although the material and geometrical parameters (especially the punch and die-radii) are fictitious. The trends shown by the predicted force–displacement diagram, up to the points of fracture initiation, are also observed experimentally.

### 5. Conclusions

The introduced finite element approach, based on an OS-ALE technique combined with remeshing, appears to be capable of handling the large, localised deformations occurring during blanking. The proposed discrete fracture model
results in realistic fracture paths for the presented test configurations. The model predicts geometrical properties like burr size, length of sheared and fractured zone, and the roll over shape. Numerical validation of the model, as well as confrontation with experimental results [29], are essential to validate, and possibly enhance the model. Further extensions of the model could include more complex material behaviour, like viscous, thermal and damage influences, or algorithmic enhancements like adaptive remeshing.

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References