SIMULATION OF THE SLITTING PROCESS WITH THE FINITE ELEMENT METHOD

H.H. Wisselink, J. Huétink
University of Twente, The Netherlands

Abstract

Slitting is a sheet metal cutting process used for dividing coiled sheet into narrower coils. It is a stationary process in which the sheet is uncoiled, cut by circular blades into strips, that are simultaneously recoiled. A three-dimensional finite element model is developed for the calculation of the steady state of this process. An Arbitrary Lagrangian Eulerian (ALE) formulation is used to be able to handle history dependent material properties and moving free surfaces. A crack front is modelled in the initial mesh. To investigate whether the assumed crack front is correct, a damage parameter is calculated. The coupling between crackfront and damage is not implemented yet. Results from the simulations of the slitting process are given, in which the influence of some parameters on the process is investigated.

Keywords: Slitting, FEM, ALE, Ductile fracture

1 Introduction

Slitting is a sheet metal cutting process with circular blades. It is used in industry to split wide coiled sheet metal into narrower widths or for edge trimming of rolled sheet. The slitting process is schematically drawn in Fig. 1. When the sheet moves from the left to the right, it passes sequentially the stages A, B and C. The undeformed sheet at A will be elastically and plastically deformed, as it moves from A to B. Continued deformation finally leads to a ductile fracture of the sheet and a complete separation of the parts at C. Next to this shearing deformation, the sheet is also bend to conform to the shape of the blades.

A slitting line consists of an uncoiler, a slitter and a recoiler. Circular blades are mounted on the two arbors of the slitter. The uncoiler, slitter and recoiler are driven by separate motors. Depending on the way the uncoiler, slitter and recoiler are driven, some different modes to drive the material through the slitter knives can be distinguished [1]. Which mode is chosen depends on the material, the sheet thickness and the number of slits. The modes are depicted in Fig. 2.
Figure 1: Slitting process

a. Straight mode slitting
In this mode the driven recoiler pulls the material from the uncoiler through the slitters. It is called pull-through slitting, when the uncoiler and slitter are only used to feed the material to the recoiler. In driven slitting the slitter is also driven during the process. The motors must now be synchronzed to maintain a constant speed of the material as it moves through the line. The advantages of driven slitting are the ability to slit thin sheets and a improved edge quality for all thicknesses.

b. Free loop mode slitting
In free loop slitting, the material is allowed to form a free loop between the slitter and the recoiler. A tensioning device in front of the recoiler is needed now, to produce well wound coils. With this method it is possible to process poor shaped coils.

Figure 2: Slitting modes

The quality of the produced strips (e.g. burr, flatness) for a specific material, depends mainly on the geometry of the blades (diameter, sharpness) , the horizontal and vertical clearance (or overlap) between the blades (Fig. 1). The amount of adjustable process parameters and the fact that the influence of these parameters on the process is not fully understood, makes it difficult to control the slitting process [2]. In practice the right setup for the slitters is mostly found by trial and error combined with experience. To contribute to a better process control, a finite element model is developed, to investigate the influence of the parameters on the slitting
process, which leads to more insight in the slitting process.

2 Finite element formulation

Slitting is modelled as a three dimensional, stationary process. To calculate the steady state of such a process a transient calculation is carried out until a steady state is reached. The model should be able to describe large elastic-plastic deformations, ductile fracture and the contact between the sheet and the blades. Another requirement is that the mesh must be well shaped during the entire calculation, and that the movement of free surfaces can be followed. These conditions can be fulfilled with an Arbitrary Lagrangian Eulerian (ALE) formulation, which is a combination of an Eulerian and a Lagrangian formulation.

2.1 ALE method

The grid displacements in an ALE formulation are not necessarily equal to the material displacements (Lagrangian formulation) nor equal to zero (Eulerian formulation). The new mesh is determined so that nodes on the surface remain on the surface and that a good element shape is preserved. This solves the problem with free surfaces in an Eulerian formulation and avoids excessive element distortion using a Lagrangian formulation. In contrary to remeshing the topology of the mesh is not changed.

An uncoupled ALE formulation is used, which consists of two parts. First an Updated Lagrangian step is carried out to calculate the material displacements. Next the grid displacements are determined using the calculated material displacements (The procedures used for slitting are explained in section 2.5). When the new mesh is known the history dependent variables have to be calculated in the new grid points. This is done with the artificial dissipation scheme of Huétink [3], [4], which is adapted to avoid crosswind diffusion. For flow in mesh direction, as is the case in the slitting simulations, the scheme is satisfactorily accurate.

2.2 Material model

An isotropic elastic-plastic material model is used with a Von Mises yield criterion. The isotropic hardening is described with the extended Nadai formula. With the yield stress $\sigma_y$ and the equivalent plastic strain $\varepsilon^p$.

$$\sigma_y = C(\varepsilon_0 + \varepsilon^p)^n$$

In the calculations in this paper stainless steel (AISI 316) is used. The properties (Tab. 1) are determined from a tensile test. The strains in slitting are much larger than the strain at necking in the tensile test, which means that the extrapolated values for large strains are less accurate.

<table>
<thead>
<tr>
<th>E-modulus $\nu$</th>
<th>$210 \text{ MPa}$</th>
<th>$\varepsilon_0$</th>
<th>$0.023$</th>
<th>$1228 \text{ Mpa}$</th>
<th>$0.4$</th>
</tr>
</thead>
</table>

Table 1: Material properties
The effect of strain-rate hardening and thermal softening, which becomes important for high slitting speeds (≈ 300 m/min), is not accounted for. This limits the model to relatively low speeds.

2.3 Ductile Fracture

The sheet is finally separated by a ductile fracture process. Ductile fracture is a process of void initiation, growth and coalescence [5]. Some different methods for the simulation of ductile fracture in 2D shearing are proposed by [6],[7], [8] and [9]. They all have in common that cracks initiate/propagate when some fracture parameter reaches a critical value. Goijaerts [10] reached a good agreement between experiments and simulations in 2D blanking with an adapted fracture criterion of Oyane [11], given by the following equation:

\[
D = \int_0^{\varepsilon^p} \left( 1 + A \frac{\sigma_h}{\sigma_{eq}} \right) d\varepsilon^p
\]

\[
D = D_c \quad \text{for} \quad \varepsilon^p \quad \text{at fracture}
\]

\[
<x> = x \quad \text{for} \quad x > 0
\]

\[
<x> = 0 \quad \text{for} \quad x \leq 0
\]

This states that cracks initiate as the integral in Eq. 2 reaches the critical value \( D = D_c \). The parameter \( A \) determines the influence of the triaxility ratio (the hydrostatic stress \( \sigma_h \) divided by the von Mises stress \( \sigma_{eq} \)) on the initiation of fracture. The parameters \( D_c \) and \( A \) are material and process dependent, and should be determined from experiments. The above described criterion will be used in this paper.

![Diagram of crack front in slitting](image)

**Figure 3: Crackfront in slitting**

In the stationary state a stable crack front is present (Fig. 3) which propagates with constant speed. Atkins [12] presents some experiments of guillotining (similar process as slitting), that show a zone of combined plastic flow and fracture before the sheet is completely separated. Therefore, a crack front is modelled in the initial mesh, which has a similar shape as found by [12]. An example of such a crackfront is drawn in Fig. 3. In the steady state, the points on the crack front should be critical, whatever criterion is used. With the ALE method and a fracture model it should be possible to adapt the crack front from an initial(damage free) estimation to the steady state position, provided that the initial shape of the crack front is a reasonable estimation of the steady state shape of the crack front. In the calculations shown in this paper, the crack front is not yet adapted to the fracture criterion, but spatially fixed at the initial position during the calculation.
2.4 Contact
An important aspect of slitting is the contact between the sheet and the slitters. To describe the contact between the deformable sheet and the rigid slitters a penalty method is applied [3]. In the small contact area very high pressures are found, therefore high penalty factors are needed, which deteriorates the convergence of the calculations. The sheet is pulled through the slitters by friction forces between the slitter and the sheet. It is the only driving force in free loop slitting. Coulomb friction is used with a coefficient $\mu = 0.1$.

2.5 Meshing and Mesh management
Starting point of the simulation is a finite element mesh, with no initial stresses or strains, of the estimated steady state geometry. (Fig. 4). The preprocessing is carried out within PATRAN [13]. A parametric function written in Patran Command Language generates an input file for the finite element code DiekA, containing the initial mesh, boundary conditions and mesh management data.

When determining the new positions of the nodes during the calculation, two things are required. No material should be gained or lost, except for the in- and outflow and secondly, a good element shape must be preserved. A structured 3D mesh of hexahedrals is used, which gives a regular grid on the surfaces. This grid is kept fixed in flow direction (x-direction). Perpendicular to the flow direction (in the yz-plane) the grid follows the movement of the free surface. The new grid positions are determined in the following order:

- First all surface nodes are put back to their original x-coordinate. The new y- and z- coordinates are calculated with a convection scheme, using the coordinates of neighbouring nodes on a gridline in flow direction [14].

- Next the surface nodes are repositioned on the surface in the yz-plane, to keep the initial refinements around the tool tips, where the largest deformations are found. The same convection scheme is used as in the x-direction. The direction of convection is determined with a procedure described by Ponthot [15].

- When the position of the surface nodes is known the new position of the internal nodes can be calculated. In the process zone a smoothing procedure is used. Outside the process zone the grid displacement of the internal nodes is related to the grid displacement of the nodes on the top and bottom surface.

- Nodes on the crack front are spatially fixed. This means that the surface is not followed, but that the crack propagates.

3 Simulation results
All simulations are carried out with the implicit finite element code DiekA, developed at the University of Twente. Some simulation results of different cases, which differ in horizontal clearance and slitting mode, are presented (Geometrical data are given in Tab. 2).

An example of an initial mesh for slitting is given in Fig. 4. The material flows in positive x-direction through the mesh. In driven slitting the displacement in x-direction of the nodes on the outflow is prescribed corresponding to the prescribed rotation of the slitters. In free loop
Table 2: Slitting geometry

<table>
<thead>
<tr>
<th>sheet thickness</th>
<th>1 mm</th>
<th>overlap diameter knives slitting mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>sheet width</td>
<td>10 mm</td>
<td>0 %</td>
</tr>
<tr>
<td>clearance</td>
<td>5/15%</td>
<td>300 mm driven/free</td>
</tr>
</tbody>
</table>

slitting only the rotation of the slitters is prescribed and the outflow is free. Both sides of the sheet are suppressed in z-direction, which is a symmetry condition in case of multiple strokes. For all simulations a crackfront is modelled initially (not always visible), in which the sheet starts fracturing at a blade penetration of 50% of the thickness of the sheet and is completely separated at 60%.

Figure 4: Initial mesh and tools

During the calculation the initial shape evolves to the steady state geometry. The results are considered steady when the material at the outflow has undergone the complete deformation history. The difference between initial and steady state mesh is shown in Fig. 5. In the steady state the sheared edge and the drawin can be recognized. In Fig. 6 the steady state meshes are given for the different modes. The difference in slitting mode is best seen at the outflow, where free loop slitting shows more permanent bending of the strip.

The resulting equivalent plastic strain and hydrostatic pressure in the steady state, for two different horizontal clearances, are shown on a slice of one element length from the complete mesh, just before the crack front starts (Fig. 7 and Fig. 8). A zone of hydrostatic tension (=negative pressure) combined with large plastic strain has developed. The stresses and strains are more localised and have larger values for the smallest clearance of 5% compared to the results for a clearance of 15%.

The value of the damage parameter (Eq. 2) is shown in Fig. 9 at complete separation. The damage varies a little over the crack front, but both maxima are almost equal. The damage should be constant and equal to $D_c$ at the fractured part of the cut edge.
the steady state is not equal to $D_c$, than the assumed crack front was not correct and has to be adapted.

The mesh around the tool tips is too coarse to model the development of a burr. Finer meshes will lead to more accurate results, but take too much CPU time and memory, even when fast iterative solvers are used. The examples shown contain about thirty thousand independent degrees of freedom and it takes about two thousand steps to reach the steady state.

Besides the shape of the sheared edge, the residual stresses are calculated. These influence the shape (flatness) of the strips and can be important for further processing of the sheet into a product [16],[17].

4 Conclusions

The ALE formulation is a suitable method for the simulation of slitting. The model is able to calculate the shape of the sheared edge, residual stresses in the strip for different slitting modes. Because the crack front is not adapted during the calculation, the results depend for a great deal on the initial estimation of the crack front. Therefore, the model should be improved with a
procedure which adapts the position of the crack front according to a fracture criterion.

The results of the simulations of slitting described in this paper give already a good insight in the process. Most trends are qualitatively well predicted. To verify the simulations, the results will be compared to experiments and data from an industrial slitter.
Figure 9: Damage value of Oyane at complete separation ($A = 3$)

References


