SIMULATING TRANSVERSE FRACTURING OF THIN PLASTIC SHEET

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ABSTRACT

Slitting or transverse fracturing of thin plastic sheet products is common practice in industry, but the process is based mostly upon empirical evidence and experience. The slitting process involves large plastic deformation and fracturing or tearing under the shearing action of the rolling knife blades. Coupling the capabilities of two finite element programs, ABAQUS and FRANC2D allows the process to be simulated numerically. ABAQUS provides capabilities for modeling elasto-plastic material behavior, geometric nonlinearity, and contact between the knives and the plastic sheet -as well as self-contact of the plastic sheet. FRANC2D provides capabilities for inserting and growing multiple arbitrary cracks using element delete and fill routines to remesh the modified geometry and topology. FRANC2D was modified to communicate with ABAQUS to perform the slitting simulations based on an updated Lagrangian formulation with remeshing algorithms to prevent element distortion. Numerical simulations of the slitting process match experiments reasonably well.

KEYWORDS

FRAC2D, ABAQUS, slitting, cutting, plastic sheet, transverse fracture, crack propagation

INTRODUCTION

Slitting or transverse fracturing during manufacturing and processing of thin sheet products is common practice in industry. Automated slitting and cutting machinery is used to cut wide sheets or rolls of material into a number of narrower strips and for trimming the edges of rolled sheets. For example, photographic film is manufactured in wide sheets and then slit into various smaller widths for different camera types. Other products that are slit include paper, plastic film, aluminum foil, adhesive tape, and even food products. Slitting is differentiated from other cutting processes based upon the use of circular knifes. Other cutting and related manufacturing processes include: (1) single-point turning, such as a lathe, (2) boring, drilling, reaming or tapping, (3) planing, (4) milling or sawing, (5) threading, (6) blanking, and (7) cropping or guillotining, Dodd and Bai [1].

Although slitting and cutting processes are widely used, they have not been well studied; the industry processes are based mostly upon empirical evidence from experiments and field studies. In metal processing, there are guidelines for cutting that are based on experiments and experience, Chang and Swift [2]. Experiments can be time consuming and expensive as cutting behavior is affected by many factors, some of which include cutting force and speed, sheet tension, material properties, and knife geometry. As new products are developed, a large number of experiments are needed to determine the best value or range of values for these factors to produce the best cut-surface. Alternatively, if experiments are not conducted, a large amount of waste material might be generated if the parameters are not optimal.

Numerical studies of cutting processes have concentrated mostly on single tool cutting related to operations like milling or drilling and are aimed at analyzing the deformation and plasticity that occurs during chip and burr formation, Hashimura et al. [3], Ehmann et al. [4]. Analytical studies to determine cutting forces have also been completed, e.g., Zhou and Wirzbickia [5], but these have limited applicability because of the complex shearing and large-scale plasticity that usually accompanies the cutting process. A recent study by Wisselink [6] examines guillotining and slitting processes in metal cutting using a special purpose finite element program, DiekA, Huetink [7]. Fractures are simulated in addition to modeling the plastic deformation and contact. Only three papers describing slitting of photographic film were found in the open literature, Bollen et al. [8], Arcona and Dow [9], and Meehan and Burns [10], but none of these include numerical simulations.

The reason for studying the slitting process is to produce higher quality cut surfaces while reducing waste material. A single, clean, cut-surface that is orthogonal to the sheet surface is desired with no extra debris generated. This is not possible in most materials, so the best that can be done is to vary the cutting parameters to produce the best cut possible. Cutting occurs in three stages: (1) initial elastic deformation, (2) significant knife penetration and plastic deformation, and finally, (3) fracture or tearing. An effective method of studying the complete cutting process is to use finite elements. Finite element analysis allows for material and geometric nonlinearity as well as contact mechanics and fracture. It allows one to study variations in knife geometry, cutting speed, and other factors without performing numerous experiments.

The cutting process is modeled herein by coupling two computer programs, ABAQUS (www.abaqus.com) and FRANC2D ([11] and www.cfg.cornell.edu). ABAQUS provides a finite element base for simulating material and geometric nonlinearity as well as contact and fracture. FRANC2D provides a finite element base for simulating multiple arbitrary crack initiation and propagation with automatic meshing. The combination of these two programs provides a unique and suitable system for simulating cutting of thin plastic sheet material.

MECHANICS AND DEFORMATION OF SLITTING THIN PLASTIC SHEETS

Bollen et al. [8] and Meehan and Burns [10] describe the knife cutting velocities associated with slitting thin plastic sheets. Figure 1 shows the relative velocity vectors of the knives as depicted by Meehan and Burns; the components of the relative velocity vector correspond to the three fractures modes - opening, sliding and shearing. They continue by analyzing the cutting force and the stress field at the crack tip. However, this analysis has limited applicability as it ignores the material and geometric nonlinearity as well as the contact conditions. Arcona and Dow [9] use the force model (Figure 2) presented by Ford [12] to determine the cutting force based on the knife geometry, cutting speed, and material properties, specifically the material yield stress. This model was designed for ductile materials and provides an initial estimate for the force required for knife penetration based on the shear yield locus of the material. These analytical models have limited applicability, as the shearing and fracturing processes are too complex. Figure 3 shows a simplified sketch of the slit surface. The actual surface in photographic film is much more complex, Bollen et al. [8], Arcona and Dow [9].

Bollen et al. describe an additional damaging phase where the cut surfaces rub on the knives and suffer additional deformation. The amount of plastic deformation is very dependent upon the material properties of the thin plastic sheet. Two types of material are used for the base material of photographic film, a relatively brittle cellulose acetate and a tough, ductile polyethylene terephthalate (PET). The PET is visco- plastic and is, therefore, dependent upon cutting speed. Polymer fracture is complex, Kausch [13]; thus, the simulations below are based on simplified models.

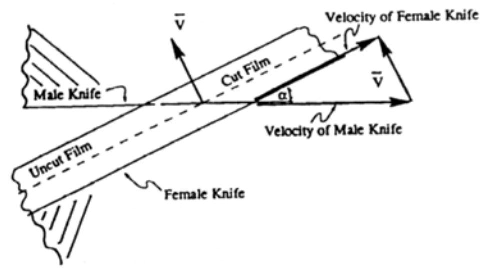

Figure 1. Relative knife velocity vector (from Meehan and Burns [10]).

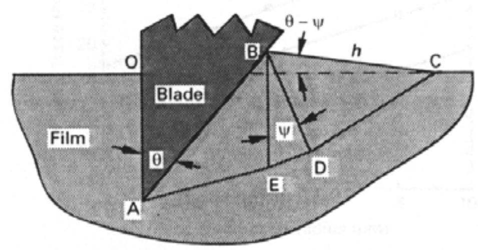

Figure 2. Cutting force model (from Arcona and Dow [9]).

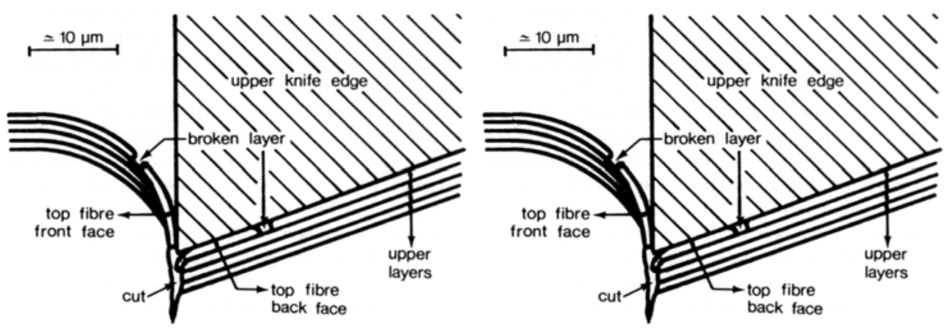

Figure 3. Sketch of deformed cut surfaces (from Bollen et al. [8]).

SLITTING SIMULATION SOFTWARE

Although no numerical simulations of slitting of plastic sheets were found in the open literature, there have been simulations of slitting of metal sheets. There have also been a number of numerical simulations of other cutting or blanking processes; Wisselink [6] provides a summary of the relevant studies. Only a few finite element simulations of the complete slitting process have been completed, and these have quite restrictive algorithms for crack growth, usually based on element extinction methods.

There are two basic finite element formulations, Lagrangian and Eulerian. In the Lagrangian formulation, the frame of reference is fixed with respect to the geometry. An updated Lagrangian formulation has a frame of reference that is fixed with respect to the geometry at the beginning of the time step, but the frame of reference moves when the geometry is updated, usually based on the deformed state at the end of the previous step. In the Eulerian formulation, the frame of reference is fixed in space and the material flows through the frame.

The Lagrangian formulation can lead to element distortion as the material deforms. Therefore, it must be augmented with remeshing algorithms. The Eulerian formulation does not suffer from element distortion, but special procedures are required to follow free surfaces and cracks as the material boundaries are not coincident with the element edges in general. An alternative formulation is that used by Wisselink [6], the arbitrary Lagrangian-Eulerian (ALE) formulation. This is a combination of the two formulations where the frame of reference can be chosen based on the material deformation. The drawback to the ALE formulation is that the mesh topology must remain constant during the entire simulation, so it is not possible to follow the complete crack growth process.

FRANC2D has been used for over a dozen years to analyze arbitrary multiple crack growth. FRANC2D has routines for modifying the topology and geometry of the model to grow the crack. During the process of growing the crack, the mesh is locally modified near the crack tip through a delete and fill algorithm. However, FRANC2D does not have geometric nonlinear analysis or contact capabilities.

The combination of the two codes, ABAQUS and FRANC2D, provides a unique and much more powerful model for simulating the complete slitting process. An updated Lagrangian formulation is employed where the model geometry is updated based on the deformed state of the current step of analysis. FRANC2D was modified to communicate with ABAQUS, along with the additional capabilities to update the state and to remesh if the element distortion becomes excessive. This system is used to produce the slitting simulations discussed in the next section.

PRELIMINARY SLITTING SIMULATIONS

The first set of analyses was conducted entirely within FRANC2D using linear elastic material properties, small strain assumptions, and linear elastic fracture mechanics. Eastman Kodak Company provided the model geometry and material properties. The FRANC2D model after 40 crack growth steps is shown in Figure 4. The knife 'load' was modelled as a point force and cracks were initiated at the top and bottom at the same time. Note that the crack trajectory does not agree with those observed from the experiment. This model was primarily used to evaluate the required boundary conditions and crack growth behaviour (specifically crack face contact).

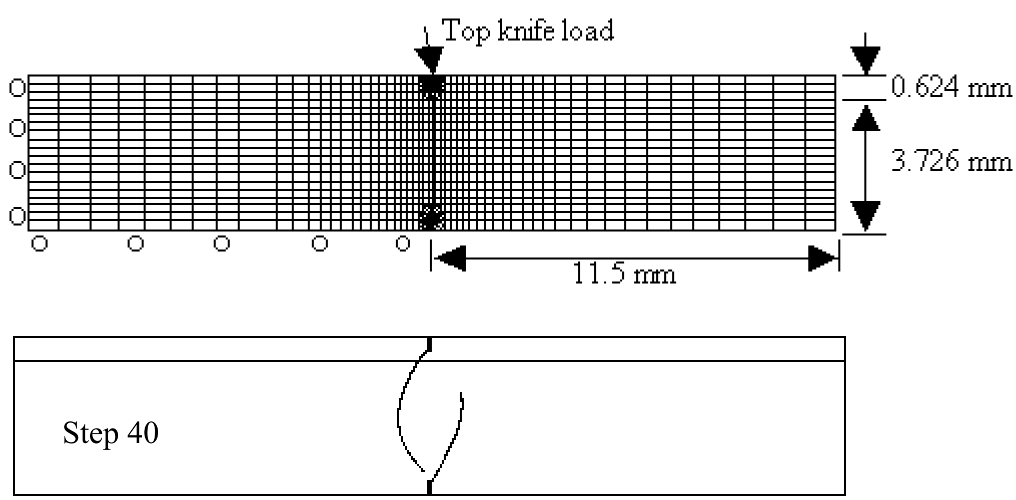

Figure 4. FRANC2D initial mesh model for slitting and model boundary after 40 crack growth steps.

The following cutting simulations used the coupled ABAQUS-FRANC2D approach. An initial ABAQUS model, with rigid surfaces for the blades and elasto-plastic strain hardening material data, was created and an initial analysis was done in ABAQUS; contact was made between the knife and plastic sheet. The model and results were sent to FRANC2D where a crack was nucleated at the top surface of the plastic sheet at the knife contact ‘point’. The results from the original analysis were mapped forward to the new mesh and the model was sent back to ABAQUS for subsequent analysis. Upon convergence in ABAQUS, the model and results were sent back to FRANC2D; the crack was propagated and the model was sent back to ABAQUS. This process continued until ABAQUS no longer converged or until it was deemed that the crack growth was sufficient such that the material effectively had been cut.

An initial cutting simulation where the stress and strain were not mapped forward is shown first. The model consists of a gelatine coating layer on top of a PET base layer. The material suffers plastic deformation at each increment and the deformation is recorded by updating the model based on the deformed state, but the plastic strain is not accumulated. A crack was initiated on the upper surface first and this crack was propagated for several steps before the second crack was initiated on the lower surface. The upper crack grew downwards while the lower crack grew very little, probably because the lower crack was located off the knife tip. The final configuration is shown in Figure 5 after 12 steps of crack growth.

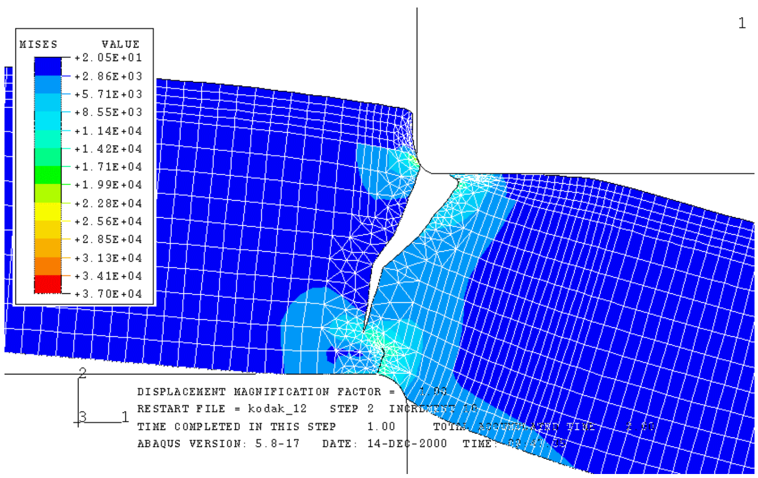

Figure 5. von Mises stress after 12 increments of crack growth (1X magnification).

The next cutting simulation was based on a simplified model consisting of a layer of acetate material only. The stress and strain were mapped forward. The material suffered plastic deformation at each increment and the deformation was recorded by updating the model based on the deformed state. The plastic strain was accumulated. A crack was initiated on the upper and lower surfaces during the same increment. Two simulations were performed. The first used the maximum hoop stress criterion to determine crack growth direction. For the second, the crack was forced to grow approximately in the direction of maximum shear. The final configurations are shown in Figures 6 and 7 after 10 and 13 steps of crack growth, respectively. ABAQUS does not converge for the subsequent steps in either series.

CONCLUSIONS

The combination of ABAQUS and FRANC2D provides a unique and powerful system for simulating the complete slitting process of thin plastic sheets. The simulations match observed slitting phenomena reasonably well. Additional effort is required to increase convergence rates and numerical stability. A more thorough study on the fracture criterion for various plastic sheet materials will also be investigated.

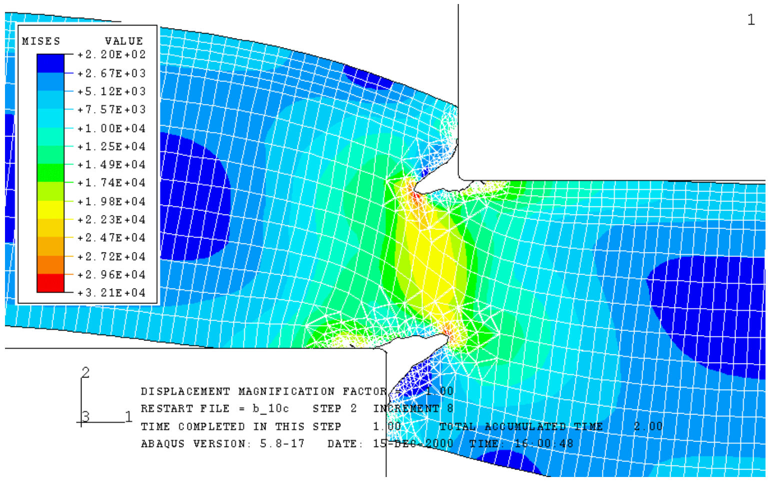

Figure 6. von Mises stress after 10 crack growth increments; LEFM fracture criterion (1X).

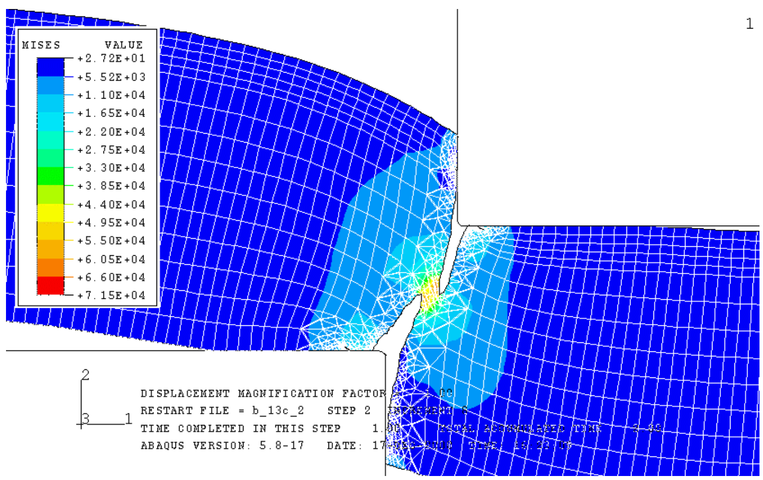

Figure 7. von Mises stress after 14 crack growth increments; fracture trajectory controlled manually based on shear stress and plastic equivalent strain (1X magnification).

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