DEFORMATION IN SHEAR SLITTING OF POLYMERIC WEBS

by

H. Lu, B. Wang, and J. Iqbal
Oklahoma State University
USA

ABSTRACT

Shear slitting of a 25.4 μm thick polypropylene web was conducted on a laboratory slitter using a pair of rotary blades at a constant speed up to 5.08 *m/s* under controlled tension. The effect of web speed on the slit-edge burr height of the web is investigated for the thick polypropylene web. A profilometer was employed to measure the edge profile. Experimental results indicate that the burr height decreases with web speed when other slitting parameters are fixed. To overcome the difficulty in observing the in-situ shear slitting process of the polypropylene web, a rubber sheet was also used in the present study for the observation of the deformation process during shear slitting, and the surface deformation field of the rubber was measured by a digital image correlation method. The finite element simulation of the early stage of rubber slitting process was performed using commercial ABAQUS code and numerical results are in good agreement with those observed in experiments. The experimental observation and the numerical simulation show that shear slitting of rubber initiates with an indentation process, followed by deformation localizations around the slitter blades; the final stage is a tearing process.

INTRODUCTION

Webs such as photographic film, newsprint and aluminum sheet are usually manufactured in wide form and slit into narrower final products using various slitting methods such as razor, shear, score, big-knife, water-jet and laser slitting. One of the most commonly used mechanical slitting methods is shear slitting, which utilizes a rotary blade engaged with an anvil roller to convert various webs into narrower forms. In slitting, it is always desired to slit the web at a fast speed while maintaining high slit-edge quality indicative of clean and straight edge without defects such as burr, sliver, micro-crack, debris, etc.

Most publications on the shear slitting of webs in open literatures are normally restricted to qualitative investigations. Among the very little quantitative investigation are: Meehan, et al [1], which investigated the effect of blade sharpness on the cutting force for razor slitting of plastic films; Meehan and Burns [2], which measured the cutting force for razor slitting of thin polymer webs at a speed up to 10 mm/s, and determined the isochromatic stress lines in a polycarbonate sheet that was used to simulate a plastic web in shear slitting. Kasuga et al [3], which investigated the deformation process in shearing process of thick ductile materials; Arocona and Dow [4], which determined a relation between the cutting force and the cutting speed for plastic films; Lu and Liu [5], which derived a solution for the stress distribution in a web during razor slitting.

Mechanical slitting of webs in most situations can be considered as a controlled fracture process. A crack is initiated by the slitter blades and propagates in the web under the guidance of the slitter blades. Razor slitting may be considered as an opening mode crack propagation process, while shear slitting may be considered as a shearing and fracturing process. Because of this consideration, on the macroscopic scale the slitting criterion can be considered as the same as crack initiation and propagation criterion. In the web near the crack tip, there exists a high stress gradient zone. Excessive inelastic deformation might occur. Damage such as micro-crazes and micro-voids most likely initiates and coalesces to form visible cracks for some web materials under certain slitting conditions. Part of the damage such as voids and cracks will remain in the wake of the crack, i.e., the slit edges, and produce deterioration in the slit quality, creating defective edge that contains defects such as debris, sliver, and possibly creating slit dusts. Understanding the deformation process of the web zone near the blade, its relation to the slit edge defects and how they affect the slit quality, dust formation, web winding quality following slitting etc. are therefore essential in the study of slitting processes.

This study deals with how the slit edge quality is controlled by the slitting conditions in shear slitting. For this purpose a laboratory slitter is setup for shear slitting using a rotary blade and an anvil roller, at a constant speed up to 5.08 *m/s* under controlled tension. Shear slitting of a 25.4 μm thick polypropylene web is performed in this study. The relation between the slit edge quality, specifically the burr height, and one of the important slitting conditions—web speed, is investigated.

Understanding the deformation process during shear slitting of the plastic webs is essential to the investigation of the relation between slit edge quality and slitting conditions. In this study we intend to measure the deformation during shear slitting process using a long distance microscope that can reach a magnification of 400 times. However the polypropylene web of 25.4 μm thick is so thin such that observation of the deformation of the cross section is not possible. A thicker polypropylene could be used for observation purpose. But a crack in the thicker polypropylene propagates at a very fast speed such that it is not permissible to use the digital image acquisition system with a frame rate of 30 Hz to acquire images. To overcome the difficulty in the observation we use a rubber sheet as a substitute material for the polypropylene web. Although the rubber behaves quite differently from the plastic web, it is expected that some qualitative features in shear slitting could be similar in both materials. Images of the cross section of the rubber sheet were acquired with a digital image acquisition system connected to a Questar long distance microscope and the surface deformations on the rubber representing the shearing process during slitting are measured by the digital image correlation method.

Additionally, the finite element method (FEM) has become a useful tool for the parametric study on the deformation and burr formation in the shear cutting of thick metal plates. Burr formation in metal cutting processes has been studied using the finite element analysis. Based on numerical simulation results using ABAQUS/Explicit code Park and Dornfeld [6] have identified four stages for burr formation in bulky metals, i.e., initiation, initial development, pivoting point, and final development stages. The influences of exit angles of the work-piece, tool rake angles, and backup materials on burr formation processes have been examined in the orthogonal cutting of 304L stainless steel [7]. However, it must be noted that web-slitting processes are quite different from metal cutting of bulk materials. The flexible rigidity of a web is very small such that the web has to be modeled as a membrane in most cases. It is still very difficult to use the finite element method to model the shearing slitting of polymer webs because of high width/thickness ratio in the web structure and the absence of appropriate failure criterion for polymeric materials in the commercial code. In this study, the finite element analysis is carried out to simulate the initial indentation stage of rubber shear slitting using ABAQUS/Standard code; numerical results are compared with experimental data.

EXPERIMENTAL ASPECTS

A laboratory slitter was set up for the investigation of shear slitting at a speed up to 5.08 *m/s* under controlled tension. A schematic diagram of the slitter is shown in Fig. 1. On the right of Fig. 1 is the unwinding part that unwinds a roll of web, a roller is placed between the unwinding roller and the load-cell roller to isolate the unwinding induced vibration. A web guide (Fife, model CSP-01-06) is used to control the web lateral movement to within ± 75 μm so that the web is centered all the time. A rotary knife blade (upper slitter) of 15.2 *cm* diameter (see also Fig. 2) is used to engage with an anvil roller (lower slitter) of the same diameter to shear-slit the web. A bowed roller is placed before the winding roller to separate the two webs after slitting so that the edges of two winding rolls do not contact with each other. A rider roller is used to push against the winding roll to reduce the amount of air entrained between layers of web in the winding roll to reach a high winding quality. Tension is measured by a pair of 225N load cells and controlled by a pneumatic tension controller (Tidland, model 2500) that controls the torque in a brake (Montalvo, model BJ2-CD-100) on the unwinding roller. The laboratory slitter is designed for shear slitting of plastic webs at a constant speed up to 5.08 *m/s* under controlled tension.

The upper slitter is hold by a knife holder capable of moving vertically and horizontally so that the blade overlapping and the contact point of blades can be adjusted. A linear transducer (Accurate Technologies, model Proscale) with a resolution of 25 μm is used to measure both the vertical and the horizontal positions of the rotary blade. A pneumatic side force is applied to push the upper slitter against the lower slitter. Calibration was performed to determine the relation between the applied air pressure through an air regulator and the side force.

The slit-edge profile was measured by a profilometer (Mutitoyo, model Surftest 402) with a height resolution of 0.05 μm . The profilometer can measure the surface topology when the stylus needle passes on the web surface. The output from the profilometer is connected to a computer with A/D board and a data acquisition program (National Instruments, Labview). Data on the slit edge profile are recorded through the computer and plotted by the Tecplot data visualization software.

FINITE ELEMENT ANALYSIS

The finite element simulation is performed on the shear slitting of a rubber sheet. Although the realistic indentation process in the initial stage of slitting is a three-dimensional structural problem rather than a two-dimensional one, it is expected that a plane strain condition could give an estimation of the deformation process on the cross section of the rubber sample. The finite element analysis on the indentation process in the initial stage of slitting of the rubber sample is performed using the ABAQUS/standard [8] software package. The two-dimensional finite element model is generated to simulate the rubber deformation under the plane strain assumption.

The numerical model consists of a deformable rubber and a rigid blade. The geometry of the rubber section and the blade is shown in Fig. 3. The nominal stress-strain curve from a uniaxial tension test on Instron material test system is depicted in Fig. 4 to characterize the hyperelastic properties of the rubber material. From the experimental curve, the uniaxial stress, σ, and uniaxial strain, ε, relation of rubber can be fitted in power law form as:

$$\varepsilon = 380\sigma^{1.61} . \qquad \{1\}$$

In three-dimensional case, the constitutive relation of rubber material can be expressed by

$$\varepsilon_{ij} = 570\sigma_e^{\ 0.61} S_{ij} , \qquad \{2\}$$

where ε_{ij} are strain components, the deviatoric stress components S_{ij} are expressed as

$$S_{ij} = \sigma_{ij} - \frac{1}{3}\sigma_{kk}\delta_{ij} , \qquad \{3\}$$

with σ_{ij} being the stress components, δ_{ij} components of the Kronecker delta tensor, $\frac{1}{3}\sigma_{kk}$ the hydrostatic components of the stress, and σ_e the effective stress defined as

$$\sigma_e = \sqrt{\frac{3}{2} S_{ij} S_{ij}} . \qquad \{4\}$$

The rubber sample is assumed to be sitting on a flat surface on the lower slitter initially. The actual displacement condition as observed during quasi-static shear slitting is used and a displacement controlled loading condition is applied at the contact point between the top slitter and the rubber sample. Boundary conditions are specified as simple support on the partial bottom region *BC*. The center point *C* of bottom edge is rigidly constrained along horizontal direction. The blade is assumed as an analytical rigid body. The mesh configuration and blade are shown in Fig. 3. There are 402 four-node quadrilateral plane strain elements and 452 nodes used in this model.

The interaction at *A* between the rubber and the blade is assigned using the "Contact Pair" definition in ABAQUS/Standard. It is assumed that there is no slip for the contact surfaces between the assumed perfectly rigid blade and the deformable rubber. The displacement control condition is used for the point loading at *A*. The blade tip displacement, as recorded by the digital image acquisition system during experiment, is applied to the rubber material. The blade will penetrate compatibly together with the deformed rubber during shear slitting. Large deformation description, namely "Nonlinear geometry" in ABAQUS/Standard package, is used in the finite element analysis.

RESULTS AND DISCUSSIONS

There are various slitting parameters that control the slit edge quality. These slitting parameters include, but not limited to, web tension, web speed, cant angle, clearance between the upper and lower blades, the amount of overlapping of the two blades, the blade offset, side force, overdrive speed of the anvil roller, blade geometry, blade sharpness, slitter blade materials and the dynamic coefficient of friction between the web and the blade. Understanding the effects of all slitting conditions on the slit edge quality requires extensive testing by varying all these slitting conditions. In this study we focus on the effect of web speed, one of the most important slitting parameters, on the burr height in the web. For this purpose a polypropylene web of 25.4 μm thick was used. The polypropylene web has a glass transition temperature of $0\,^{\circ}C$, thus its viscoelastic effect is significant at room temperature ($22\,^{\circ}C$).

To understand the mechanism of shearing and fracturing process during shear slitting, we also made in-situ observation of the slitting process with the use of a long-distance microscope connected to a digital image acquisition system. Because the 25.4 μm thick polypropylene is too thin for this observation purpose, we used a rubber sheet of 1. 78 *mm* thick for quasi-static shear slitting on the laboratory slitter while images were acquired. Results on the deformation process are presented in this section as well.

Numerical simulation has many advantages such as low cost for parametric study on the effect of various slitting parameters on the deformation and burr formation in shear slitting. Consequently, the finite element analysis is conducted in the early stage of rubber shear slitting process using ABAQUS/ Standard. Deformation is obtained under the plane strain condition; numerical results are compared with experimental data.

Burr Height—Web Speed Relation

A 25.4 μm thick polypropylene web was used in this study. Various slitting parameters were tested, and it was found that slitting with a blade overlapping of 0.81 *mm,* a blade offset of 6.35 *mm*, 8% of overdrive speed of the anvil roller and a side force of 58.5 *N* was able to produce clean and straight slit edge and these parameters were used in this study. The web speed was varied to determine its relation with the burr height at the slit edge. The topology along a line perpendicular to the slit-edge was measured by the profilometer described in the Experimental Aspects section. Fig. 5 shows a typical edge profile for the side of the web with burr. The burr height of a polypropylene web in shear slitting at a web tensile stress 10.3 *MPa* and a web speed 2.02 *m/s* is 3.2 μm, localized in a 0.06 *mm* narrow band.

Fig. 6 shows the burr height as a function of web speed at five different web tensile stresses. It can be seen that in general the burr height decreases with web speed for the speed range between 2.02 *m/s* and 5.08 *m/s.* At a web tensile stress of 6.9 *MPa,* the burr height is 4.6 μm at 2.02 *m/s,* it decreases to 0.5 μm at a speed of 304.8 *m/min.* The results indicate that the speed is helpful in reducing the burr height in shear slitting of plastic webs. While the underlying mechanism for this to happen is not completely understood, it can be inferred that the rate dependence in the viscoelastic behavior of polypropylene web material can contribute to this behavior. Since the room temperature at which the slitting was conducted is $22\,^{0}C$ higher than the glass transition temperature of the polypropylene web, it is expected that the viscoelastic effect is very significant at the slitting temperature. At a higher slitting speed, the strain rate in the web near the slitters is higher, since the viscoelastic material tends to behave more elastically at a higher strain rate, the yielding behavior will be much less pronounced at a higher speed, leading to a much more elastic deformation and thus a smaller burr height induced by permanent out-of-plane yield-like deformation in the web.

Deformation Field in a Rubber Sheet During Quasi-static Shear Slitting

The deformation field in a web during quasi-static slitting was measured by digital image correlation (DIC) methods developed by a group of researchers at University of Southern Carolina [9, 10, 11] and refined by Vendroux and Knauss [12]. In this study, the algorithm proposed by Lu and Cary [13] was used. This algorithm has introduced second order deformation gradient terms in displacement mapping, and the incremental methods for large deformation proposed by Gonzalez and Knauss [14]. The method of introducing the second order displacement gradient terms has intrinsically increased the capability of DIC mapping relatively more distorted deformation field, and the incremental methods through a series of images acquired during deformation enabled the measurements of large deformations, on the order of 90% of nominal strain in this study.

Strain measurements indicate that a narrow area in the rubber strip between the edges of the two slitters is subject to compressive strains. Because the rubber is an incompressible material, and it tends to maintain its volume unchanged, the areas on both sides of the compressive zone are subject to tensile strains.

During the continuous shear slitting process, the indentation and tearing processes are happening along the web moving direction, there is a smooth transition from an indentation process at one location to the final tearing process. Along the machine direction, i.e., the web moving direction, the web that has passed the shear slitters has been converted into two webs so that a crack with the tip located around the contact point of the pair of slitters is always present in the web, the singularity in stress field can be different from those represented by the first 5 frames in the top two rows in Fig. 7, but can be the same as the third frame in the second row in Fig. 7. The presence of a crack in tearing mode justifies a slitting criterion based on fracture mechanics, which can be represented by $K_{III} = K_{IIIc}$, with K_{III} representing the mode-III applied stress intensity factor and K_{IIIC} its critical value, or mode-III fracture toughness.

On the other hand, when the strain distribution can be locally measured or computed for an actual web under slitting that involves a complicated three-dimensional structural problem with new fracture surface being created during slitting, a strain controlled slitting criterion can be used. Even though the shear blades are normally sharp, they are not as sharp as an idealized crack with a zero tip radius. In reality, there is always a non-zero radius, so that the non-singular strain field can be computed, and a strain controlled failure criterion may be used as the criterion for crack initiation in a web under slitting.

Comparison of Numerical and Experimental Results

Through the finite element simulation for rubber sample, the deformation fields computed at different blade penetrations are shown in Fig. 7, and the deformation results are compared with those measured in experiments by digital image correlation. It can be seen that the deformed configurations based on finite element analysis agree very well with those obtained in actual experiment. Fig. 7 shows that shear slitting of a rubber sheet initiates by indentation of the upper blade into the rubber, followed by deformation localization that occurs in the small area near the contact points between the rubber and the slitter blades; the final process is a tearing process. In the current experimental setup, it is clear from the third image in the second row of Fig. 7 that a burr could be formed on the top left surface of the right piece of split material if the material exhibits plastic deformation. Similarly a burr could be formed in the right bottom surface of the left piece of the material if the material behaves plastically.

Fig. 8 plots the normal strain along the horizontally axial direction ε_{xx} at a point in the rubber right below the upper slitter blade tip as a function of blade penetration. This figure shows that the strain increases with blade penetration. It can be seen that the strain results from finite element simulation agree very well with those from experiment. These numerical results have thus demonstrated that finite element analysis, with the use of appropriate boundary conditions observed during the actual slitting process, can simulate well at least the initial indentation process during the shear slitting process. A complete finite element simulation of the whole shear slitting process requires the capability of the code to handle the creation of new surfaces during shear slitting, and could be investigated with a software that has capability to simulate the three-dimensional crack initiation and propagation process in a thin web undergoing shear slitting.

CONCLUSIONS

A laboratory slitter was set up to carry out shear slitting of plastic webs at a constant speed up to 5.08 *m/s* was performed in this study. The relation between the burr height and the web speed is investigated for a 25.4 μm thick polypropylene web. The burr height was measured by a high precision profilometer, and found to generally decrease with web speed within a web speed between 2.02 and 5.08 *m/s*. This result indicates that increasing web speed in shear slitting helps reduce the burr height. Investigation was also made to understand the deformation process during shear slitting. Because it is not possible to observe the deformation during the shear slitting process of the 25.4 μm thick polypropylene web due to the magnification and focus limitations of the Questar long distance microscope, a 1.78 *mm* thick rubber sheet was used in shear slitting for deformation observation. Deformation on the rubber sheet under slitting was determined using digital image correlation technique. The finite element analysis was also carried out to model the initial indentation process during shear slitting of rubber materials. Experimental results agree very well with those simulated from finite element analysis. The experimental observation and the finite element simulation indicate that shear slitting initiates with an indentation process, followed by deformation localizations around the slitter blades; the final stage is a tearing process. For a material that may deform plastically such as the polypropylene web, the final tearing process can cause some material to flow plastically in the out-of-plane direction of the web, causing the formation of burr at the slit edge.

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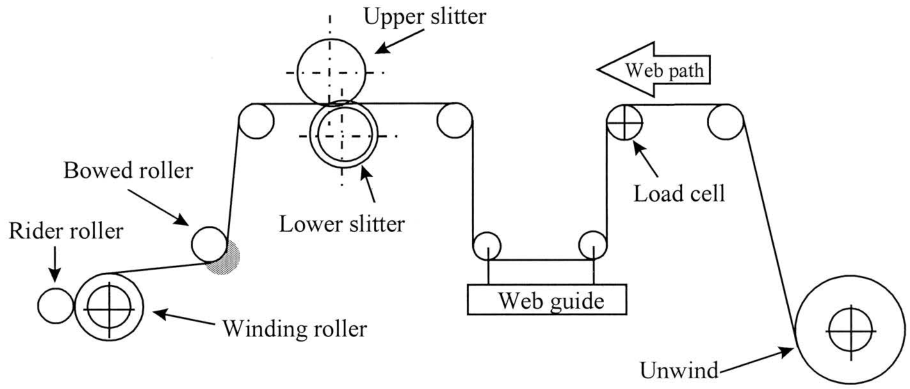

Fig. 1 A schematic diagram of the laboratory slitter

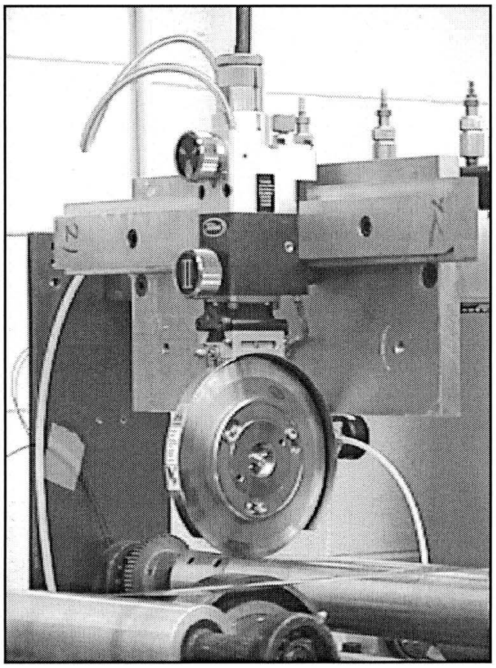

Fig. 2 A pair of shear slitters on the laboratory slitter

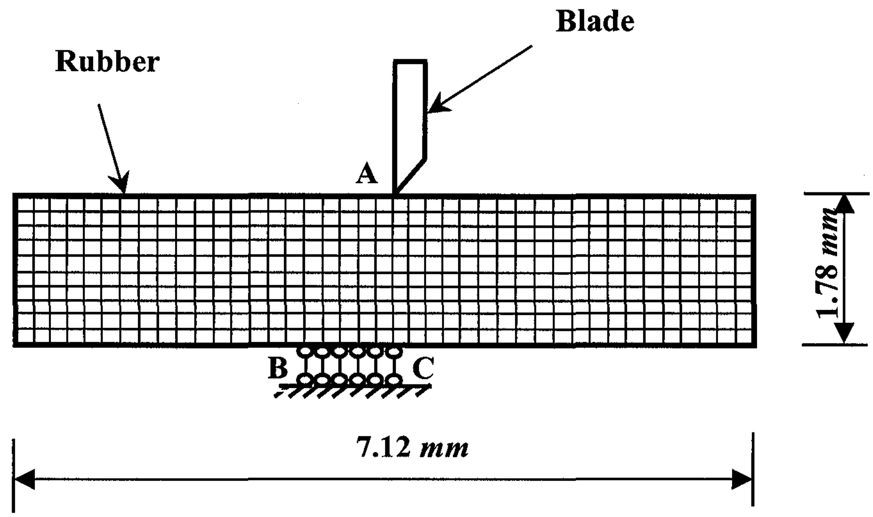

Fig. 3 Geometry and mesh configuration of the finite element model

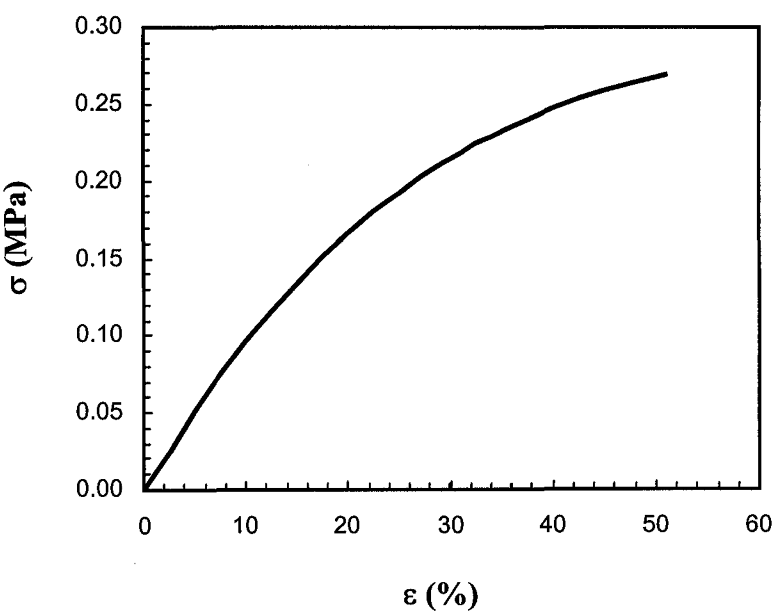

Fig. 4 Nominal stress-strain curve of rubber

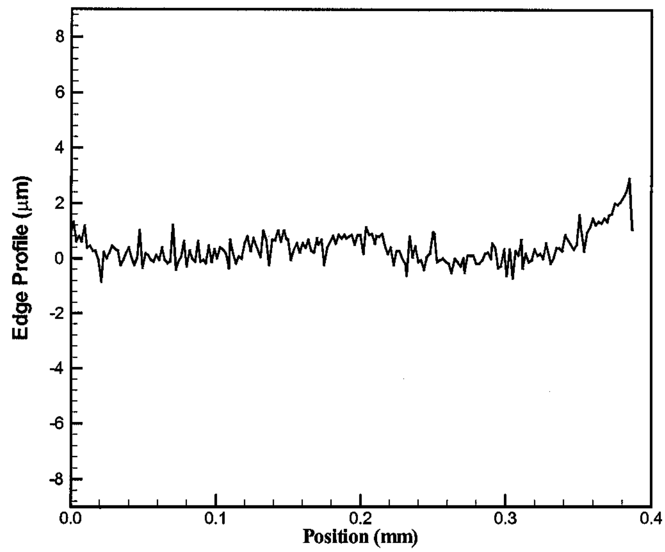

Fig. 5 A typical slit edge profile of a polypropylene under shear slitting

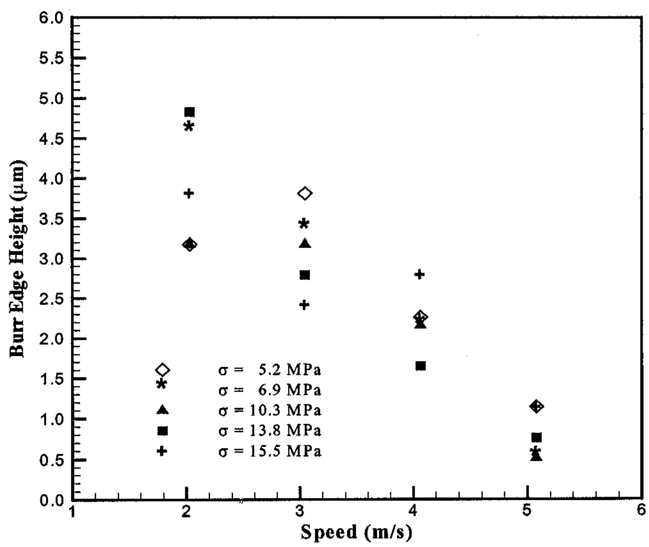

Fig. 6 Burr height as a function of web speed

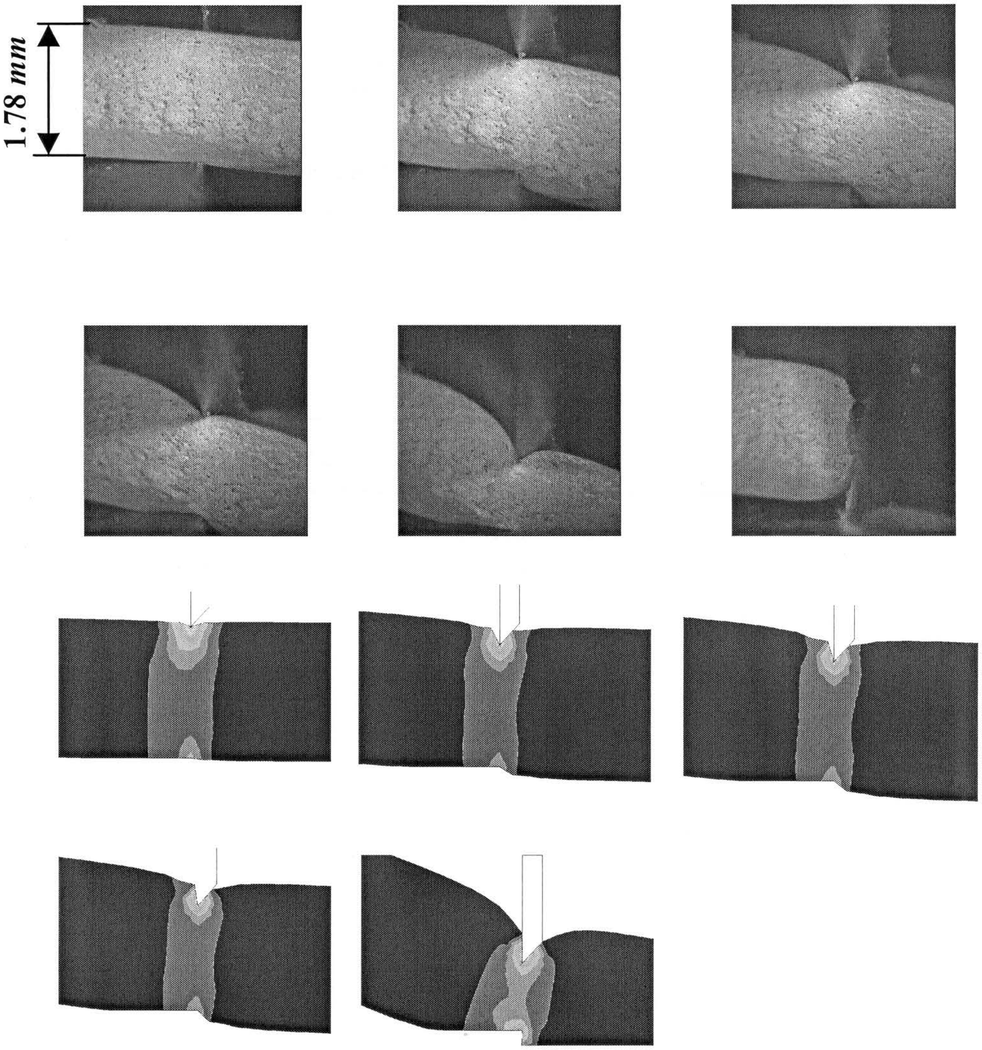

Fig. 7 Surface images of the rubber strip during shear slitting: top six images were acquired in experiment; bottom five images were simulated by finite element analysis

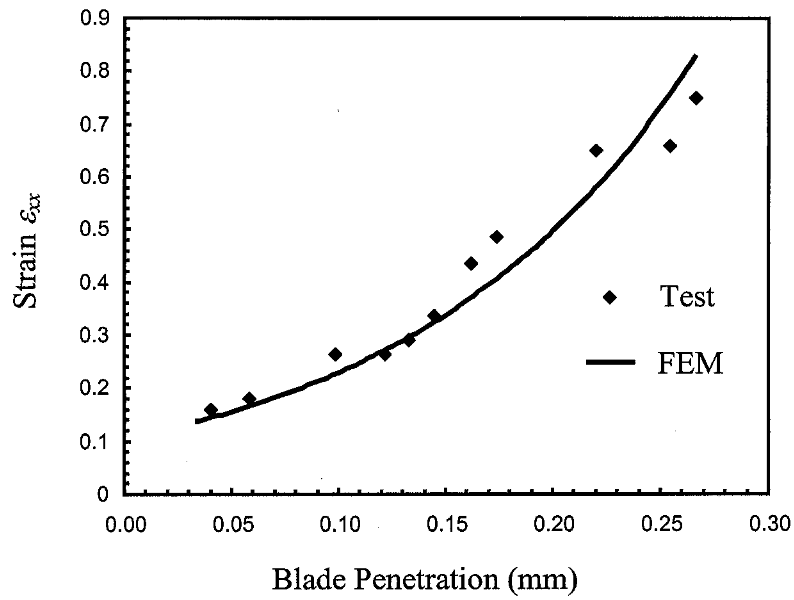

Fig. 8—Comparison of finite element analysis and experimental results

Name & Affiliation	**Question**
W. Qualls – Imation	This question pertains to Figure 5 where you show the edge profile versus position and where you determined the burr height. Which of the 4 corners did you measure and if you were to measure burr height on each of those 4 corners would you find a difference?
Name & Affiliation	**Answer**
H. Lu – OSU	We chose the worst case of the four to scan with the profilometer.
Name & Affiliation	**Question**
G. Homan – Westvaco	For the material that you were slitting and the slitter variables that exist did you find an optimum set up for that material?
Name & Affiliation	**Answer**
H. Lu – OSU	For the material we slit we tried different slitting parameters. We found there is a range of parameters that can give us good slit edge quality and we just chose randomly some parameters within the range of optimized slitting parameters. But this does not necessarily represent the actual slitting parameters that must be used in the actual environment. For instance we used 8% overdrive, which is fairly high, and we can certainly create a good slit edge but this will seriously decrease blade service life. We probably do not need the overdrive to be that high, but we happened to choose that and we did not use 1 or 2 %.
Name & Affiliation	**Question**
G. Homan – Westvaco	What about the slitter blade geometry, the angles?
Name & Affiliation	**Answer**
H. Lu – OSU	This is one of the blades we obtained from part of a donation from Tidland. We did not optimize the blades and it was not our objective to look at the geometry effects.
Name & Affiliation	**Question**
D. Pfeiffer – JDP Innovations	You mentioned a high tension between the two cutting points due to the influence of the Poisson ratio. I've seen evidence of slitting solid plastics that are quite thick (in the neighborhood of a millimeter thickness) where that tension causes fracture of the materials in between the cutting points and then the cutting shear takes place and throws slivers out of the web.
Name & Affiliation	**Answer**
H. Lu – OSU	I agree. The final process is actually a combined tension and shearing process. This could pull some material out of the web and produce some debris.