MECHANICS OF THE TRANSITION FROM PLASTIC FLOW TO DUCTILE FRACTURE IN GUILLOTINING

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The transition from flow to fracture at a critical blade penetration δ_{cr}, showing tool marks in the 'smeared' flow phase on the cut edge and a different 'rough' appearance in the crack region, is usually very distinct and easily measured in cropping and guillotining. The mechanics of the transition, based on minimum energy arguments, are presented and a simple relationship is derived which relates δ_{cr} with the fracture toughness R, and the flow stress in shear. Experiments on a range of ductile metals demonstrate that a novel method of determining R in the presence of extensive plastic flow is thus available.

INTRODUCTION

When a sheet or plate is cut in cropping, guillotining, bar shearing and so on, there is a well-marked boundary on the cut edge between the initial region of tool indentation and the onset of crack formation by which mechanism the cut is completed. Figure 1 shows a schematic side-view of a guillotined surface in a ductile material. Three regions may be seen, viz:

(i) a small chamfered region 1-2 where the cutting blade, on first contacting the sheet, produces some "sinking-in" (familiar in indentation hardness testing of annealed solids, see Tabor (2));

(ii) a region of plastic flow indentation 2-3 on which tool marks are seen; followed by

(iii) a ductile fracture region 3-4 on which tool marks are absent.

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The relationship between these features and events perpendicular to the cut edge may be established either from metallographic investigation of back-polished sections through partial cuts, Atkins (1), or from cutting workpieces containing split faces on which grids have been marked, Chang & Swift (3). From such observations, a single shear plane model for cropping seems to be adequate for ductile metals, as illustrated in Figure 2. After any "sinking-in" (or indeed lip formation possibly in highly work hardened metals, again by analogy with hardness testing) there is simple plastic flow during blade penetration: regions X and Y are still attached to one another. At some critical depth δ_{cr}, crack initiation occurs and this corresponds to line 3 in Figure 1. At subsequent depths of blade travel, deformation consists of combined plastic flow and crack propagation, and any previously-marked grid lines on split planes are severed by the passage of cracks from the blade downwards and from the base-plate upwards. Continuity is lost between regions X and Y. In this sort of operation, the cracks often run ahead of the blade so that cropping or guillotining is complete before the blade has travelled the full thickness of material being cut. The load falls to zero at δ_f where $\delta_f < t$ the plate thickness. Alternatively, cracks may not be freestanding ahead of the tool and may simply keep pace with the blade, which has to travel the full thickness of the plate before complete separation occurs, Atkins (1). In either case, whether cracks run ahead of the tool or not, the onset of crack formation is at δ_{cr} and subsequent total crack lengths are given by

$$L = \ell + (\delta - \delta_{cr}) \qquad \ldots(1)$$

where ℓ is the length of the free standing crack (if it exists) measured <u>relative</u> to the punch. The relationship between ℓ and $(\delta - \delta_{cr})$ is discussed elsewhere, Atkins (1),(4), but is not important for this paper. What is important is the realisation that even if a crack cannot be seen readily at blade penetrations greater than δ_{cr} in back-polished cross-sections, a crack nevertheless exists at least alongside the blade of length $(\delta - \delta_{cr})$ and longer if cracking runs ahead of the tool. The critical depth δ_{cr} marks a transition between flow alone and flow plus fracture.

What determines the magnitude of δ_{cr}? It is the purpose of this paper to consider how δ_{cr} may depend on material parameters such as fracture toughness R and flow stress τ_y and geometrical parameters such as plate thickness t and blade sharpness.

ANALYSIS

At the transition marked by δ_{cr} it becomes energetically preferable for flow and fracture to occur rather than for indentation flow alone to continue on. How this sort of thing occurs even though there are then two energy sinks rather than one has been explored elsewhere, Atkins (1),(4),(5). Since events controlling δ_{cr} occur in the cut plane of intense shear, an analysis for δ_{cr} in terms of hole punching (with no "offcut" deformation) is likely to apply equally as well to orthogonal bar shearing and guillotining in the sense that effects of width of cut, or blade angle etc. on the various bending actions consequent on having a free edge, are common incremental work inputs which continue through the transition.

Consider Figure 2. At some punch penetration δ, if shear flow alone occurs, the plastic volume being deformed is $(t-\delta)w$ for unit thickness material in-and-out of the paper, with w the thickness of the shear band. If, however, fracture has occurred at $\delta = \delta_{cr}$ with a free standing crack of length ℓ currently running beyond the punch, the plastic volume is $(t - \delta - \ell)w$ for unit thickness material. The difference in plastic volumes expressed incrementally is therefore $(- w d\ell)$ for unit thickness plate.

Consequently, if fracture commences at $\delta = \delta_{cr}$, there will be an incremental reduction in the expected plastic work done in unit thickness plate of magnitude

$$\text{(work/volume)(volume)}$$
$$= \left[\tau_o \, (\delta/w)^{n+1}/(n+1)\right] w d\ell \qquad \ldots(2)$$

where $\tau_y = \tau_o \gamma^n$ and the shear strain $\gamma = \delta/w$.

On the other hand, fracture work has to be done of magnitude

$$R d\ell \qquad \ldots(3)$$

for unit thickness of material, where R is the specific work of fracture (i.e. fracture toughness) of the material. The principal modes of fracture are presumably mode II in orthogonal cropping and mode III in guillotining; but the picture is complicated since clearance between blade and baseplate introduces a mode I component. In what follows, R is that appropriate to the particular conditions of clearance and blade sharpness obtaining in a given experiment.

At the transition when $\delta = \delta_{cr}$ and when the reduction in incremental plastic work is balanced by the occurrence of incremental fracture work, we have

$$\left[\tau_o \, (\delta_{cr}/w^{n+1}/(n+1) \right] w d\ell = R \, d \, \ell \qquad \ldots(4)$$

that is

$$R = \tau_o \, (\delta_{cr}/w)^{n+1} \, w/(n+1)$$

$$= \tau_o \, (\delta_{cr}/w)^{n} \, \delta_{cr}/(n+1)$$

$$\approx \tau_{mean} \, \delta_{cr} \qquad \ldots(5)$$

assuming that the mean flow stress is governed by plastic flow up to the shear strain (δ_{cr}/w) at the blade penetration δ_{cr} at which the transition occurs. Note that the relationship between L, ℓ and δ is irrelevant in this derivation, since $d\ell$ cancels to give Equations (4) and (5).

In the absence of information on the width w of the shear band which would give an estimate of the critical shear strain at the transition, it may be appropriate to make use of the relationship between indentation hardness H and mean flow stress resisting penetration, i.e. $H \approx 6 \, \tau_{mean}$, Tabor (2). Then Equation (5) becomes

$$R \approx (H/6)\,\delta_{cr} \qquad \ldots(6)$$

in consistent units.

EXPERIMENTS

A wide range of experiments has been carried out to study the forces and deformations involved in cropping and guillotining, Atkins (4). Some representative results for δ_{cr} of relevance to this paper, are shown in Table 1. All data relate to cutting with a sharp blade with zero clearance between blade and baseplate.

The fracture toughness values have sensible values for ductile metals of the order of 10^2 kJ/m^2.

Experiments with a deliberately-blunted blade of edge radius 1 mm give greater δ_{cr}, by approximately 10-15 %.

Again, experiments in which the clearance between blade and baseplate is increased show that δ_{cr} is affected and, other things being equal, δ_{cr} is smaller

TABLE 1 - Derived Values of R

Material	Thickness (mm)	Hardness (kg/mm^2)	δ_{cr} (mm)	$R = (H/6)\delta_{cr}$ (kJ/m^2)
low carbon steel	2	200	0.17	57
" "	5	200	0.40	133
soft low carbon steel	1	158	0.30	79
" "	3	158	1.00	263
brass	6	110	0.95	171
stainless steel	2.4	175	0.40	114

the greater the clearance. For example in 6 mm thick copper plate of hardness 83 VPN, sharp blades at 0.1 mm clearance gave $\delta_{cr} \approx 1.6$ mm, but at 0.6 mm clearance gave $\delta_{cr} \approx 1.3$ mm; blunt blades gave similar results (proportionately greater as explained above).

Lubrication of the blade appears to have an insignificant effect on δ_{cr} (and also not on forces, Atkins (4)).

DISCUSSION

It has been shown that measurement of δ_{cr} in a cut face, together with knowledge of hardness, enables the fracture toughness in shear to be determined in a simple way which, as far as the author is aware, is novel. Results show that δ_{cr} (and by implication R) varies with blade sharpness, blade clearance and material thickness, and, at first sight, this seems strange. Ought not there to be a 'true' toughness? On further consideration, the observations are perhaps not unexpected, because they relate to the problem of whether a one-parameter characterisation of crack initiation in ductile fracture is adequate, e.g. Atkins & Mai (6).

What appears to be happening is this: metallographic examination shows that the width of the shear band w also increases with material thickness t, Atkins

(4). Consequently, at fixed blade sharpness and clearance, (δ_{cr}/w) = constant = γ_{cr} a critical shear strain for ductile fracture in the cut plane of intense shear. For example, Figs. 4 and 5 in Atkins (1) show that in a particular set of circumstances for the guillotining of 1.7 mm thick low carbon steel of hardness 133 VPN, $\delta_{cr} \approx 0.05$ mm and $w \approx 0.2$ mm, whence $\gamma_{cr} = 0.05/0.2 = 0.25$. Again, in other experiments on low carbon steel of 200 VPN (Table 1), it was found that $\delta_{cr} \approx 0.08\,t$ and $w = 0.2t$, Atkins (4). Consequently for these circumstances, $\gamma_{cr} = 0.08/0.2 = 0.4$. The values of γ_{cr} are different because the materials are different and the test geometry is different. Experiments still in progress show that the proportionality constants between δ_{cr}, w and t vary with blade angle and blade sharpness, so that the critical shear strain at the transition is not constant. This accords with the influence of blade sharpness on hydrostatic stress in the shear band and mixed modes of fracture depending on clearance. Work in progress is attempting to link the combined effects of hydrostatic stress and shear strain at fracture in the shear band with McClintock-type models (7) of microstructural void growth and coalesence.

An alternative, but equivalent, interpretation of R varying directly with material thickness is that R varies directly with shear band width w since $w \propto t$. Hence R/w is constant and, insofar as w is a measure of the "process zone" for fracture, (R/w) represents a critical plastic work/volume at crack initiation. In the case of the 200 VPN low carbon steel mentioned above

$$\begin{aligned} R/w &= (H/6)(\delta_{cr}/w) \\ &= (200/6)(9.81)(0.08/0.2) \\ &= 133 \quad MJ/m^3 \end{aligned}$$

(in cases where the work-hardening characteristics are known, Equation 4 could be used instead). Once again, this value will vary with blade sharpness and clearance. What is being investigated at present is whether, at fixed clearance (fixed combined fracture modes) the trends in plastic work/volume for crack formation agree with the trends in change of hydrostatic stress produced by blades of different sharpness.

It is tempting to think that δ_{cr} may fall to a constant value at some blade sharpness (probably expressed as a blade edge radius-plate thickness ratio) and that the R then given is the true material property. This would correspond to elastic fracture mechanics studies in which the critical stress intensity factor K_{IC}, for example, levels out at small crack tip radii, e.g. Knott (8). The reason why sharper blades would not give earlier cracking is bound up with microstructural arguments: sharper cracks give intenser 'strains', but over a volume too small to encompass the microstructural features controlling ductile fracture; blunted cracks affect a bigger volume of material than the 'representative' volume determined by microstructure, but the strains are not great enough. It remains true, however, that for given tooling, R obtained in the way suggested in this paper indicates the specific work required for shear fracture which is single-valued and is uncoupled from the simultaneous plastic shear flow which accompanies cutting, the magnitude of which depends on offcut overhang width and so on in guillotining.

SYMBOLS USED

H = hardness (kg/mm^2)

L = total length of crack (m)

ℓ = length of free-standing crack measured relative to the blade (m)

n = work hardening index in $\tau = \tau_o \gamma^n$

t = thickness of plate (m)

w = width of shear band (m)

γ = shear strain

γ_{cr} = critical shear strain corresponding to δ_{cr}

δ = blade travel (m)

δ_{cr} = critical blade travel at transition from flow to flow and fracture (m)

δ_f = blade travel when cut is complete (m)

τ = shear stress (Pa)

τ_o = constant in shear stress-shear strain relation $\tau = \tau_o \gamma^n$ (Pa)

τ_{mean} = mean flow stress in shear (Pa)

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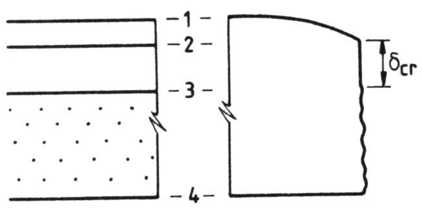

Figure 1 Side view of cropped edge

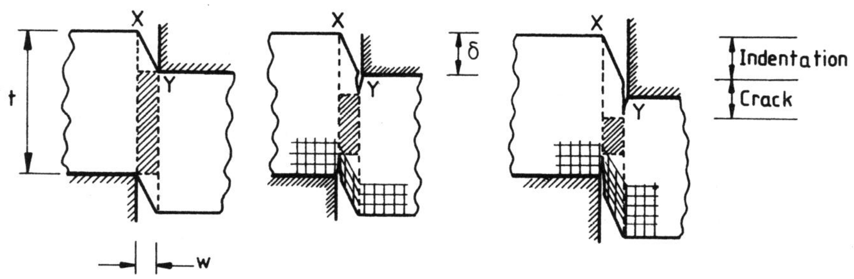

Figure 2 Single shear plane model of cropping showing flow, and flow and fracture