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FRACTURE INITIATION UNDER METALWORKING CONDITIONS

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INTRODUCTION

Some features of metalworking processes are the following: (1) free surfaces, (2) rigid boundaries made by surfaces of tools and dies, (3) sliding and sticking friction conditions (surface defects such as the extrusion defect are not considered here), (4) gradients in stress, strain, temperature, (5) hydrostatic stress components, and (6) portions of a work piece in the state of flow against portions which are acting in a rigid manner.

The modes of fracture initiation, both internal and at free surfaces, are discussed in terms of the above listed characteristics.

FRACTURE INITIATION MECHANISMS

It is proposed that there are but two fracture initiation processes. The first is by decohesions at substrates, generally termed the "ductile fracture mechanism". This fracture process must be subdivided according to the method of joining or coalescence of the cavities formed at substrates. These are (a) coalescence by continuing plastic deformation, termed here "pure ductile fracture", and (b) activation of shearing instabilities in the matrix between cavities in directions of pure shear (zero extensional strain). This process is designated "mixed mode fracture". The ductility in many technical alloys is limited by onset of these instabilities rather than by the reduction to zero cross-section of the ligaments between cavities.

The second initiation process is the result of the shearing instability itself. This instability is manifested as a tangential velocity discontinuity in a plastic zone along directions of pure shear or the "characteristics" direction as defined in continuum mechanics [1]. The result is an intensely localized shearing deformation with the material on either side of the instability band now acting in a rigid manner. Fracture initiation is by relative displacement of the two rigid segments along the characteristic surface. The basic necessary condition is

$$d\sigma = \left(\frac{\partial\sigma}{\partial\varepsilon}\right)_{\dot{\varepsilon},T}\delta\varepsilon + \left(\frac{\partial\sigma}{\partial\dot{\varepsilon}}\right)_{\varepsilon,T}\delta\dot{\varepsilon} + \left(\frac{\partial\sigma}{\partial T}\right)_{\varepsilon,\dot{\varepsilon}}\delta T \leq 0 \qquad (1)$$

or a maximum in the true flow stress in contrast to a load maximum for necking in tension ($dL = 0$). Physically this signifies the loss of strain hardening and the onset of the dynamic ideal plastic state. It follows that plastic flow is stabilized by high strain hardening capacity and high

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strain rate sensitivity. Only the third term is normally negative and which arises from adiabatic heating produced by plastic flow and any energy flux from external sources. The effect of rate of energy input in meeting this rheological condition is not clear but it may have an important influence on the ability to fill die cavities.

Other conditions necessary for instability fracture initiation are (a) a stress (strain) gradient, and (b) a free surface. A relationship between plastic strain gradient and stress gradient is given by Gensamer [2] as

$$\frac{d\varepsilon}{dx} = \frac{d\sigma/dx}{\sigma}\cdot\frac{\varepsilon}{n} \qquad (2)$$

Notice the effect of the strain hardening exponent in mitigating against strain gradients.

INITIATION AT EXTERNAL FREE SURFACES

Fracture initiation at external free surfaces can conceivably occur as a result of (a) the shearing instability, or (b) formation of sub-surface cavities directly under the surface which eventually coalesce and reach the free surface.

The former requires a critical degree of straining to attain the condition $d\sigma = 0$ and gradients in stress and strain. The direction of propagation will be *specific* and controlled by the stress state at that site (direction of the characteristics). For plane strain this direction will be at 45° to the free surface. *Fracture initiation by this mechanism at rigid boundaries* (tools, dies) *is not possible*. This is so because tangential velocity discontinuities are reflected at rigid boundaries.

A manifestation of the activation of localized plastic flow resulting from the shearing instability is the generation of "heat lines" in forging [3].

Edge cracking in upsetting solid cylinders and in rolling are generally regarded to result from the ductile fracture mechanism. Subsurface pores in the bulge produced by upsetting are reported in the literature [4]. A toublesome feature is the directionality of the edge cracks. *There is no inherent basis for strict crack propagation directions in pure ductile fracture*. Edge cracks are found to occur both in the vertical direction and at 45° to the vertical. Directionality must reside in the activation of the shearing instability either as a primary mode or in the joining of cavities. The Kuhn treatment of edge cracking [4] is based on the model of local thinning which is here interpreted as a manifestation of the shearing instability.

In biaxial stretching of sheet, the usual sequence is local thinning (at $dL = 0$) followed by localized flow in specific directions, often called "grooving" (at $d\sigma = 0$). The former event is eliminated for the state of stress $\sigma^2/\sigma_1 = 0.5$, $\sigma_3 = 0$ [5].

INTERNAL INITIATION

If a perfectly sound billet is assumed prior to deformation, an instability fracture cannot be initiated in the interior because of the absence of free surfaces. The only possibility is the formation of cavities by

decohesion at substrates.

There appears to be general agreement that plastic flow is required for decohesion. The most common substrates for decohesion are those associated with nonmetallic inclusions. Once a pore is formed, two of the three conditions for shearing instability are achieved, namely a free surface and a stress gradient. Remaining is the local achievement of the condition $d\sigma = 0$ locally for joining of pores. A basic effect of a hydrostatic pressure component is to forestall the onset of the condition $d\sigma = 0$ [6]. It is of course possible that the cavities will coalesce by continuing plastic straining.

A second type of substrate for cavity formation is formed by a portion of a billet flowing over another portion which is acting in a rigid manner, possibly termed a "self substrate". An example of such a phenomenon is in the initiation of central bursts in the extrusion of an aluminum alloy (Figure 1) according to F. J. Gurney [7]. Such fracture initiation is observed in torsion testing of high strength steels. Fracture is observed to occur at the interface of a band of intense shearing deformation and the now rigid matrix. A suggested mechanism by Tanaka and Spretnak [8] is depicted in Figure 2 (a, b, c depict the mechanism (d) a relaxation mode, and (e) a propagation mode) having to do with a discontinuity at the plastic-rigid matrix interface. A single crack nucleus can be propagated to failure in such a situation, depending on the brittleness of the alloy.

In the case of torsion, the interface is a characteristic surface (contains directions of zero extrusional strains). It is not known in the case of the extrusion central bursts whether or not the interface is a characteristic surface. The apparently orthogonal intersection of the two branches suggests that it may be.

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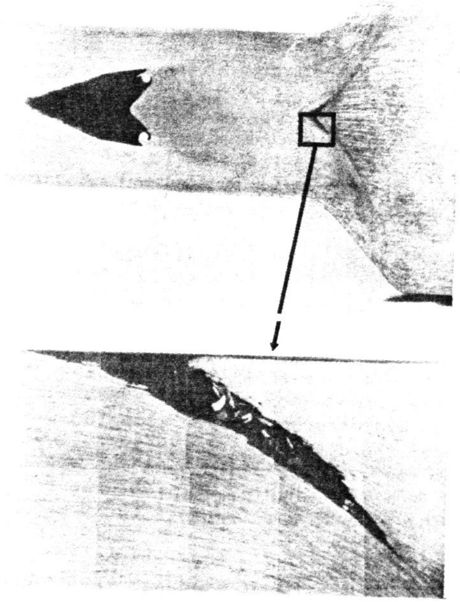

Figure 1 Initiation of Central Burst Defect in Extrusion (Reference 7)

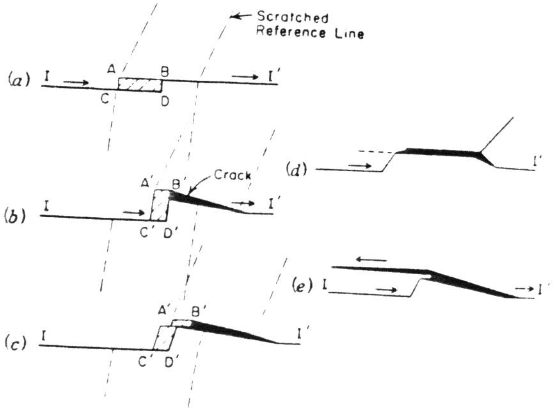

Figure 2 Suggested Mechanism for Crack Initiation at the Plastic-Rigid Interface (Reference 8)