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Re: Final Report on Department of Energy Grant DE-FG02-95-ER14561

Ductile necking and fragmentation of ductile materials at high rates of extension

It has been known for some time that when a ductile metal cylinder is expanded at a slow rate, say by internal pressure, it deforms more or less uniformly into the plastic range until a strain localization site, or "neck", develops at some point on the circumference; ductile fracture follows almost immediately. In contrast, if the same plastic deformation is induced at a rate of loading typical of explosive loading, high speed machining or dynamic rupture, experiments reveal that *many* necks form around the circumference of the cylinder at more or less equally spaced sites. This remarkable nonlinear material failure mode was first demonstrated experimentally by N. F. Mott more than 50 years ago and, in spite of its relevance to dynamic fracture, explosive metal forming and other technologies, understanding of it has remained elusive. This puzzle has been resolved through a series of steps carried out in the course of this project. First, to gain insight into the process of neck formation and failure, large scale numerical simulations of the phenomenon were undertaken to determine its sensitivity to the many material parameters which might be relevant, with a view toward isolating those which are most significant for the process. Results were reported (Sorenson & Freund, European Journal of Mechanics, 1998 and International Journal of Solids and Structures, 2000) which led to the conclusion that the process of neck formation was dominated by material inertia, flow strength and, in an indirect way, by strain hardening characteristics. A typical cross section sector of an expanding shell at about 50% mean

Figure 1. A 22.5 degree sector of a thin-walled shell of ductile material expanding at high rate. The shading represents level of effective plastic strain (darker is higher) for an average circumferential strain of about 50%.

strain is shown in Figure 1. After a certain amount of plastic straining occurs, an array of plastic necks appears spontaneously. The array is more or less equally spaced and the configuration appears to have no correlation to any initial distribution of imperfections in the wall of the cylinder. The key findings and their ranges of validity

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were discussed in detail in these papers.

With the material characteristics that dominate the process of dynamic ductile neck formation established, we turned to analytical models involving only these characteristics in order to establish a clear understanding of the mechanics of the process. In particular, the findings were incorporated into a dynamic stability or bifurcation analysis. It was found that multiple equally-spaced necks which grow at rates large compared to the rate of background deformation form naturally in the process as a true bifurcation phenomenon. Growth of many of these incipient necks to fracture eventually results in ductile fragmentation of the material. The theoretical model predictions were found to be qualitatively consistent with experimental observations of the process as reported in the literature. A result that facilitated comparison with experiment is the observation that a universal relationship exists between the number of necks q_{max} formed in a particular expanding cylinder, the geometry of the cylinder represented by a thickness-to-circumference ratio α , the rate of expansion represented by the ratio of loading speed v_0 to circumference, and the material strength of the form represented by the plastic wave speed at a strain of unity with the form

$$q_{max} = KN_c^{1/4} \alpha^{-1/2} \sqrt{v_0 / v_p}$$

where K is approximately equal to one. The bifurcation analysis and the consolidation of the results into this universal form were reported in a paper (Shenoy & Freund, journal of the mechanics and physics of solids, 1999) along with an assessment of the range of

Figure 2. Bar of ductile material being extended at high rate. Periodic array of necks has formed, and some necking sites are progressing toward ductile failure.

applicability of the results obtained.

A quantitative comparison with experimental observations had to await an analysis of the same phenomenon in rings of circular cross-section, rather than in thin walled shells. Both the computational simulation and the bifurcation analysis were extended to this more complex but more realistic case. It has been found that both short wavelength and long wavelength perturbations are suppressed by inertia and an intermediate wavelength is favored in strain localization. The analysis predicts an increase in the number of necks and an increase in the bifurcation strain with increasing extension rate, in agreement with the experimental observations. In terms of the number of necks formed as a function of extension rate, good quantitative agreement has been found between the experiments and the analysis (Guduru & Freund, International Journal of Solids and Structures, to appear in 2002). At any given aspect ratio, the model also predicts that the mode number of the dominant perturbation increases rapidly beyond a critical extension rate and the perturbation begins to look more like a surface instability. This could lead to a fragmentation mechanism at high extension speeds which is different from multiple necking. Currently no experimental results are available to test this prediction. In this study, the stages of process beyond multiple neck formation, that is, involving the actual growth of necks into fractures, was also taken into account in the computational studies. Numerical simulations have been conducted to simulate the fragmentation results, using Gurson's constitutive law along with a porous failure criterion. An advanced stage of the process is illustrated in Figure 2. Good agreement between the experimental observations and the numerical results has been obtained for the fragmentation statistics. However, the numerical results consistently overestimate the number necks and the fracture strain, possibly due to uncertainty in the constitutive data used, especially at large strains. Altogether, the results in this sequence of papers represents the first fundamental explanation of the dynamic ductile bifurcation phenomenon. The results are consistent with available experimental observations and they significantly broadened our understanding of dynamic ductile failure of materials.

Crack growth and crack pattern formation in strained thin films

Another study (Shenoy, Schwartzman & Freund, International Journal of Fracture, 2000) was directed toward understanding crack growth and crack pattern formation in a brittle elastic film bonded to an elastic substrate with different properties; a residual tensile stress is presumed to exist in the film due to the constraints of epitaxy across the interface with the substrate. The focus of the study was the influence of the mismatch in elastic properties on patterns of crack formation in the film. The stress intensity factor and crack driving force for growth of a periodic array of cracks in the direction normal to the interface under two-dimensional conditions were determined for any crack depth and any mismatch in elastic parameters; see Figure 3.

It was found that, even for a relatively stiff film material, the stress intensity factor as a function of crack depth exhibits a local maximum. The driving force for crack extension in the direction parallel to the interface was then determined, and the equilibrium spacing of crack arrays was estimated for given residual stress. The results of the calculations were used as a basis for understanding the crack patterns which have been observed in GaN films on Si substrates. These crack patterns are deleterious to the function of electronic devices made of such films and the long-term

goal is to understand how to suppress the formation of these cracks in the course of device fabrication.

Figure 3.

This study has been extended in several directions, and the results obtained that are of a fundamental nature are being incorporated into a monograph on thin films and layered materials being written jointly with Professor Suresh of MIT. The current draft of the chapter dealing with film delamination and fracture is enclosed for information purposes. The preface of this book will include an acknowledgment of the support of the Department of Energy as well as the support of other agencies supporting various aspects of work being incorporated into the book.

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