TENSILE FRACTURING IN DYNAMIC COMPRESSION

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ABSTRACT

Both brittle and ductile materials can fracture under overall compressive loads. For brittle materials, microcracks are seen to develop at preexisting microflaws and grow in the direction of maximum compression. In dynamic loadings, this phenomenon is highly strain rate dependent. The micromechanical model of Nemat-Nasser and Deng (1994), which seems to capture the essential feature of this process is briefly reviewed.

Similarly, very ductile materials, such as copper and mild steel, can undergo brittle-type fracturing when subjected to high strain-rate dynamic compression which produces suitable heterogeneous plastic deformation fields, for example, by collapsing preexisting voids. Nemat-Nasser and Hori (1987), presented a model which suggests the possibility of such tension cracking. Nemat-Nasser and Chang (1990), showed in a series of experiments on single and polycrystalline copper and in mild steel, that fracturing of this kind does actually occur. These and related issues are briefly examined in this paper.

KEYWORDS

Dynamic Compression; Brittle and Ductile Materials; Tension Cracks; Damage Models; Experimental Results

INTRODUCTION

Over the past fifteen years, several major developments have helped to bring the issue of *brittle failure in compression* to a satisfactory level of basic understanding. The unexplained Bridgman paradoxes have been resolved; Scholz *et al.* (1986), Nemat-Nasser and Hori (1993). Models which satisfactorily and quantitatively explain axial splitting, faulting, and transition from brittle to ductile modes of failure have been developed; Nemat-Nasser and Horii (1982) and Horii and Nemat-Nasser (1985, 1986). And, most importantly, the mechanisms of fracturing in *loading* and *unloading* have been conclusively captured experimentally and by means of laboratory models; Myer *et al.* (1992). These have given credence to the simple but effective micromechanical modeling of brittle failure on the basis of preexisting flaws with frictional and cohesive resistance. Such a model can effectively capture the observed phenomenon of axial splitting in the absence of confinement, as well as the related phenomena of exfoliation or sheet fracture, and rockburst; Holzhausen (1979), Nemat-Nasser and Horii (1982), and Ashby and Hallam (1986). In the presence of moderate confining pressures, furthermore, faulting by the interaction of preexisting microflaws has also been modeled by considering the interactive growth of tension cracks from an echelon of suitably oriented microflaws; Horii and Nemat-Nasser (1985). Furthermore, by including, in addition to tension cracks, possible zones of plastically deformed materials at the tips of preexisting flaws, the transition from brittle-type failure to ductile flow under very high confining pressures has been modeled; Horii and Nemat-Nasser (1986). A series of experimental model studies supports these analytical results. In particular, the influence of confining pressure on the mode of failure of brittle materials seems to have been understood and modeled.

The above mentioned results are all for quasi-static loading and address microcracking during compressive loading: *the microcracks grow in the general direction of the maximum applied compression.*

During unloading, however, the microcracks are expected to grow essentially *normal* to the direction of the applied compression. This has been vividly illustrated by a set of *dynamic* experiments by Nemat-Nasser and Chang (1990). It has been illustrated that, even extremely ductile crystalline solids such as single-crystal copper (an fcc metal), and mild steel and pure iron (bcc metals) can undergo *tensile cracking normal to the direction of compression,* possibly during the unloading phase, under suitable conditions. In these experiments the sample is never subjected to any externally applied tensile forces: only compressive loading and unloading. Nevertheless, tension cracks are seen to develop basically *normal* to the applied compression.

In this paper we focus on two main issues: (1) the mechanism of the dynamic failure of brittle materials under confining pressures; and (2) the mechanism of failure of ductile materials under dynamic compressive loads. This second topic also bears on the proper post-mortem interpretation of compressively failed specimens, since it demonstrates how tensile cracks are created *normal* to the direction of maximum compression, apparently during the unloading (removal of compression) of specimens which may have never been subjected to any (overall) tensile forces.

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Failure Mode: Experimental Observations

As is shown by early experiments of Perkins *et al.* (1970), using a compression Hopkinson bar, the stress to failure of rocks and similarly, of concrete, is strain rate-dependent. Similar results are reported by Lankford (1981a,b) and others[1] for ceramics, who show that the compressive failure stress and the resulting fragment sizes depend on the *strain rate* and the *stress state.* This result supports that the generation, dynamic growth, and coalescence of microcracks at preexisting inhomogeneities and flaws, are the major features of this dynamic process.

Another class of experiments which again support the above comment, involves plate-impact loading of thin circular cylindrical specimens, using a gas gun; see, e.g., Shockey *et al.* (1974) and Grady and Kipp (1987) who review dynamic rock fragmentation and provide references to earlier work. Some of these experiments are recovery tests. However, many are not. A proper recovery experiment for rock and concrete samples

[1] See, also Rosenberg *et al.* (1985), Cagnoux and Longy (1988), Lankford (1989), Lankford and Blanchard (1991), and Cosculluela *et al.* (1991).

which have relatively coarse microstructures, requires relatively thick and large samples. Momentum traps must be provided to take away both the axial and the lateral momenta, in order to leave a central portion of the sample, having been subjected to only the uniaxial strain. For the pressure-shear test, the situation is more complex, and only recently have satisfactory recovery experiments on alumina been performed; see, Machcha and Nemat-Nasser (1994, 1996). These experiments also support the notion of microcrack induced mechanism of dynamic compression failure.

Recently, Nemat-Nasser and Deng (1994) have developed a model based on the *interacting dynamic growth of multiple cracks* and show that the model produces the failure stress versus strain rate relation, in (at least qualitative) accord with experimental observations. In a related effort, Deng and Nemat-Nasser (1994) include plastic flow, and examine brittle-ductile transition at high strain rates. Some of these results are reviewed briefly in the sequel.

Mathematical Modeling

Nemat-Nasser and Deng (1994) consider an infinite array of microcracks under dynamic farfield biaxial compressive loads, as shown in Fig. 1a, b. In Fig. 1(a), the flaws have a common length of 2c, are spaced 2w apart, and have produced wing cracks of a common length $2l$ under the action of $|\sigma_{11}|>|\sigma_{22}|$.

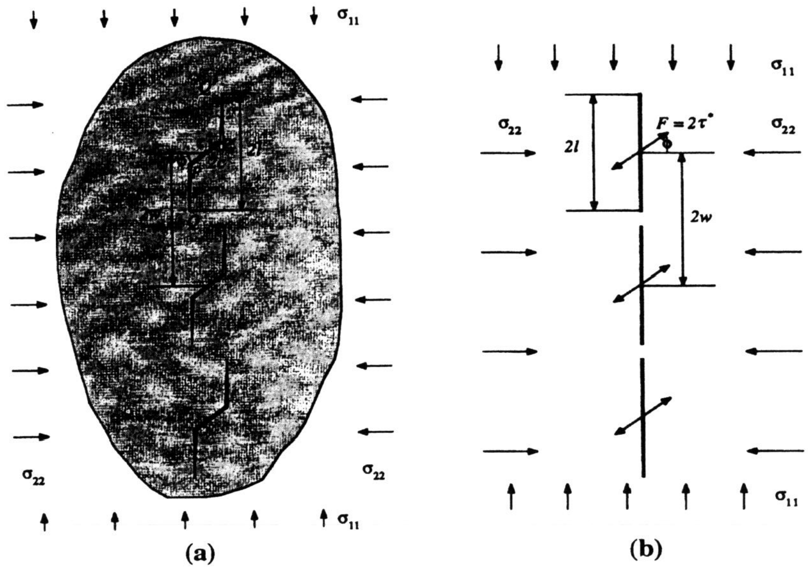

Fig. 1. (a) An array of interacting wing cracks under biaxial compressive loads; (b) a collinear crack array loaded by concentrated forces and uniform stresses

The compression induced tension cracks are approximated by straight tension cracks which nucleate at the preexisting crack tips P and P', and grow in the direction of maximum compression. To simplify the analysis, the growth and coalescence of these tension cracks are modeled by those of a collinear crack array shown in Fig. 1(b), where each crack in this collinear crack array is loaded by a pair of concentrated forces which represent the effect of the deformation of the preexisting flaws. The collinear crack array is also loaded by the farfield compression.

This simplified collinear crack array model has a closed-form solution, and, at the same time, seems to capture some of the basic features of compression failure, such as the influence of the microstructure, loading condition, and strain rate on the crack growth and coalescence.

Model Results and Discussion

The overall failure of brittle solids at the macroscopic scale is generally defined in terms of the failure stress. The failure stress is the maximum applied compressive axial stress which, at a given loading rate, causes failure in the presence of a given lateral confinement. The microstructure is represented by the microflaw size and spacing in a wing-crack array. The failure stress predicted by this model for a uniaxial compressive loading, is plotted as a function of the strain rate in Fig. 2(a) for indicated microflaw spacing w and fixed microflaw size c, and in Fig. 2(b) for indicated flaw size and fixed microflaw spacing. For increasing microflaw spacing, the failure stress increases with a decreasing strain rate. For increasing microflaw size, the failure stress decreases at low strain rates and increases at high strain rates. The decrease at low strain rates is due to the decrease of the normalized fracture toughness as the length scale (flaw size) increases. The increase at high strain rates is mainly due to material inertia effects during crack growth.

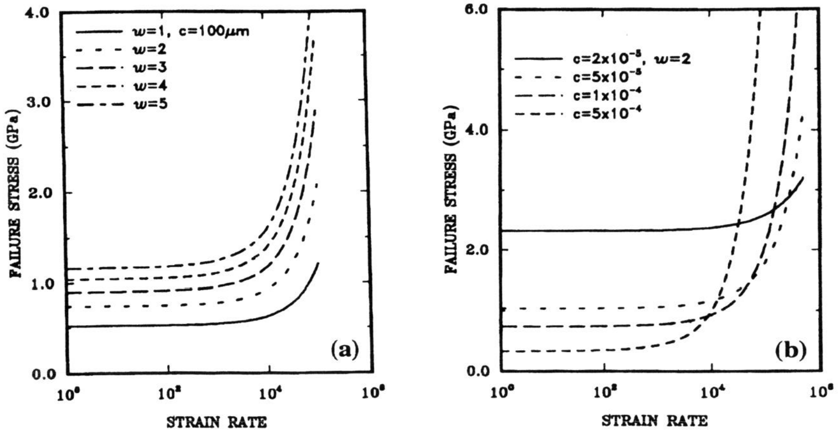

Fig. 2. Effect of microflaw spacing (a), and microflaw size (b) on failure stress

Consider now the effect of lateral confinement on the failure stress. Assume the lateral confinement is proportional to the applied compression. The growth of compression-induced tension cracks is restrained by the presence of the confinement. The overall axial failure stress increases with increasing lateral compression, as shown in Fig. 3. The maximum flaw spacing, which still results in failure by crack coalescence, decreases with increasing lateral confinement, as shown in Fig. 4 for indicated strain rates and microflaw sizes. The fragment size which is related to the spacing of active flaws that lead to crack coalescence, decreases with increasing confinement.

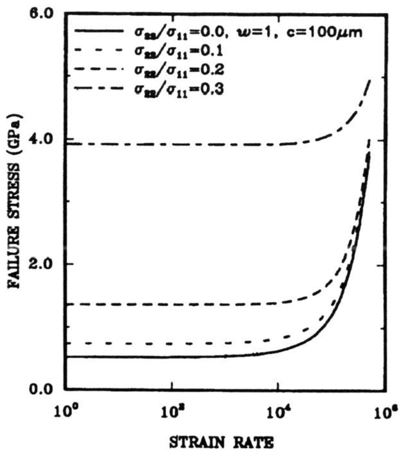

Fig. 3. Failure stress at given lateral confinement

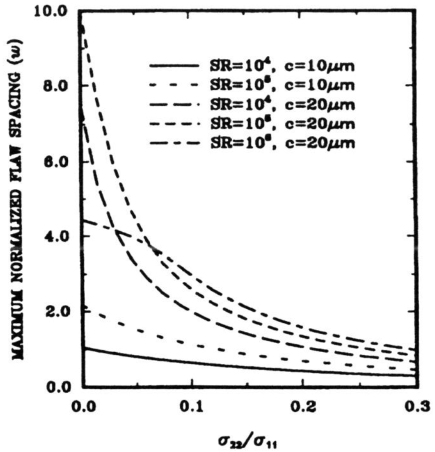

Fig. 4. Effect of lateral confinement on maximum flaw spacing

FAILURE OF DUCTILE MATERIALS IN COMPRESSION

As discussed in the preceding section, the main characteristic of the failure of brittle materials in compression is the formation of microcracks predominantly in the direction of maximum compression. An interesting recent observation is that ductile materials such as copper, mild steel, and iron, *can fail in compression by the formation of tensile cracks normal to the direction of the applied compression.* The phenomenon is highly rate-dependent and requires heterogeneous large plastic deformations to precede the removal of the compressive stresses. It is believed that the cracking occurs during the unloading; Nemat-Nasser and Chang (1990).

The possibility of tensile cracks developing in an fcc single crystal during the removal of compression, was brought into focus by micromechanical calculations of Nemat-Nasser and Hori (1987) who used a rate-dependent slip-induced plasticity theory to calculate void growth and void collapse in single crystals. Assuming that the response of the solid during unloading is essentially elastic, these authors examine possible tensile cracking from the tips of a collapsed void in a single crystal. The calculation shows that indeed, tensile cracking can take place during unloading in a specimen which has been subjected to overall compressive forces at high strain rates.

Computational Results

The computation of void collapse (or growth) by Nemat-Nasser and Hori (1987) is based on decomposing the total deformation rate tensor into an elastic part and a plastic part. The stress rate is expressed in terms of the elastic part of the deformation rate tensor, by Hooke's law. The rate of plastic slip of each slip system is assumed to be governed by a power-law, $\dot{\gamma} = \eta\,(\tau/\tau_r)^n$, where η, τ_r, and n are regarded as material parameters, and τ is the resolved shear stress. The exponent n is large, say, n = 100, for small strain rates, and is taken to be unity when the strain rate exceeds 10^4/s. The flow stress τ_r, in general, depends on the deformation history and includes the material hardening effects. In the actual analytical computations of Nemat-Nasser and Hori (1987), τ_r is assumed to remain constant. The solution is obtained incrementally.

The analysis of possible tensile cracking is based on the assumptions that unloading occurs elastically and that the crack may grow if the Mode I stress intensity factor exceeds a given critical value. The Mode I stress intensity factor at the tip of a crack of length $2a_1$ (which is formed by a collapsed void), due to the superposition of accumulated stresses during loading and released stresses during unloading, is given by

$$K_I = \int_{a_1}^{a} \sigma_n^{(\ell)}(\xi)\, 2\sqrt{a}\, \frac{d\xi}{[\pi(a^2 - \xi^2]^{1/2}} + \sigma_n^{\infty(u)}\sqrt{\pi a}\,, \qquad (1)$$

where the subscript n denotes the stress component normal to the crack face, it is assumed that the crack faces remain traction-free, and that the farfield stresses existing prior to unloading are removed by the amount $\sigma_n^{\infty(u)}$. In (1), superscript ℓ on σ stands for the magnitude of the stress during loading, and superscript u stands for the unloading stress. In the actual calculation the extended crack length defined by a, is chosen such that the value of K_I, calculated from (1), equals the prescribed critical value of the stress intensity factor.

The calculation shows and experiment verifies that higher compressive loads are required at higher loading rates, in order to collapse a void. Hence, larger stress intensity factors are attained in complete unloading, when void collapse occurs at higher loading rates. Thus the response of the same material containing the same microvoids will not be the same when the loading rate is changed: *the material becomes stronger but more brittle at higher (compressive) loading rates.*

The process of void growth and void collapse and the subsequent failure mechanisms depend on the orientation of the slip systems, the state of stress, the rate of loading, and the initial void size. The following general results are obtained in this model study:

1) Even under all-around uniform hydrostatic compression, an initially spherical (circular in two dimensions) void quickly becomes nonshperical and may collapse into a crack. Depending on the rate of loading, the ductility of the material (which is also affected by the rate of loading), and the initial void size, the crack which is formed by the void collapse may extend in its own plane during the course of unloading, leading to failure by a brittle type tensile fracture, even though the material has not been subjected to any overall tensile loads. This occurs at high strain rates for sufficiently large voids. The minimum void size required for such a failure decreases with an increasing compressive loading rate.

2) Void collapse in compression and void growth in tension are basically different processes and one cannot be regarded as the reverse of the other.

3) An initially circular (in two dimensions) void may collapse into a crack, even under uniaxial tension, if the orientations of the slip systems are suitable. Similarly, overall shear stresses can collapse a void into a crack. However, under tensile loads, voids usually expand into ellipsoidal cavities which may then grow self-similarly in an unstable manner, leading to ductile failure.

Experiments

In a series of experiments, Nemat-Nasser and Chang (1990) have conclusively established that tension cracks normal to the direction of the applied compression can actually develop in both fcc and bcc metals when the (high-strain-rate) plastic deformation preceding dynamic unloading is highly heterogeneous, and a suitable stress concentrator does exist.

Figure 5 shows a partially collapsed void in single-crystal copper axially strained by about -9% at a 1,100/s strain rate. The crystal is cut in such a manner that two slip systems in the plane of the specimen are activated. Hence, the thickness remains essentially constant.

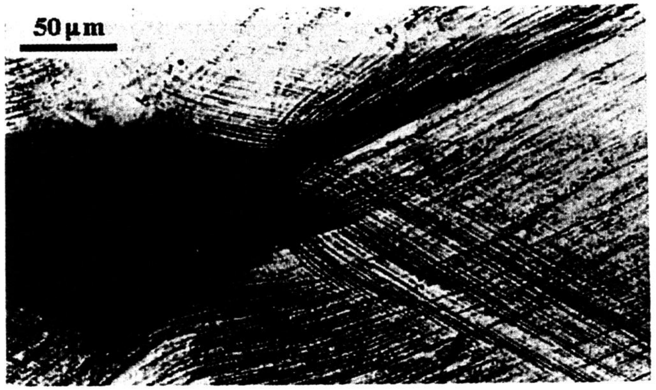

Fig. 5. Nucleation, growth, and coalescence of cracks at certain distance ahead of the main crack tip at the end of the collapsed void in a Cu single crystal

The figure suggests that, at the intersections of the slip planes. Lomer-Cottrell (L - C) sessile dislocations can be produced from the associated partial dislocations. The L - C sessile dislocations may be formed by the energetically favorable dislocation reactions,

$$\frac{a}{2}[\bar{1}10]+\frac{a}{2}[10\bar{1}]\rightarrow\frac{a}{2}[01\bar{1}], \quad \text{and} \quad \frac{a}{2}[01\bar{1}]\rightarrow\frac{a}{6}[01\bar{1}]+\frac{a}{6}[\bar{2}1\bar{1}]+\frac{a}{6}[21\bar{1}]. \tag{2}$$

The dislocations on the (100)- plane which is not a slip plane, are immobile. These triads of dislocations can serve as obstacles to the movement of mobile dislocations on the $(\bar{1}\bar{1}1)$- and $(1\bar{1}1)$- planes. The density of these dislocations increases with plastic flow during the compression phase, as the void collapses, resulting in substantial work hardening. During unloading, however, their presence may result in crack initiation and growth, as a more favorable mechanism of stress relief than plastic slip.

The microfracturing process is perhaps most vividly illustrated by the results shown in Fig. 6. Figure 6(a) shows the highly deformed region ahead of a collapsed void in a single-crystal copper specimen which has undergone an overall nominal strain of -31%, at a 10^4/s strain rate. There are three main cracks, one in the [100] - direction, straight ahead of the tip of the collapsed void. The surface structure of the specimen around this crack clearly shows extensive plastic deformation on the $(\bar{1}\bar{1}1)$- and $(1\bar{1}1)$- planes. This is a region with high-density L-C locks. Microcracks are then nucleated in unloading, and grow along slip lines. Close to the tip of the collapsed void, extremely high tensile stresses are produced during the removal of compression. This then leads to the formation of macroscopic cracks, straight ahead in the [100] - direction. Figure 6a also shows two additional main cracks, located almost systematically about the [100] - direction, along highly deformed curved slip-directions. The structure of these cracks is better seen in the polished specimen, Fig. 6(b).

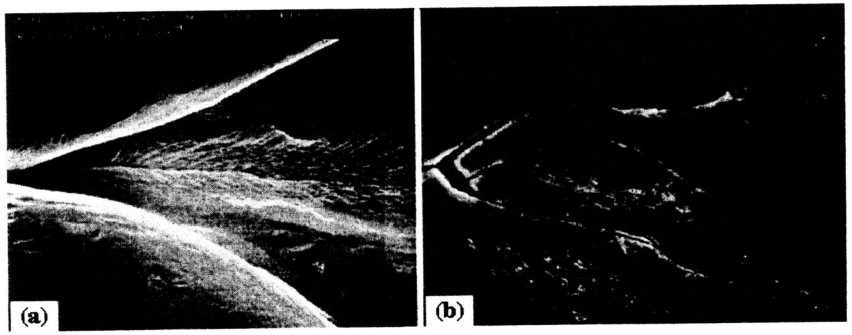

Fig. 6. (a) Highly deformed area ahead of a collapsed void in Cu single crystal; (b) polished surface of (a)

Recrystallization and Fracturing in Compression

Void collapse involves strains of several hundred percent, at the vicinity of a collapsing void, even though the overall nominal strain is 20-30%. This results in high-density plastic work near the tips of the collapsing void. At a strain rate of 10^4/s, an almost adiabatic plastic flow takes place. The temperature close to the collapsed void can become exceedingly high, reaching several hundred degrees.

Extremely large plastic deformations (very high dislocation density) and the accompanying plastic heating associated with very high strain rates can produce conditions favoring recrystallization. This, indeed, happens when the overall nominal strain exceeds -25%, at the overall nominal strain rate of 10^4/s, as exemplified in Fig. 7(a). What is most interesting in this figure is that both recrystallization and fracturing have occurred.

Fig. 7. In Cu single-crystal specimen at 10^4/s strain rate: (a) recrystallization occurred at the tips of void collapsed at 31% strain, (b) back scattered electron image showing recrystallized grains on the electro-polished surface

The experiments clearly show that recrystallization must occur *prior to unloading,* as is evident from the results of Fig. 7(b). As is seen, the tensile cracks which can only occur in unloading, extend into the new crystals.

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