MICRO-MECHANISMS OF COMPRESSION FAILURE

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ABSTRACT

Materials such as rocks, concrete and ceramics fail under different modes ranging from brittle to plastic failure depending on the deformation conditions. The underpinning micro-mechanisms of dynamic brittle failure in compression are examined over a broad range of deformation rates, from quasi-static to strain rates encountered in ballistic experiments. An overview of recent advances in novel experimental techniques to study the dynamic behavior of brittle materials is presented. Recent data on damage initiation and evolution in ceramic armor materials are considered with a view toward deciphering the essential feature of failure phenomena. It is observed that under moderate confining pressures and at moderate deformation rates, brittle failure involves initiation of micro-cracks at dominant micro-flaws and pre-existing micro-cracks and their subsequent interactive growth, leading to axial splitting, faulting or a mixture of brittle-ductile failure. Recent data on SiC is compared to a wing-crack array model, which describes the influence of microstructure on the dynamic behavior of ceramics.

Under great confining pressures, common in ballistic impact on the other hand, classical crack-growth models seem inadequate for representing the actual failure initiation and evolution. Computational simulations of the early stages of impact response of ceramic armor show development of stress states involving extremely high shear stresses within the target ahead of the projectile. This suggests a region conducive for pulverization. Transmission electron microscopy examination of recovered Al₂O₃ powder from a confined sample impact-penetrated by W (X21-alloy) at high velocity shows extensive twinning with sub-micron spacing.

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1.0 INTRODUCTION AND BACKGROUND

Ceramics, rock and concrete are characterized by brittle failure under compression. These materials find varied applications based on their mechanical properties. SiC, Al₂O₃ and TiB₂ find extensive usage in high velocity impact applications such as multifunctional armor. It is important to understand the micro-mechanisms of compressive failure so as to help design improved structural elements. Under quasi-static compressive loading conditions, micro-structural factors such as mismatches in elastic compliance between adjacent grains and inherently present processing flaws (e.g. pores and inclusions) create local tensile stresses. Tensile micro-cracks originate at pre-existing flaws and grow unstably in the direction of maximum compressive load. Failure occurs by fragmentation caused by formation and coalescence of these tensile micro-cracks. This mode of failure is termed as axial splitting. Micro-mechanical models based on pre-existing flaws, which include frictional and cohesive resistance, have been presented to describe the failure process. Brace and Bombalakis¹ present a sliding crack model, also termed as wing-crack. The corresponding failure process has been quantified analytically by Nemat-Nasser and Horii." At higher strain rates it is observed that a many more micro-cracks are nucleated resulting in finer fragment size. The Hopkinson bar has been modified and extensively used to study the dynamic behavior of ceramics.³⁻⁶ Sarva and Nemat-Nasser⁷ have studied the dynamic compressive strength of SiC under uniaxial compression. It has been observed that the compressive strength of SiC, drastically increases at strain-rates higher than 1000 s⁻¹. Some researchers have focussed on the energetics of nucleation and growth of these microcracks.⁸,⁹

It has also been observed that the dynamic properties of brittle materials are sensitive to confinement.¹⁰ In the presence of moderate confining pressure, failure is inhibited resulting in an improvement in mechanical properties. Failure eventually occurs by faulting due to a preferential growth of micro-cracks. Horii and Nemat-Nasser¹¹,¹² have suggested that faulting may be a result of unstable growth of tension cracks at suitable sets of interacting flaws. Chen and Ravichandran¹³ have studied the dynamic compressive behavior of a soft ceramic Macor under confinement.

When confining pressure is extremely large, a transition from brittle failure by faulting to a ductile response by overall plastic flow takes place. Horii and Nemat-Nasser¹² include possible zones of plastically deformed materials at high shear stress regions around pre-existing flaws to model the transition from brittle failure to ductile flow under very high confining pressures. The use of Hopkinson bar to study the dynamic response under very high confinement pressures is difficult. However extremely high inertial confinement can be induced in the ceramics by high velocity impact.
Deng and Nemat-Nasser\textsuperscript{14} have proposed a two dimensional model to simulate dynamic damage evolution in uni-axial compression. To study the strain rate effect at moderate strain rates and confinements, Nemat-Nasser and Deng\textsuperscript{15} have developed a simple model of an array of interacting wing cracks to describe the influence of microstructure on behavior of brittle materials at high strain rates. A brief summary of the wing-crack array model is presented below.

**Wing-Crack Array Model:**

Nemat-Nasser and Deng consider an infinite array of interacting, dynamically growing wing-cracks.\textsuperscript{15} The wing-crack array is subjected to a dynamic farfield compressive load. See Fig.1(a). A bi-axial compressive field is considered to include lateral confinement. The tensile cracks emanating from the tips of wing-cracks grow unstably in the direction of the maximum compressive load at limited speeds. Coalescence of these tensile cracks results in failure. The model is simplified to an array of collinear cracks as shown in Fig. 1(b). The dynamic stress intensity factor is calculated by superposition of the solution for a crack array under pairs of concentrated forces applied at the crack centers and the solution for a crack array under uniform farfield stresses. The solution to this collinear crack array displays the influence of the microstructure and the loading conditions on the dynamic behavior. The microstructure is described by the flaw-size $c$ and spacing $w$. See Appendix for the mathematical solution.

![Echelon of wing cracks and collinear crack array model](image)

Figure 1 (a) and (b). Echelon of wing cracks and collinear crack array model
The model helps study the effects of strain-rate, microstructure and lateral confinement on the compression failure. It predicts that the length scale at which the material heterogeneities interact with each other leading to micro-cracking and possible pulverization is dependent on magnitude of compression and strain rate. At low level of pressure, large defects interact and lead to failure. As the amplitude of compression is increased, the length scale at which the defects interact diminishes. The effect of length scale is illustrated in Fig. 2. The model also predicts that the compressive strength increases with strain-rate and lateral confinement.
3.0 EXPERIMENTAL PROCEDURES

3.1 Uniaxial compression

The Hopkinson bar has been extensively used to study the dynamic behavior of brittle materials at moderate strain-rates and confinement. Ceramics have very high compressive strengths and low failure strains. Hence, the classical Hopkinson bar is modified.\textsuperscript{16,17,18} Since, the behavior is essentially linear elastic, a pulse shaper, in form of a copper cushion is placed at the front end of the incident bar to generate a ramp loading and hence maintain uniform strain-rate. Strain gages are attached to the sample to help measure strains accurately. Impedance matched platens increase specimen-bar interface area and help reduce stress concentrations. Previously reported dynamic tests\textsuperscript{7} of uniaxial compression of SiC were performed on a 12.7 mm Hopkinson bar. Elastic wave propagation relations used to calculate the constitutive behavior are valid at the specimen-bar interface. However, the strain gages that measure the wave pulses are located
mid-bar length away from the specimen interface. This shift causes perturbations. To eliminate the error induced due to these perturbations, the wave pulses are corrected for dispersion. However, dispersion effects limit the accuracy at high strain rates (>1500 s\(^{-1}\)) for a 12.7mm Hopkinson bar.

Hence, to attain higher strain rates, a 4.76 mm diameter Hopkinson bar is used. Further experiments were conducted using cylindrical samples of hot-pressed SiC. The samples were of 2.03 mm diameter and 3.05 mm length. The samples were polished parallel to a tolerance of less than 3 \(\mu\)m. A striker bar of 38.11 mm length was used to attain a strain rate of nearly 9000 s\(^{-1}\). Impedance matched platens were used to prevent bar damage. The W\(_4\)C platens were confined in Kovar, to improve their strength. The failure stress was calculated from the transmitted pulse. Due to the miniature size of the samples, it was not possible to attach strain-gages onto the sample for accurate measurement of strain. Hence the strain-rate was inferred from the transmitted pulse and the Young’s modulus of SiC (470 GPa), assuming that the behavior is linear elastic until failure. To confirm the validity of the above procedure, experiments were conducted on a 12.7 mm Hopkinson bar, with strain-gages attached to a SiC sample. Results indicate that the strain-rate calculations made using the above technique matched well with the strain-rate measured by the strain gauge attached to the sample.

For other brittle materials such as concrete, mortar, rock and other relatively coarse microstructures materials, a 76 mm Hopkinson bar can be used. Strain rates of nearly 1000 s\(^{-1}\) can be attained.

3.2 Moderate confinement

3.2.1 Interference fit technique: An interference-fit, maraging steel sleeve can be used to achieve a static lateral confinement on the SiC samples. Maraging steel has a Young’s modulus of 200 GPa and a yield strength of more than 2.34 GPa. This method consists of fitting a sleeve over the sample, with the sleeve’s inner diameter smaller than the outer diameter of the SiC sample. Due to the radial misfit, the sleeve exerts lateral confinement on the SiC sample. Recently, experiments were conducted to study the compressive strength of SiC under confinement, using this method. See Fig. 3 for the confinement assembly design. The radial misfit was about 0.01 mm. The sample was mechanically forced into the sleeve. Alternatively, they can be shrunk-fit. The confining pressure was calculated by using the solution for a linear elastic axisymmetric boundary value problem\(^{19}\). It was calculated to be approximately 300 MPa.

When the sample-sleeve assembly is axially loaded, it undergoes compressive strain in the direction of loading. However, it expands in the radial direction. The Poisson's ratio for the maraging steel is much higher than that of SiC. Hence, it can be expected that as the axial loading increases, the sleeve expands a larger amount than the SiC sample. This results in the reduction of
lateral confining pressure provided by the sleeve. To counter this, another maraging steel sleeve, slightly smaller in length was used as an additional sleeve. The second sleeve was 0.25 mm shorter in length. The inner diameter of this additional sleeve was chosen to be the same as the outer diameter of the first sleeve. It helps retain the confining pressure on SiC sample, without inducing any additional confining pressure. The smaller length of the second sleeve prevents it from being affected during elastic loading of the sample. Chen and Ravichandran\(^{13}\) have used a similar technique to laterally confine Macor samples.

The 12.7 mm Hopkinson bar was used to study the dynamic compressive strength of the confined SiC samples. Since the attachment of strain gauge onto the sample is not feasible, the strain rate is inferred from the transmitted pulse. The failure stress was calculated from the transmitted signal. The failure stress calculation for the confined ceramic is corrected for the inclusion of the metal sleeve. This adjustment is made by deducting the elastic energy of the metal sleeve during deformation. The Young’s modulus of maraging steel is 200 GPa. The sleeve is assumed to be in its elastic regime until the sample fails. This gives the approximate failure stress for SiC sample.

![Sample and confinement design](image)

3.2.2 Pneumatic confinement: For large size samples of materials such as concrete, rock and polymeric composites, confinement can also be attained pneumatically.\(^\text{20}\) Fig. 4 shows the 76 mm Hopkinson bar and the pneumatic confinement assembly. A large diameter pressure vessel, constructed such that it encompasses the entire sample, provides confinement. The pressure vessel is placed onto the incident and transmission bar. The proper assembly of pressure vessel is important to ensure safety and good results. Concrete samples can be tested at confining pressures of a few hundred MPa and up to a strain-rate of 1000 s\(^{-1}\), using this system.
Figure 4. Pneumatic confining techniques for a 76mm Hopkinson bar

Figure 5. Tri-axial test configuration
3.2.3 Triaxial tests: The Hopkinson bar can be modified to simultaneously load the sample in radial and axial directions. It consists of larger (27.1 mm) and smaller (19.1 mm) incident bars and transmission bars as seen in Fig. 5. Incident and transmission tubes which encompass the smaller incident and transmission bars, but move independently of them, help load a Teflon sleeve. The Teflon sleeve surrounds the sample and is restricted by an aluminum sleeve on the outside. During the test, a large hydrostatic stress is induced in the Teflon sleeve, which in turn exerts a large radial stress on the sample. The radial stress increases during the test, as the incident and transmission bars axially load the sample and the Teflon sleeve. The radial stress is estimated by measuring the hoop strain on the outer surface of the aluminum sleeve. Strain rates of several thousand s\(^{-1}\) and radial stresses of several hundred MPa can be attained with this system.

3.3 Huge inertial confinement

Experimentally it is very difficult to achieve extremely high confining pressures or strain rates using the Hopkinson bar. However, large lateral confinements can be attained by high velocity planar or projectile impact, due to mass inertia. Nemat-Nasser et al. have studied the effect of high velocity impact by Tungsten X21 alloy on the microscopic failure mechanisms of Al\(_2\)O\(_3\). A 2.54 cm thick Al\(_2\)O\(_3\) tile confined in a steel casing was impact penetrated by W (X21-alloy) projectile (dia. = 4.8 mm) at about 900 m s\(^{-1}\). A single stage gas-gun was used to propel the projectile. During the very initial stages of impact, the sample is shock loaded and a stress-state similar to that of uni-axial strain exists ahead of the projectile head. However, as penetration progresses, the emanating stress waves result in a much more complex state of stress. The ceramic fragments from the pulverized zone were recovered and examined microscopically by TEM.

4.0 RECENT EXPERIMENTAL RESULTS AND FAILURE MODES

4.1 Uniaxial compression

As can be seen from Fig. 6, ultra-high strain rate tests indicate that the uniaxial compressive strength of SiC is approximately 8.5 GPa at a strain rate of 9000 s\(^{-1}\). Fig. 6 also includes previously reported uniaxial compressive strength data for comparison. Similar to previously reported results, failure occurred by fragmentation as a result of axial splitting.
4.2 Moderate confinement

Lateral confinement results in a substantial improvement in the ceramic strength. The quasi-static failure strength, as measured on an Instron test machine is 7 GPa. The dynamic strength at a strain rate of 1100 s\(^{-1}\) is 9 GPa. It is seen that the compressive strength improves by 2 GPa, for a lateral confining pressure of 300 MPa. The strain rate sensitivity of the failure strength is maintained. For the laterally confined samples, it was observed that the failure is by fault formation rather than by axial splitting. Fig. 7 indicates the top and bottom view of the recovered samples. The faults formed were conical in nature. The apex of the fault cone can be observed in the top view. It runs diagonally across the top face. The samples were mounted in epoxy resin and ground. The cross section was observed at regular intervals to examine the failure mode. Fig. 8 is the schematic of comparison for quasi-static and dynamic failure. It was observed that, for the same amount of strain, the faults formed for the dynamic test were wider. Also considerably more microcracking was observed in the dynamic failure as compared to the quasi-static case.

Figure 6. Experimental results and comparison to Nemat-Nasser – Deng Model
Figure 7. Top and bottom view of the failed samples under moderate confinement

Figure 8. Schematic of faulting for moderately confined samples
4.3 Large confinement

Extremely high compressive stress, lateral confinement and temperatures are attained due to shock loading during impact-penetration. The ceramic samples fail by a combination of failure processes, which include pulverization and fragmentation due to radial and circumferential cracking. In the pulverized zone, fragments smaller than the grain size are formed. Transmission electron microscopy of Al₂O₃ powder recovered from the pulverized zone indicates extensive localized plasticity. Deformation twins in the sub micron scale were observed. See Fig. 9 (a). A solitary deformation twin has been isolated and its electron diffraction pattern studied in Fig. 9 (b). The electron diffraction pattern displays mirror images of a single pattern super-imposed on each other indicating that the twin is a ‘reflective-twin’. The characteristic axis of the twin is given by ‘m-m’. Part of the atomic lattice crystal has symmetrically re-oriented itself such that its structure is a mirror image of the parent matrix lattice. Though Al₂O₃ has a HCP crystal structure and a very high degree of symmetry, it is not commonly known to exhibit twinning under moderate loading conditions. Under extreme loading conditions, twinning can accommodate extensive plastic deformation with very little volume change. It is expected that micro-cracks resulting in the eventual pulverization of the ceramic, accompanies twinning.

Numerical simulations on DYNA 2D (a two-dimensional hydrodynamic finite element code) indicate that during the initial stages of impact, release waves emanating from the edge of the projectile, produce a zone of high shear stress and low pressure ahead of the projectile at a distance of the order of its diameter. The state of stress in this zone lasts only a fraction of microsecond, but is sufficient to produce pulverization of ceramic.
5.0 COMPARISON TO NEMAT-NASSER – DENG MODEL

The model has been compared to compressive failure strength data of SiC for both unconfined and moderate-confinement tests. See Fig. 6. Since the axial load is substantially larger than the lateral confining pressure, the multi-axial loading is approximated to bi-axial loading. The model includes the effect of the microstructure in terms of micro-flaw size and micro-flaw spacing. For comparison purposes, the model is plotted for pre-existing micro-flaw size of 90 µm and flaw spacing of 950 µm.

The material constants of SiC are taken as: Young’s Modulus \( E = 470 \) GPa; fracture toughness \( K_{IC} = 4.5 \) MPa√\( m \); and the effective Rayleigh wave speed \( c_R = 2000 \) ms\(^{-1} \). Rayleigh wave speed is the limiting crack velocity. It is expected that the damage caused by wing-cracks reduces the effective Rayleigh wave speed of the material. Hence a wave speed, which is approximately third of an intact material, is chosen. For multi-axial loading, the model is plotted for a
confining pressure of 300 MPa. Other parameters defining the wing cracks are taken as: co-efficient of friction $\mu = 0.4$; and preferred orientation of micro-flaws $\varphi = 72^\circ$.

6.0 CONCLUSIONS

It is observed that the compressive strength of SiC improves from a quasi-static strength of 4.2 GPa to 8.5 GPa at a strain rate of 9000 s$^{-1}$. Moderate confining pressures (300 MPa) can be achieved with a ‘two-sleeve interference fit technique’. The compressive strength of SiC sharply increases under lateral confinement. A lateral confinement of 300 MPa improves the compressive strength by about 2 GPa. The strain-rate sensitivity of the compressive strength is maintained. Under lateral confinement, the failure mode changes from axial splitting to fault formation. For cylindrical samples, it was observed that conical faults were formed. Preferential crack growth results in fault formation. An increased amount of micro-cracking during a dynamic test results in wider faults during dynamic tests. The Nemat-Nasser – Deng model gives a quantitative description of the high strain rate behavior of ceramics. It correlates well with experimental data obtained from the unconfined and moderately confined tests.

Under high amplitude shock compression, the interaction length scale diminishes to grain size and eventually to nano dimensions. Classical crack-growth models are no longer applicable under such conditions. In such a regime even very brittle solids may deform plastically. Thus, comminution may occur under great confinement through coupling between shear stress, low pressure and material microstructure. The resulting failure stress will depend on confinement as well as length scale at which micro-defects interact. TEM results of Al$_2$O$_3$ samples recovered after impact-penetration by W (X21-alloy) show plastic deformation in form of extensive deformation twinning.

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REFERENCES

APPENDIX

The Mode I dynamic stress intensity factor at the crack tips in a crack array under both concentrated and uniform loads is given by

\[
K_{ld}^{\text{array}} = k_{l_{1t}} (\hat{l}) K_{l_{1t}}^{\text{array}} + k_{l_{2t}} (\hat{l}) K_{l_{2t}}^{\text{array}}, \quad K_{l_{2t}}^{\text{array}} = \sigma_{22} \sqrt{2w \tan \frac{\pi l}{2w}},
\]

\[
K_{l_{1t}}^{\text{array}} = F \cos(\phi) \left( w \sin \frac{\pi(l + l_0)}{w} \right)^{\frac{1}{2}}, \quad K_{l_{2t}}^{\text{array}} = \sigma_{22} \sqrt{2w \tan \frac{\pi l}{2w}}.
\]  

(1)

As seen from Fig. 1, \( w \) is the crack spacing and \( c \) is the flaw size. The functions \( k_{l_{1t}} (\hat{l}) \) and \( k_{l_{2t}} (\hat{l}) \), which represent inertia effect during dynamic crack growth in the stress intensity, are approximately given by

\[
k_{l_{1t}} (\hat{l}) = \frac{c_R - \hat{l}}{c_R - 0.75 \hat{l}}, \quad k_{l_{2t}} (\hat{l}) = \frac{c_R - \hat{l}}{c_R - 0.5 \hat{l}}
\]

(2)

where \( c_R \) is the Rayleigh wave speed. \( F = 2c_\tau^* \), where \( \tau^* \) is the driving shear stress acting on the pre-existing flaw, given by

\[
\tau^* = -\frac{1}{2} (\sigma_{11} - \sigma_{22}) \sin 2\phi - \tau_c + \frac{1}{2} \mu \{\sigma_{11} + \sigma_{22} - (\sigma_{11} - \sigma_{22}) \cos 2\phi \},
\]

(3)

where \( \mu \) is the frictional co-efficient, \( \tau_c \) is the cohesive stress describing the wing crack. The small length \( l_0 \) is introduced to make the model applicable at \( l = 0 \).

For fracture criterion, it is assumed that the dynamic stress intensity factor does not exceed a constant fracture toughness, i.e. \( K_{ld}^{\text{array}} \leq K_{lc} \). The common growth speed of the compression induced tension cracks is now
\[ i = c_R \frac{1.5K_{Ih}^{array} + 1.75K_{Ih_2}^{array} - 1.25K_{lc} - \sqrt{X}}{K_{Ih_1}^{array} + 1.5K_{Ih_2}^{array} - 0.75K_{lc}} \]  

(4)

where

\[ X = \left[ 1.5K_{Ih_1}^{array} + 1.75K_{Ih_2}^{array} - 1.25K_{lc} \right]^2 - 4 \left( K_{Ih_1}^{array} + K_{Ih_2}^{array} - K_{lc} \right)(0.5K_{Ih_1}^{array} + 0.75K_{Ih_2}^{array} - 0.375K_{lc}). \]  

(5)

The crack length is obtained by integrating the crack tip speed until failure or complete unloading occurs. To obtain failure stress for a given stress pulse and material microstructure, the time to failure is calculated from the crack speed and the length to which the cracks must grow for coalescence to occur. The failure stress is then defined by the value of the applied axial compressive stress at crack coalescence.