Characterizing Damage Evolution and Yield in Sandstone under Triaxial Loading as a Function of Changing Effective Pressure*

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Abstract

Experimental rock deformation was used to study 1) the accumulation of microscopic damage preceding macroscopic failure across the brittle-ductile transition (BDT) in granular porous rocks, and 2) how damage induced at one effective pressure (P) affects failure at a different P. Granular porous material is idealized as an elastic-plastic material, where failure occurs by localized dilatant shear at low P and compactant cataclastic flow at high P. Given distinct failure modes in the low and high P regimes, different types of damage may develop prior to failure at different P.

Water saturated cylinders of Berea sandstone (18% porosity, 185 μm grain size) were deformed in triaxial compression at a shortening rate of 4 μm/s. During each experiment, the confining and pore pressure were held constant; acoustic emissions (AE), axial stress, axial displacement, and pore volume changes were recorded. Samples were deformed at pore pressures of 10, 20, and 30 MPa, and confining pressures of 50, 180, and 260 MPa to investigate the brittle, transitional, and ductile regimes. Three different load paths were used. The first involved loading to failure to establish a baseline response. The second involved initial loading to 80% of the differential stress at failure, unloading, and reloading to failure at a different pore pressure. The third was similar to the second, except confining pressure was changed between load and reload to cause failure in a different regime than the initial load. AE is used to quantify damage evolution, and the Kaiser effect was used to map damage states in stress space.

The experiments show that contours of equivalent damage are subparallel to the failure envelope across the BDT, and that macroscopic failure depends on load path and the cumulative damage state. Damage induced in either the low or high pressure regimes has little effect for failure in the other deformation regime, supporting the concept of distinct processes and damage

development in the two regimes. These results could be important in predicting formation damage and permeability changes in over-pressured reservoirs that undergo large drops in pore pressure, as well as for reservoirs undergoing advance recovery methods and sequestration that increase pore pressure. This could also aid in understanding deformation in tectonic basins that experienced P changes due to burial or exhumation, or from cyclic loading along faults.

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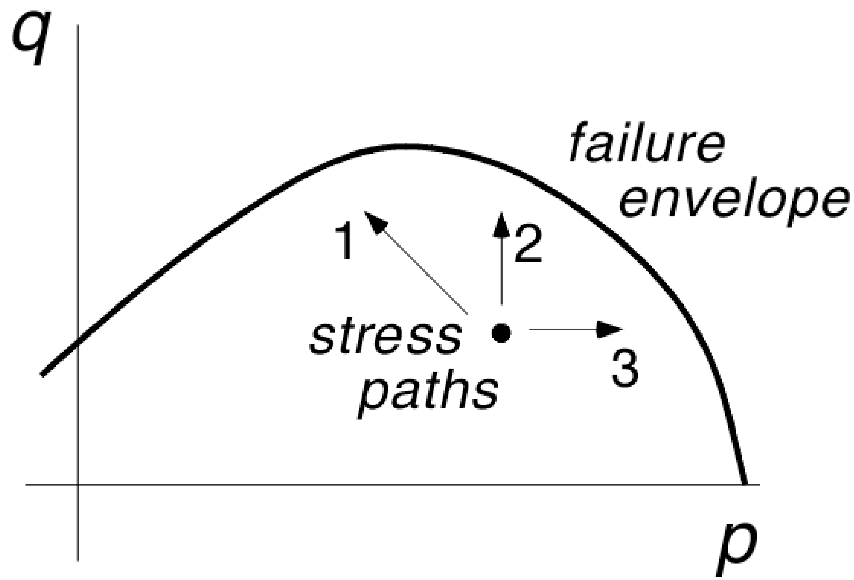
Mechanical Behavior of Reservoir Rock During Production

- Poroelastic response from changes in stress
- Differential stress (*q*) and effective mean stress (*p*) vary with position and time
- Deviation from ideal poroelasticity from plastic yielding and accumulation of damage leading to failure

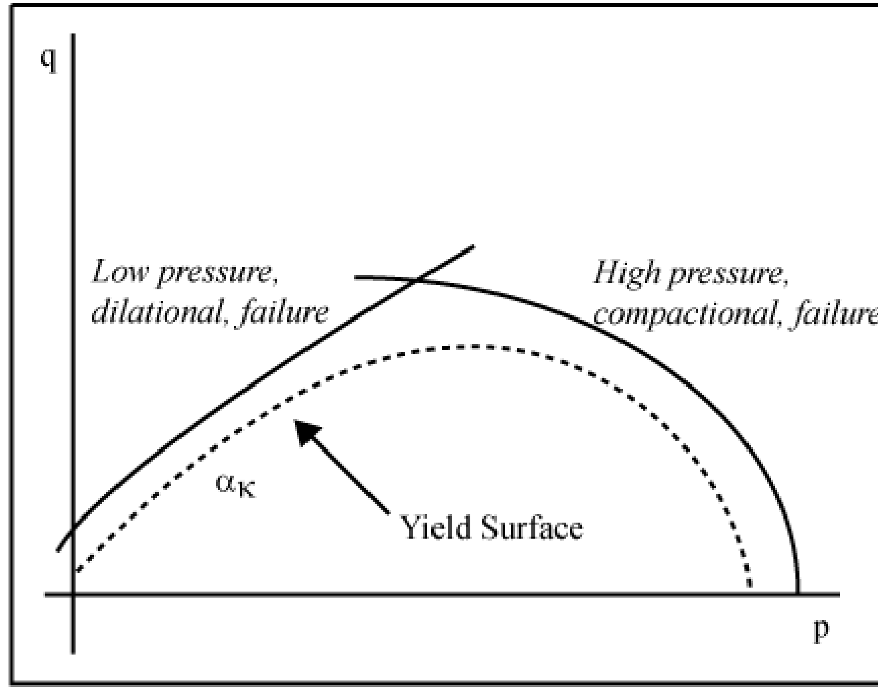


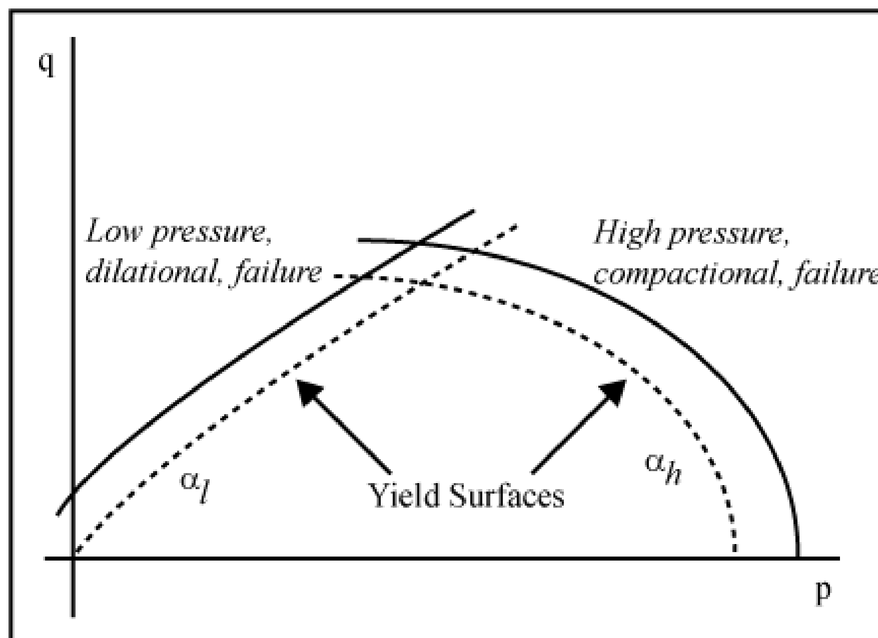
Damage Mechanisms and Failure at Low and High Effective Mean Stress

- Low Pe regime: Localized, dilatant shear fracture described by Mohr-Coulomb envelope
  - Intergranular cracking, breaking cemented boundaries, grain boundary sliding and grain rotation
- High Pe regime: Distributed, compactional cataclastic flow described by elliptical CAP
  - Fracturing of grains initiating at Hertzian contacts, porosity collapse, and grain rearrangement
- Transitional regime: Combined distributed deformation and localized deformation bands
  - Mix of low and high Pe mechanisms of damage

Failure Envelopes and Models of Yield Surface(s)

- Failure: major deviation from elastic response
  - Formation of fractures and deformation bands
  - Low and high P envelopes
- Yield: Onset of plastic deformation and damage
  - Defined by yield surface function $F(p, q, \alpha_\kappa)=0$
- Single or multiple yield surfaces best description?





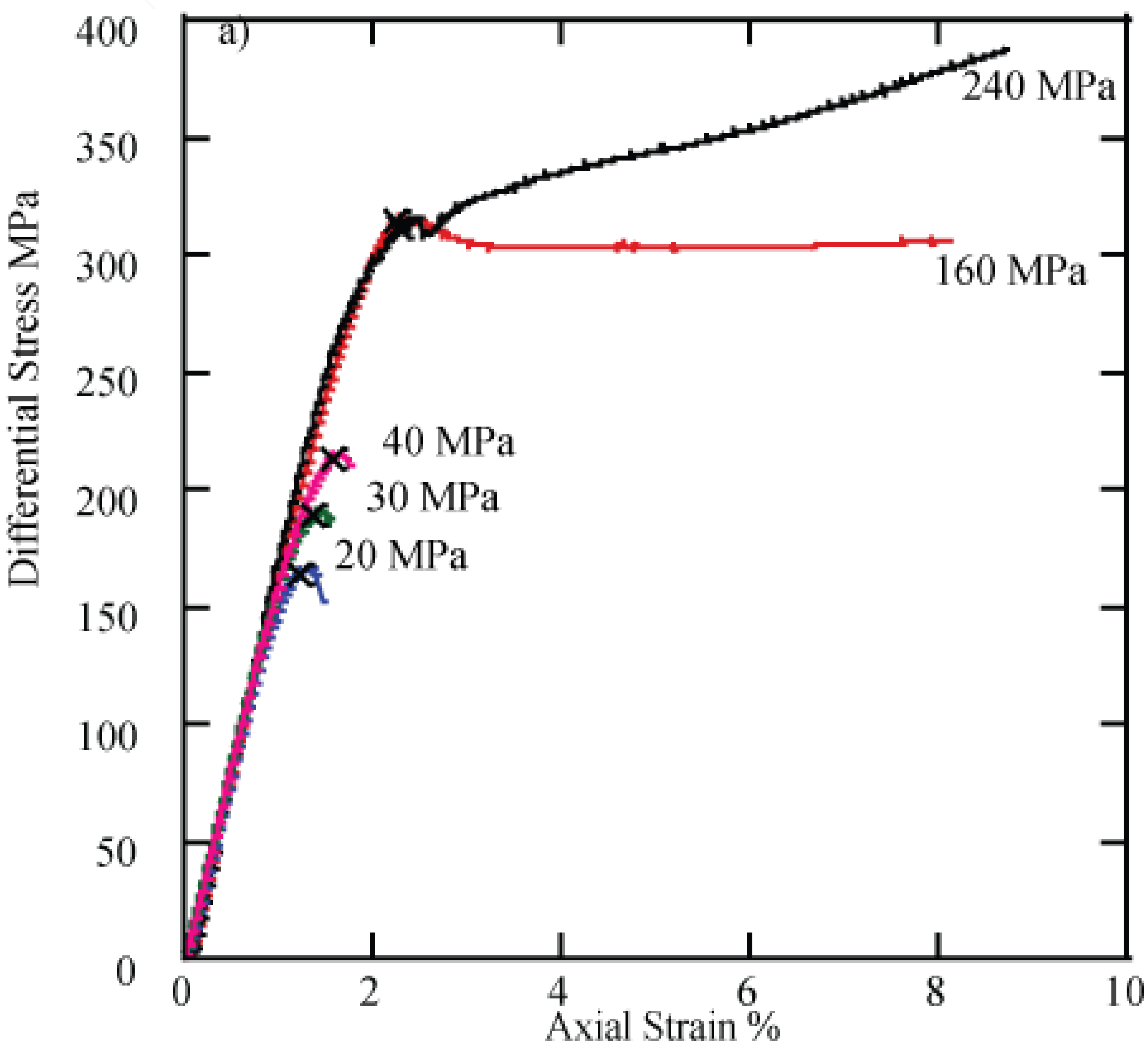
Purpose and Experimental Load Paths

- Characterize yield, damage development, and failure across the brittle-ductile transition
- Determine how yield and failure depends on load path and cumulative damage
- Test models of single and multiple yield surfaces to describe behavior at low and high Pe
- Three load paths
  - Single, direct load to failure
  - Load to yield-Reload to failure in same pressure regime
  - Load to yield-Reload to failure in different pressure regime

Samples and Experimental Apparatus

- Berea Sandstone cylinders
  - 75% quartz, 10% feldspar, 5% calcite and 10% clay, but varies based on sample
  - 185 µm mean grain diameter
  - 16-19% porosity
- Axisymmetric triaxial compression in large-sample, gear-driven apparatus
- Independent confining pressure and pore pressure systems
- Axial and volume strain measurement
- Acoustic emission (AE) counting

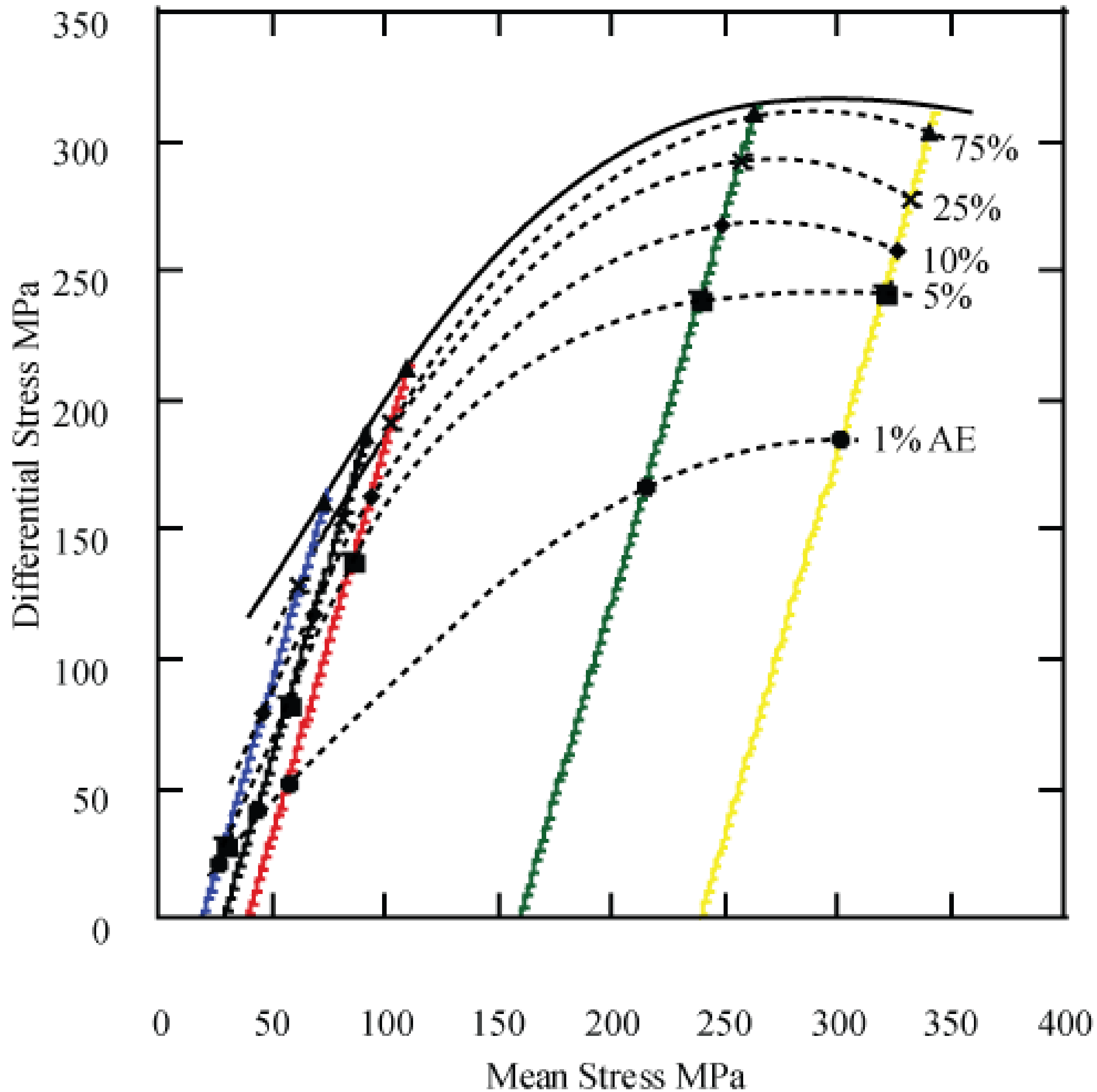
Results from Single Load Experiments



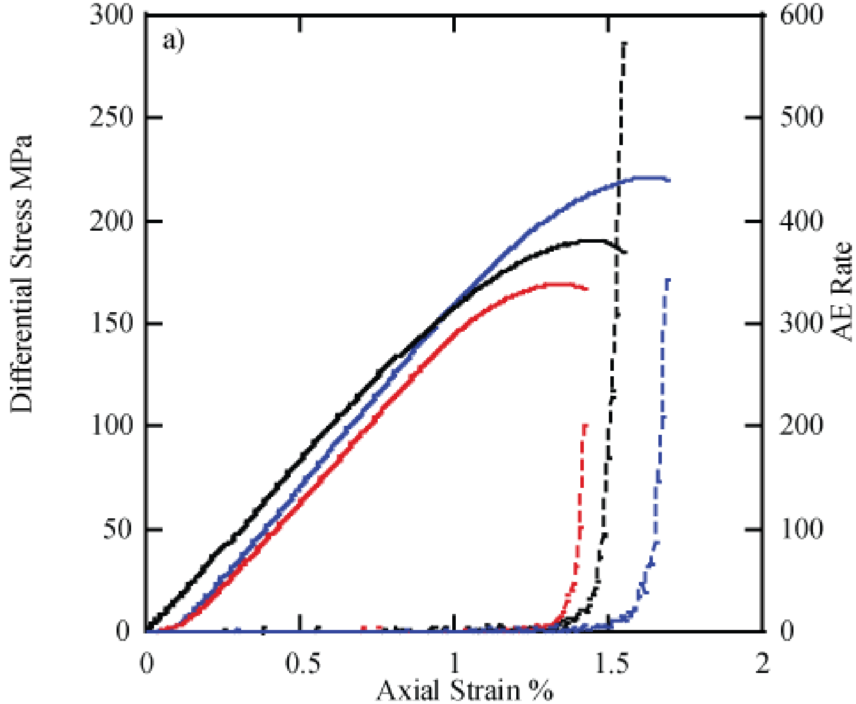
- Low Pe regime: localized dilatant shear fracture at 30° to axis
- High Pe regime: ductile compacting flow, strain hardening
- Transitional regime: ductile, compacting flow with formation of high angle conjugate shear bands, strain softening

Equivalent Yield Surfaces Determined by AE Count

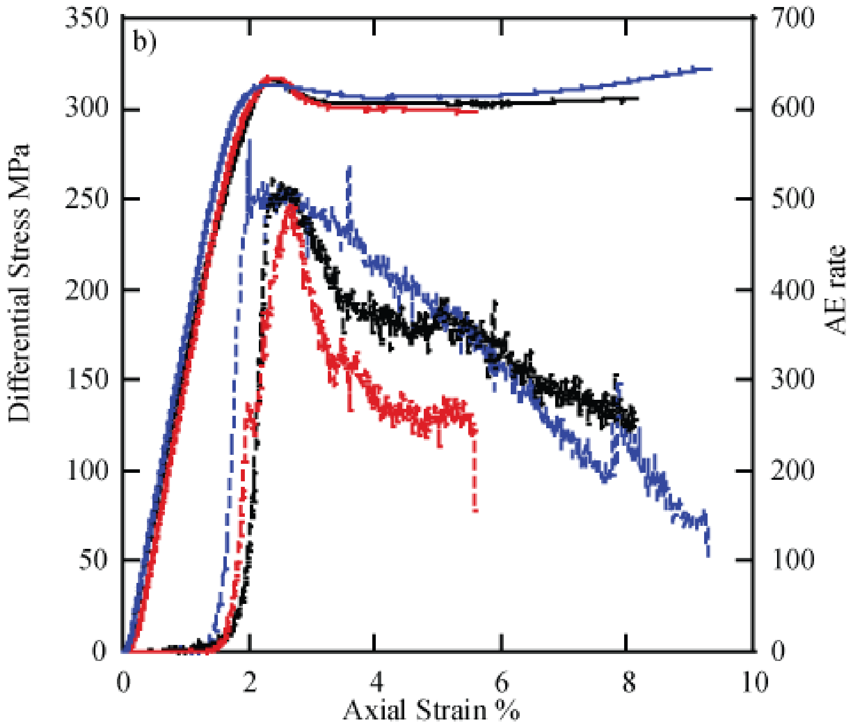
- Yield surfaces mimic shape of failure envelope
- Post yield damage evolves in similar ways across the brittle ductile transition
- Load-Reload experiments
  - Initial load to stress at 25% AE yield surface

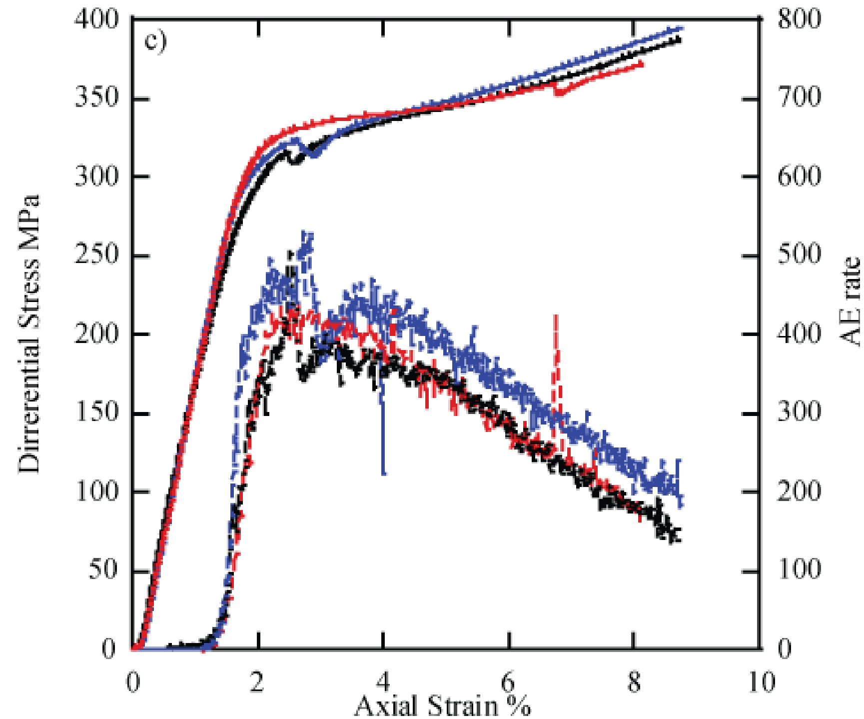


Results from Load-Reload In Same Regime



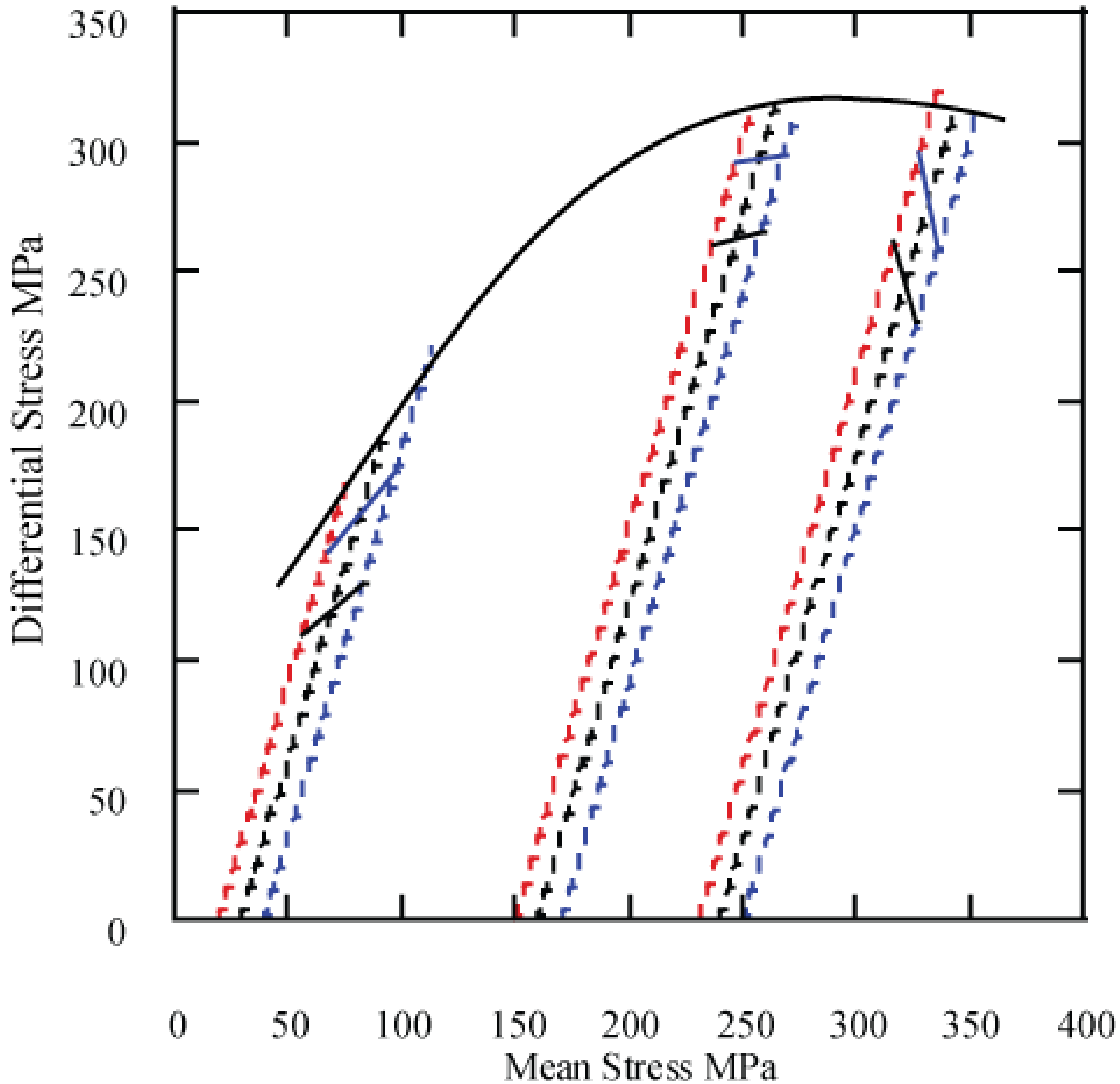
- Failure and macroscopic behavior similar within each regime
- Yielding different in load and reload
  - Kaiser effect

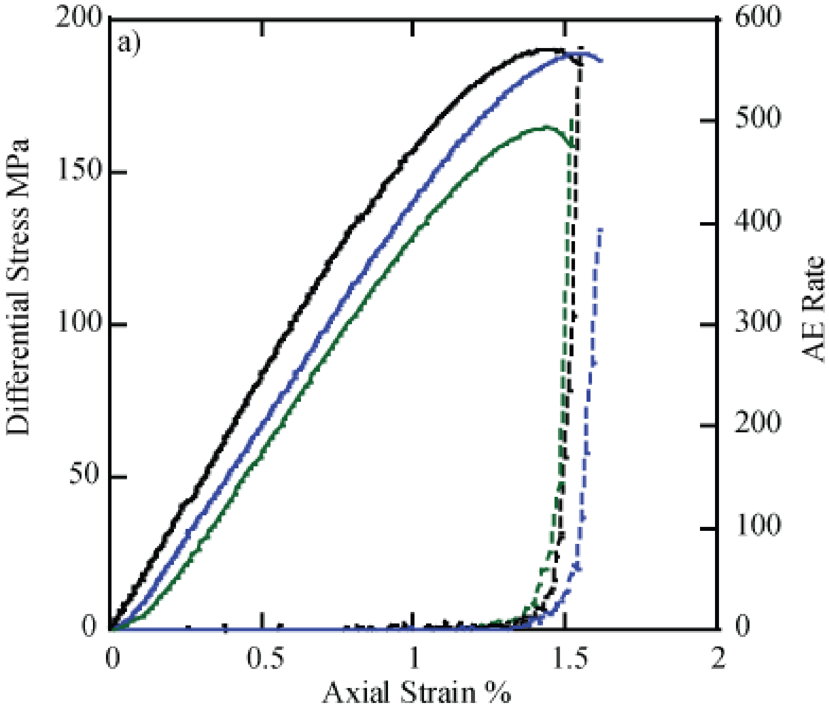




Local Yield Surfaces Determined in Load-Reload Tests by Kaiser Effect Showing Equivalent Damage States

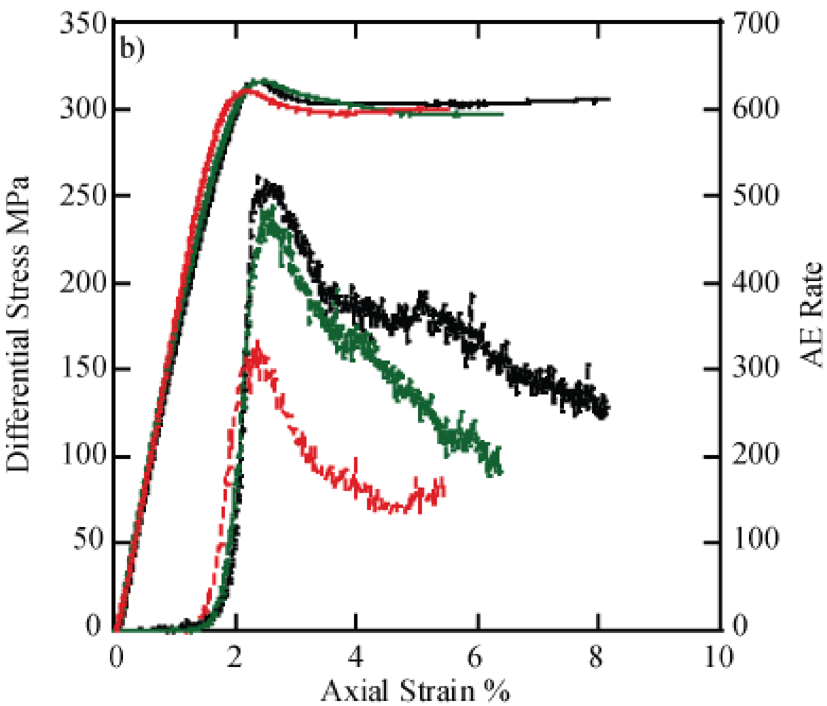
- Yield surfaces subparallel to failure envelope
  - Greatest deviation (a more negative slope) in high Pe regime
- Yield mechanisms responsible for accumulation of damage depend on Pe similar to failure

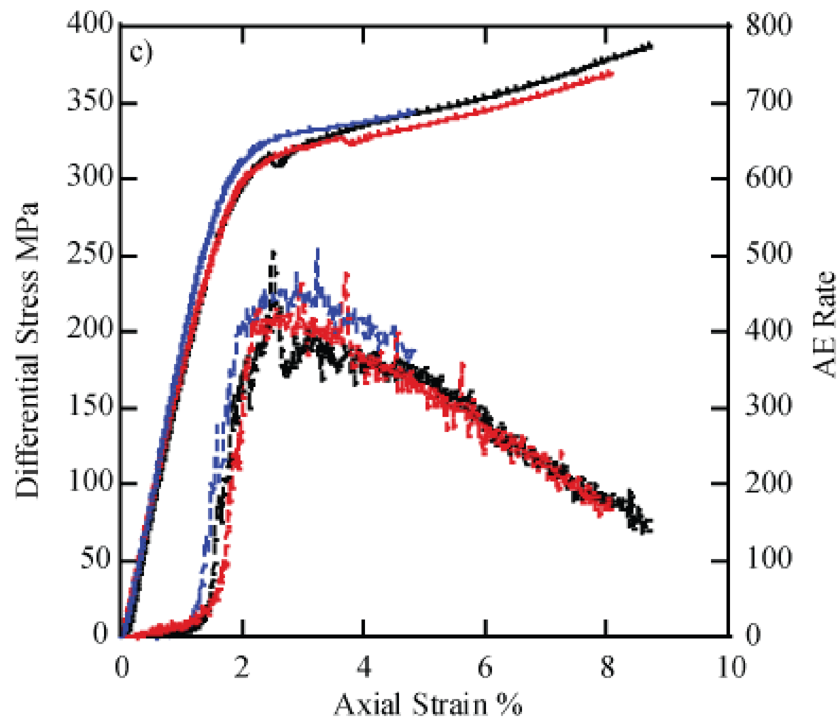




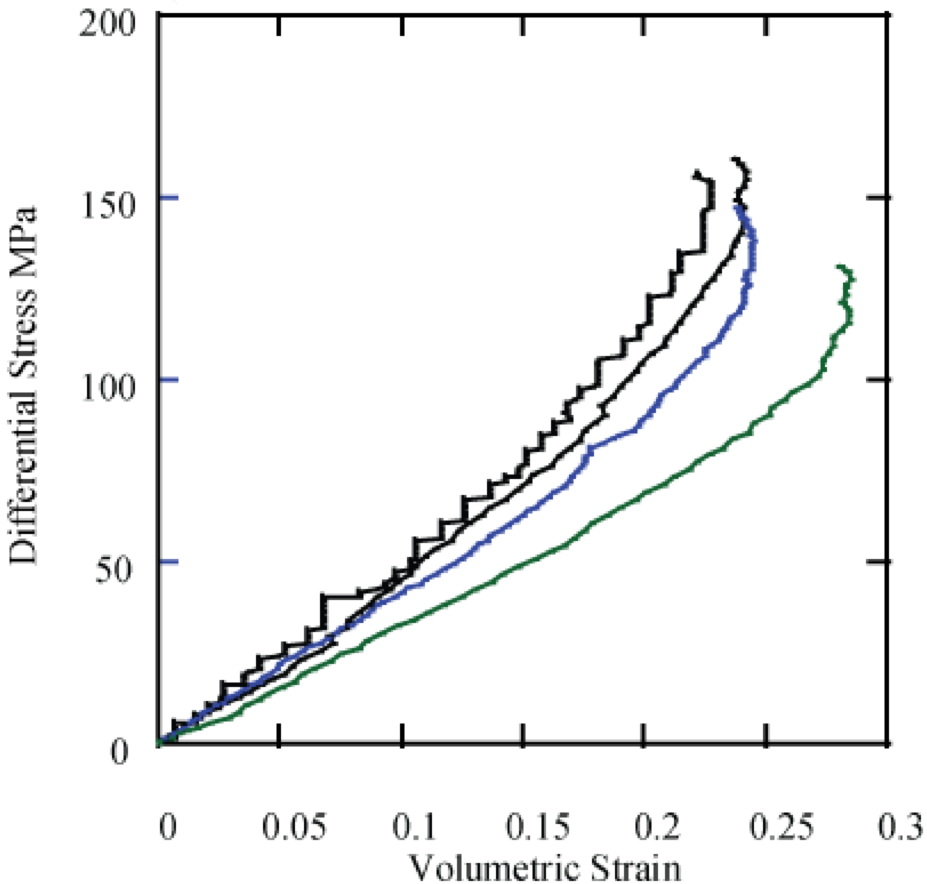
Results from Load-Reload in Different Regimes

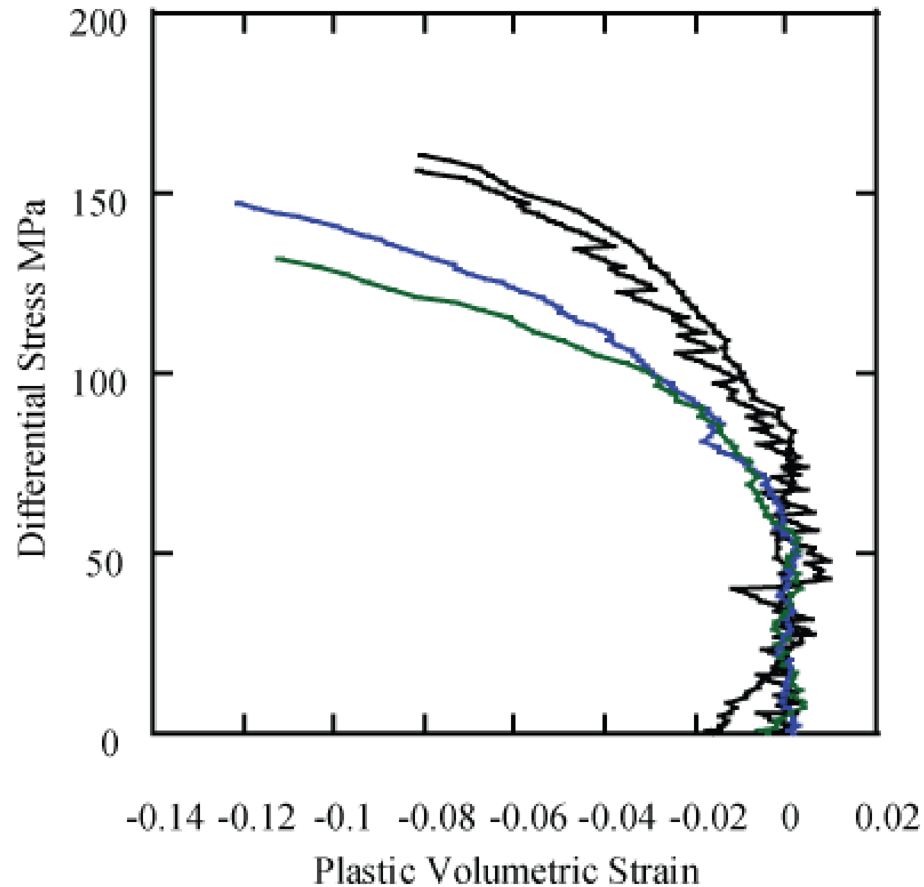
- Failure varies with load path
  - Low Pe: weakened by high Pe damage
  - Transitional Pe: lowered AE rate by low Pe damage





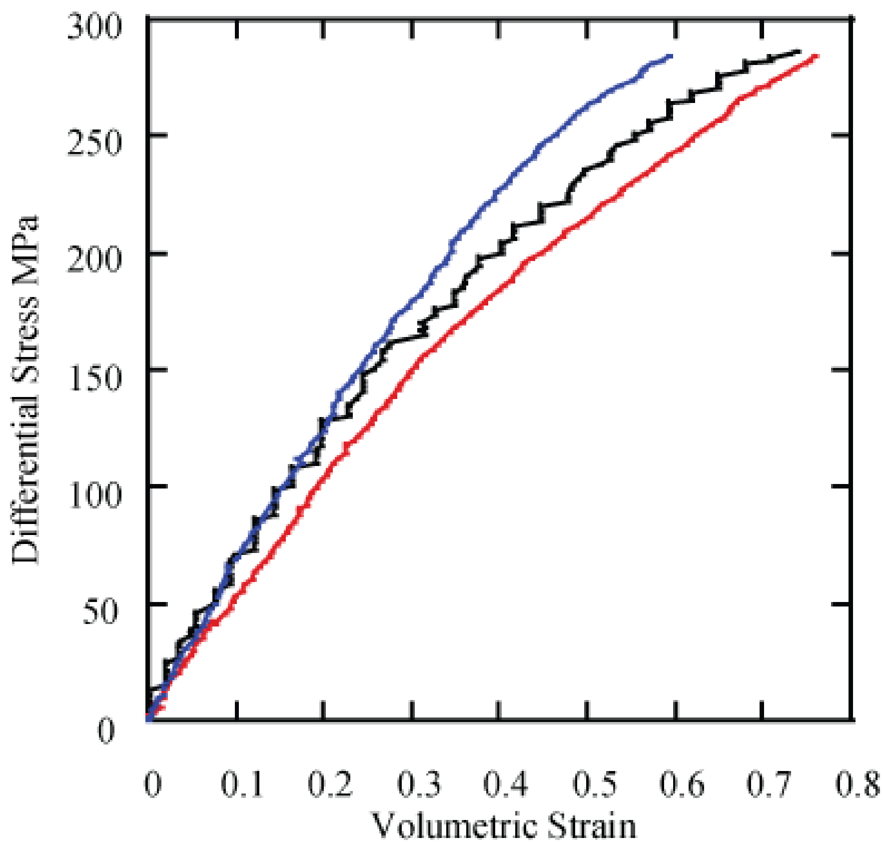
Effect of Load Path on Yielding in Low Pe Regime

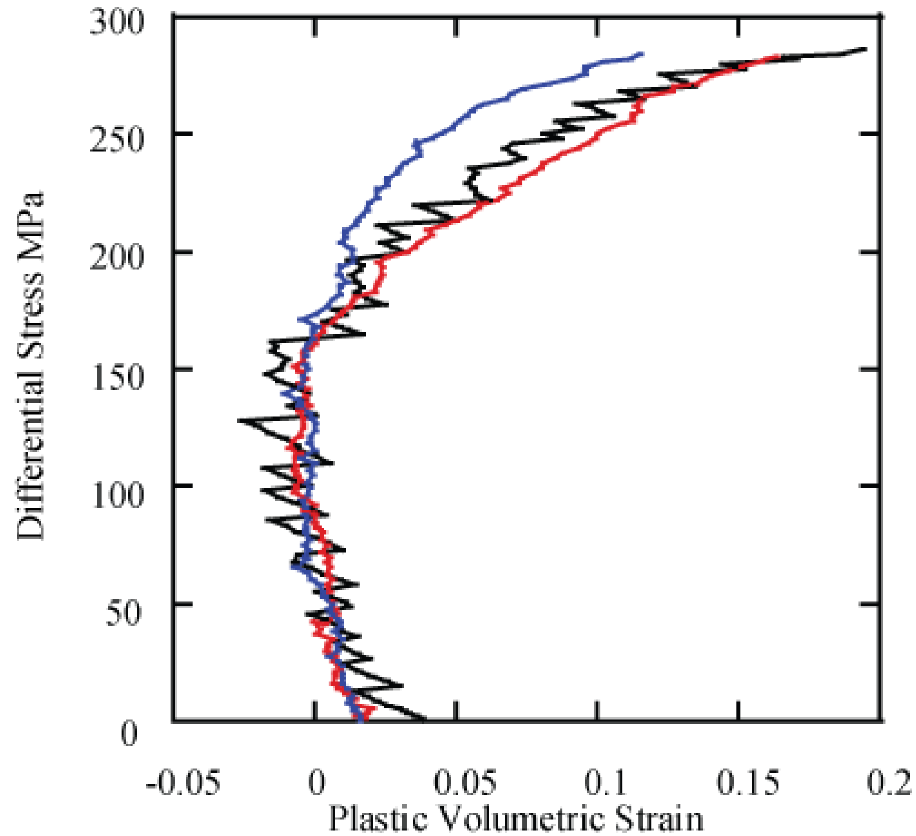




- Advanced onset of plastic deformation with initial load at transitional and high Pe
- High Pe damage mechanisms produce Low Pe equivalent damage

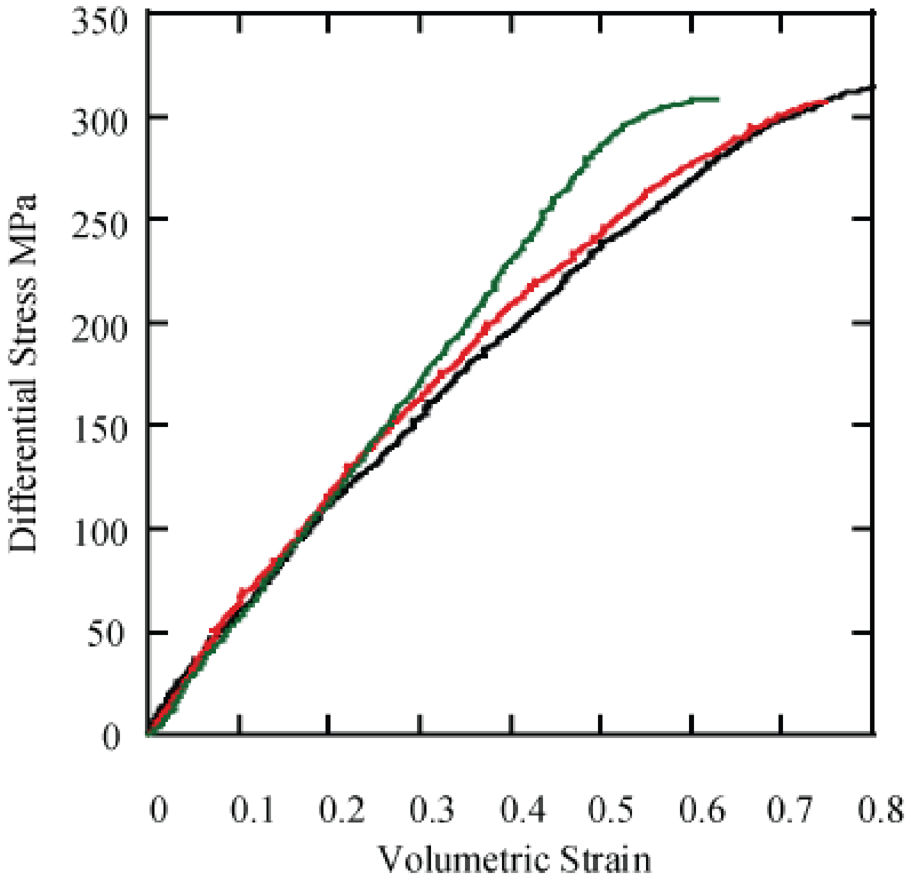
Effect of Load Path on Yielding in High Pe Regime

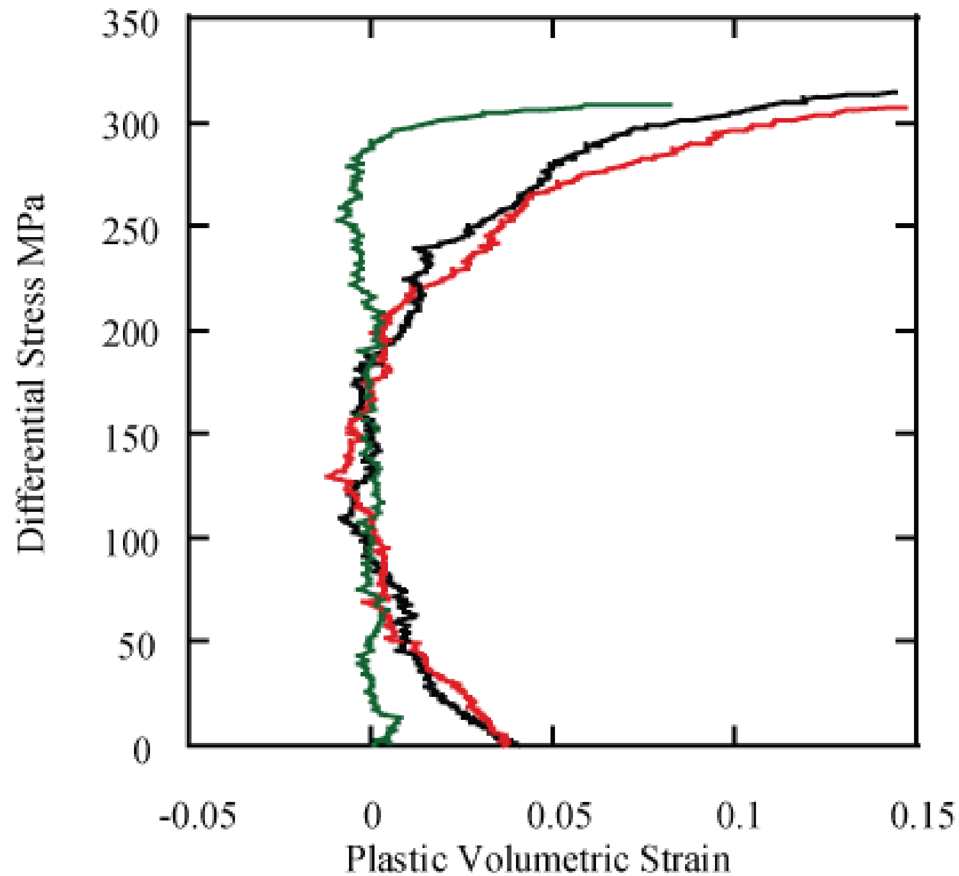




- Plastic deformation largely unaffected by initial load at Low Pe
- Low Pe damage mechanisms do not produce equivalent high Pe damage

Effect of Load Path on Yielding in Transitional Pe Regime

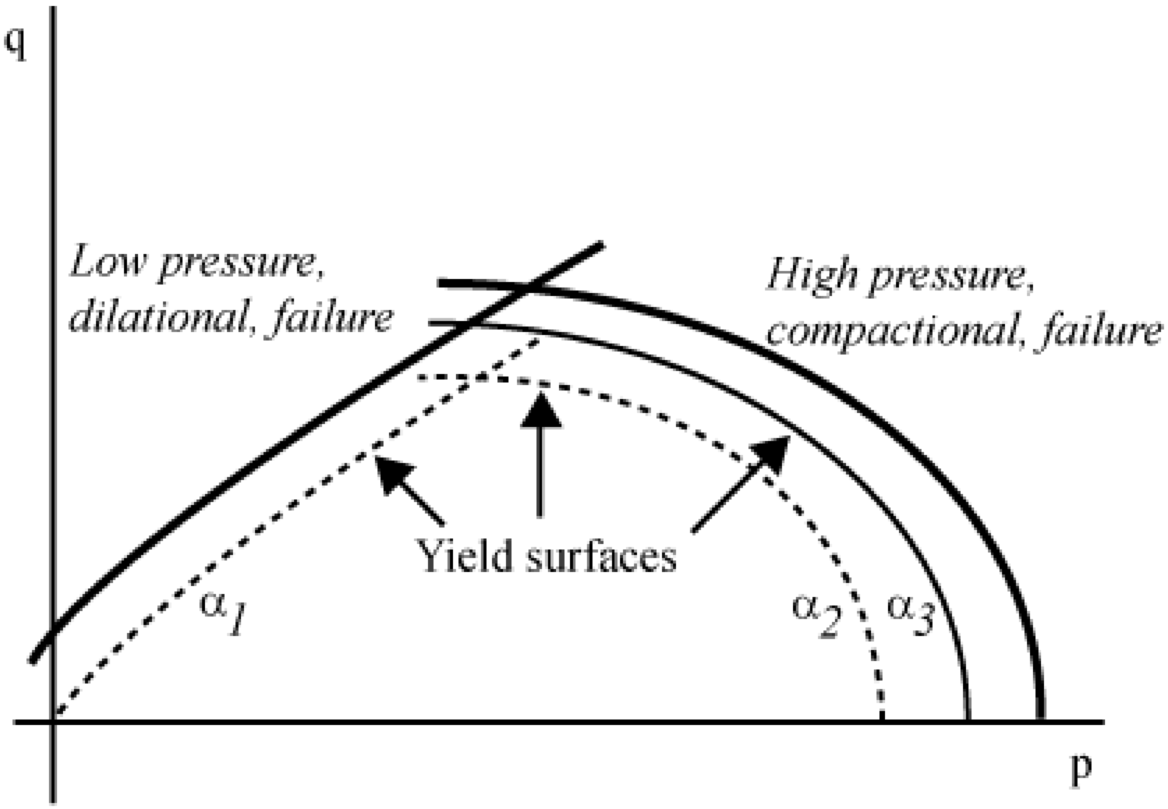




- Delayed onset of plastic deformation with initial load at high Pe
- Plastic deformation unaffected by initial load at low Pe
- High Pe damage mechanisms produce transitional Pe equivalent damage

Multiple Damage Mechanism Model for Yield and Failure Across the Brittle-Ductile Transition

- Behavior best represented by multiple yield surfaces corresponding to different mechanisms
  - α_1: grain boundary cracking
  - α_2: fracturing of grains at Hertzian contacts
  - α_3: porosity collapse
- α_1 and α_2 create cohesionless boundaries, but high Pe involves additional damage, α_3, not produced at low Pe



Conclusions

- Yield surfaces are roughly parallel to the failure envelope
- Multiple mechanism yield model most consistent with experiment AE and plastic strain observations
- Behavior in transitional regime (failure envelope horizontal) dominated by high pressure damage mechanisms.
- Yield and failure can be affected by load path particularly for loading in different Pe regimes