

Quantitative relationships between stress distributions, microstructure
and high strain rate performance of advanced ceramics

What factors affect the behavior of ceramics under rapid high compressive stress, high pressure, large strain, or high strain rates? How to design advanced ceramic materials to have desired properties? How to characterize the quality of ceramics with resonant ultrasound spectroscopy or nondestructive evaluation methods? Once the factors which affect behavior have been mathematically analyzed and expressed, how can these factors be included into numerical simulations? These questions are just some of the sweeping problems in the behavior of advanced ceramics. They cannot all be answered in a single project, but this study will add to the body of knowledge by providing some answers and clarifying some questions.

Statement of the problem:

This study proposes to investigate the relationship between both stress distributions and microstructure (e.g. crystallographic texture, misorientation, grain size and geometry) in the material response of ceramics under high strain rates.

The investigation will consist of studies of existing empirical evidence, studies of existing numerical simulations, and mathematical analysis of the effects of stress distributions and microstructure on advanced ceramic material response under high strain rate conditions. Proposals of experiments and simulations designed to test specific hypotheses and models developed during the study are expected to arise in the course of the investigation.

Background and relevance to previous work:

The relationship of stress distributions on overall performance of ceramics is not well understood. In numerical simulations of uniaxial strain compression of silicon carbide, Zhang et al. found that both the mean and standard deviation of normalized longitudinal stress versus volume fraction increased with increasing compressive strain. They suggest that the micromechanical states of the sample become increasingly heterogeneous with increasing applied strain. Investigation of the micromechanical states of ceramics and related stress distributions may lead to a better understanding of failure criteria under high compression.

Prediction of cracking and fracture is necessary to improve the reliability of ceramics under conditions such as those expected in armor or ballistics applications. For advanced ceramics under such extreme conditions it is possible that average material properties will not be indicative of material performance; rather, it is possible that extremes in the material properties will be more reliable indicators of behavior. Since locally high stress levels are generally thought to precede the formation of cracks, stress distributions which

result from high strain rates may better predict or indicate the extent of cracking in ceramics than mean stress measurements alone. In other words, the small volume fraction of material at the tail ends of a stress distribution curve may affect failure more than the large volume fraction close to the mean stress.

At grain level size, single crystal elastic constants describe the anisotropy of elastic response on this small scale. The effects of this anisotropy can extend into the macroscopic scale due to preferred orientations of grains (crystallographic texture). Some other factors influencing anisotropy are preferred grain shape distribution and misorientation (a measure of the relative orientations of neighboring grains). The effects of microstructure and whether it can predict failure or cracking in ceramics under high strain rates needs to be clarified. Perhaps extreme distributions of these microstructure elements can influence the distribution of stresses throughout a sample and so the relationship between microstructure and stress distribution should also be studied.

General methodology:

I expect to clarify the exact definition of stress distribution, as it pertains to micromechanical and statistical continuum mechanics framework already in general usage, to be certain the term is well defined. Existing empirical evidence and existing numerical simulations will be analyzed to determine reasonable first approximations to the effects of stress distribution on performance. Then, I expect to use mathematical analysis to incorporate stress distributions into current micromechanical and statistical continuum mechanics models. Models suitable for computation and simulations will be developed.

Definitions for crystallographic texture, grain size, and misorientation will be studied in the literature to determine their suitability for application to ceramics. Other sources of anisotropy, such as preferred grain shape distribution, will be explored. Existing empirical data and numerical studies will be researched to attempt to clarify the most important elements affecting advanced ceramics in high strain rate applications. Mathematical analysis will incorporate those elements in micromechanical models of ceramic deformation and failure; relationships between microstructure and stress distributions will be considered as well. Models suitable for computational simulation will be proposed. Nondestructive evaluation techniques or resonance ultrasound measurements will be proposed to quantify specific characteristics (such as single crystal elastic constants, texture, grain size, etc.) for experimental verification of models developed.

New or unusual techniques:

I do not expect any of the mathematical or experimental techniques to be new. The mathematical models developed will be new within the context of existing micromechanical and statistical continuum mechanics paradigms.

Expected results, significance, and applications:

I expect to find a correlation between stress distribution and types and magnitudes of failures. The small volume fraction of material at the extreme ends of a stress distribution curve may predict certain types of failure more accurately than the average stress. The nature of the distribution itself (narrow distribution, constant distribution, Gaussian distribution, etc.) may also play a role in the susceptibility of a material to cracking.

I expect to find a relationship between microstructure such as crystallographic texture, misorientation, grain size, and grain geometry on the performance of ceramics in high strain rate compressive loading. I expect to be able to quantify the effects of these relationships in such a way as to be conducive to numerical simulations and to be mathematically enlightening. I expect to propose experimental tests using ultrasound or nondestructive methods to test the models and relationships developed.

Understanding the behaviors of ceramics under high strain rate conditions will be beneficial to users of ceramics for applications such as armor or ballistics. Knowledge gained from this project may also shed light on the mechanisms affecting response under other extreme conditions and other applications. Understanding the factors that influence characteristics and predict behavior of advanced ceramics will ultimately allow more ways to control the manufacture of these ceramics and increase opportunities for scientists to design materials for specific uses.

Literature:

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