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Title: **Dynamic Deformation of Advanced Materials**

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Author(s): George T. Gray III, MST-5
James N. Johnson, T-1
Robert S. Hixson, DX-1
Diane E. Albert, MST-6
Shihong Song, MST-5

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Dynamic Deformation of Advanced Materials

George T. Gray III*, James N. Johnson, Robert S. Hixson,
Diane E. Albert, and Shihong Song

Abstract

This is the final report of a three-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). The objective of this project was to provide high-quality experimental measurements on composite materials and to develop computational models describing the deformation response of these materials. Specifically, we studied the influence of strain rate and shock loading on the deformation and fracture response of a 6061-T6 Al - 50 vol.% Al_2O_3 continuous fiber-reinforced composite as a function of composite orientation. The stress-strain response was found to vary substantially as a function of loading orientation with the quasi-static yield changing from nominally 300 MPa transverse to the fibers to ~1000 MPa parallel to the fibers. Transverse VISAR wave profile and spall measurements revealed a small, well-defined elastic precursor followed by a reasonably sharp shock rise. The failure response of the composite transverse to the fibers, under both uniaxial stress (quasi-static and dynamic) and uniaxial strain loading, displays a protracted but substantial load drop after yield followed by continued degradation in load carrying capacity. Lack of ideal parallel fiber construction leads to systematic bending failure of the alumina fibers through the sample under uniaxial stress and slow spallation kinetics as various fibers fail and pull out of the matrix across the spall plane.

1. Background and Research Objectives

Composites (metal, ceramic, or polymer-matrix) and advanced materials, such as intermetallics and nanostructured materials, are receiving increasing attention due to their higher specific strengths, stiffnesses, and high temperature properties. Increased utilization of these material classes under dynamic loading conditions requires an understanding of the

Principal investigator, e-mail: rusty@lanl.gov

relationship between high-rate/shock-wave response as a function of microstructure if predictive material behavior capabilities are to be attained. In contrast to single-phase materials, composites and ordered intermetallics feature: 1) heterogeneous mixtures (either a layered, woven, laminated, etc., composite or a structurally-ordered matrix), 2) anisotropic elasticity and plasticity, and 3) interfacial effects that influence the plastic flow and fracture behavior. These three attributes cause distinct and unusual material response when composites are subjected to dynamic loading. Because these advanced materials are significantly more complicated structurally than single-phase-pure metals and alloys, it is imperative that shock-wave research is begun to systematically investigate the additive and synergistic nature of multiple strengthening mechanisms on their response to shock-wave deformation. Los Alamos possesses the research breadth to investigate shock deformation of these emerging materials with an interdisciplinary team, integrating material science and real-time wave profile experiments, to understand and model the effects of shock processes on material response and vice versa.

The objective of this project is to facilitate the development of predictive computational models of the mechanical response of advanced materials that are based on a fundamental understanding of the influence of structure/property relationships on high-rate and shock-wave deformation. Physically-based theoretical models will improve our ability to predict the manner in which the dynamic response of advanced materials may depend on loading and unloading stress paths, strain rate, microstructure, orientation, and temperature. This capability will enable us to better select or design materials for large-strain, high-strain-rate loadings.

2. Importance to LANL's Science and Technology Base and National R&D Needs

The scientific impact of this research was aimed at increasing our fundamental understanding and predictive modeling capability of the deformation response of microstructurally more complex materials than previously undertaken. The thrust to date in shock-wave deformation and modeling has been chiefly focused on single-phase materials. The successful completion of high quality experiments and modeling on complex non-isotropic materials will significantly advance the state-of-the-art in shock-wave physics. The research in this project also contributes to basic research through the challenging problems related to a fundamental understanding of the dynamic behavior of advanced materials at extreme rates of loading and its multidisciplinary nature involving shock-wave physics, materials science, continuum mechanics, and numerical methods. Advanced material classes, particularly composites, will be increasingly important in the future to a variety of

Department of Energy (DOE), Department of Defense (DoD) and advanced manufacturing programs. The use of high-technology and high-leverage technologies to address safety, survivability, durability and operational flexibility of future weapons placed in stockpile is critical to national defense programs.

This project serves as a basis for establishing a long-term, coordinated capability at Los Alamos to investigate the response of advanced materials under extreme dynamic loading conditions. Such a capability is necessary for virtually every conventional and nuclear weapons-related project at Los Alamos and is also crucial if these material classes are to be utilized under dynamic conditions in non-defense applications such as those experienced during vehicle crash-worthiness and foreign-object damage assessments. The fundamental deformation and modeling tools developed in this project are directly applicable for technology transfer and cooperative research and development agreements (CRADAs) in the areas of crash worthiness of civilian vehicles, foreign-object damage, and blade-containment concerns in aerospace.

3. Scientific Approach and Results

The research strategy of this project was a correlated and balanced three-pronged combination of structure/property studies of defect generation in advanced materials with high-resolution "real-time" shock and release wave profile data and theoretical modeling. Model composite metallic systems were utilized to systematically examine the influence of reinforcement distribution, reinforcement deformation character, and reinforcement/applied stress orientation relationships on defect generation, defect accumulation, and wave-profile response. Measured wave profiles were compared with those predicted using Los Alamos wave propagation codes coupled with equation-of-state and thermoelastic-plastic constitutive models. We have completed a number of dynamic deformation studies, wave-profile and spallation measurements, and theoretical wave-propagation modeling studies of three model 6061-T6 Al /Al_2O_3 composites, a Cu-Nb composite, and a 6061-T6 Al-50 vol.% Al_2O_3 continuous reinforced metal-matrix composite (MMC) produced by 3M corporation.

Initial work on composites consisted of systematic studies of materials with random reinforcement. The theoretical thrust was to represent material behavior in terms of dissipation-like behavior. The theoretical study of one-dimensional periodic and random systems then allowed the determination of this dissipative-like response, and also put the concepts related to mechanical energy trapping on a more secure footing. The next step was to investigate composite material behavior in the presence of some degree of periodic construction.

Composites possess unique dynamical properties in contrast to common single-phase materials. Fiber reinforcement not only results in mechanical anisotropy, but produces internal interfaces that cause wave interactions on the spatial scale of 10 - 100 micrometers. When impact results in low-amplitude elastic waves and the internal interfaces are perfectly periodic as well as ideally bonded, the composite acts as a band-pass filter. In modern practical applications, however, wave amplitudes drive composite materials beyond the elastic limit, internal interface locations may not be perfectly periodic, and tension can result in interfacial separation. Not only do the individual components undergo rate-dependent plastic deformation, but they do so in the presence of second-phase components that can have a strong influence on microstructural response.

The stress-strain response of the 3M fiber composite was seen to vary with fiber orientation, strain rate, and temperature (Fig. 1). The composite yield strength parallel to the fibers is ~4 times that exhibited orthogonal to the fibers quasi-statically at 298 K. This finding is consistent with the high strength of alumina carrying the bulk of the stress when loading is parallel to the fibers. The lack of rate sensitivity at 298 K parallel to the fibers follows the documented weak rate dependency of alumina. The samples tested in this orientation failed via buckling or "brooming" of the alumina fibers. The strain rate and temperature dependency of the composite when loaded orthogonal to the fibers reflects the rate and temperature behavior of the high-density dislocation substructure in the Al-matrix formed during fabrication.

Preliminary wave profile data obtained for the continuous-fiber-reinforced Al/Al_2O_3 composite, measured across the fibers, is shown in Fig. 2 along with data obtained under similar loading conditions for particle reinforced Al/Al_2O_3. In both cases Z-cut quartz impactors were used, and a projectile velocity very close to 0.5 mm/μs was realized. In spite of the very similar impact conditions, the final particle velocities are quite different for the two materials. It is also clear that the elastic precursors are different in nature; the fiber material shows a well defined although low amplitude elastic wave, but the particle material shows dispersive behavior. Shock rise times are similar for the two data sets, but the fiber material exhibits what looks like a multiple wave structure. This is possibly an experimental artifact caused by the impedance mismatch at the sample/LiF window interface. More data is needed with a higher impedance window to determine the origin of this feature. The bulk part of the release paths agrees well, with the final particle velocity for the fiber material lower than that for the particle material. This is due to the use of a glass-reinforced foam backing on the quartz impactor for the fiber experiment, with polymethylmethacrylate (PMMA) used for the particle MMC experiment.

Another interesting observation is the very distinct separation between the elastic precursor and the plastic wave in the rod material. This was not observed in the material containing discontinuous reinforcement [ref. Johnson, Hixson, and Gray, J. Appl. Phys. **76**, 5706-5718 (1994)]. The behavior of the uniaxial-fiber-reinforced material may have something to do with its unique plasticity properties and material anisotropy, which result in enhanced separation between elastic and plastic waves, and a very distinct particle-velocity overshoot in the precursor. The latter is reminiscent of an upper/lower yield point and rapid dislocation multiplication at the elastic wave front. This response is not characteristic of 6061-T6 aluminum. The difference in behavior between continuous (fiber) reinforcement and that of the matrix material alone (as well as that of aluminum/alumina composites at low volume fractions of discontinuous reinforcement) is dramatic in this regard.

Spallation experiments (solid lines) for the various particulate alumina composites are shown in comparison to simulations (dashed lines) in Fig. 3; the horizontal axis is time. The pull-back signals in free-surface velocity contain information on spall strength at depth for the following three composite materials: (a) 20 vol. % mullite particles, (b) 8 vol. % alumina, and (c) 17 vol. % alumina, all embedded in a 6061-T6 aluminum matrix. The spall strengths in these three cases are (a) 1.9 GPa, (b) 2.0 GPa, and (c) 1.1 GPa. These measured values are considerably less than the 2.8 GPa spall strength of the metal matrix. Also apparent in the data of Fig. 3 is the experimentally observed sluggishness of the spallation process in these composite materials. Time-dependent effects in composite spallation remain to be investigated; the data shown here contain considerable information of this type.

New modeling work for the continuous-reinforced composites has focused on the response of materials possessing significant periodicity in their construction. The theoretical path that has been followed involves the method of cells (pioneered by Jacob Aboudi), in which the high-frequency motion is described in terms of microstructural spatial variables expanded to various orders (N=1, contains the quasi-static, long-wavelength response, as well as dynamical effects related to dispersion; N=2 gives a better approximation to the dynamical effects.) The approach has been to write these dynamical equations in finite-difference form and attempt to solve for transient effects in composites in exactly the same way that is done for homogeneous, monolithic materials. Initial formulations have been unsuccessful; the mathematical theory in going from discrete components to the continuum involves subtle effects necessary for the preservation of stress and displacement continuity on the microscale.

Additional information on our work is given in Refs. 1-3.

References

[1] Gray , G. T. III, R. S. Hixon, and J. N. Johnson, "Dynamic Deformation and Fracture Response of A 6061-T6 Al-50 Vol. % Al_2O_3 Continuous Reinforced Composite," APS '95 Topical Conference on Condensed Matter, Seattle, WA, August 14-18, 1995 (in press).

[2] Song, S. G. , G. T. Gray III, and M. F. Lopez, "Deformation Response of Zr After Shock-Loading," APS '95 Topical Conference on Condensed Matter, Seattle, WA, August 14-18, 1995 (in press).

[3] Hixon, R. S. , J. N. Johnson, G. T. Gray III, and J. D. Price, "Effects of Interfacial Bonding on Spallation in Metal-Matrix Composites," APS '95 Topical Conference on Condensed Matter, Seattle, WA, August 14-18, 1995 (in press).

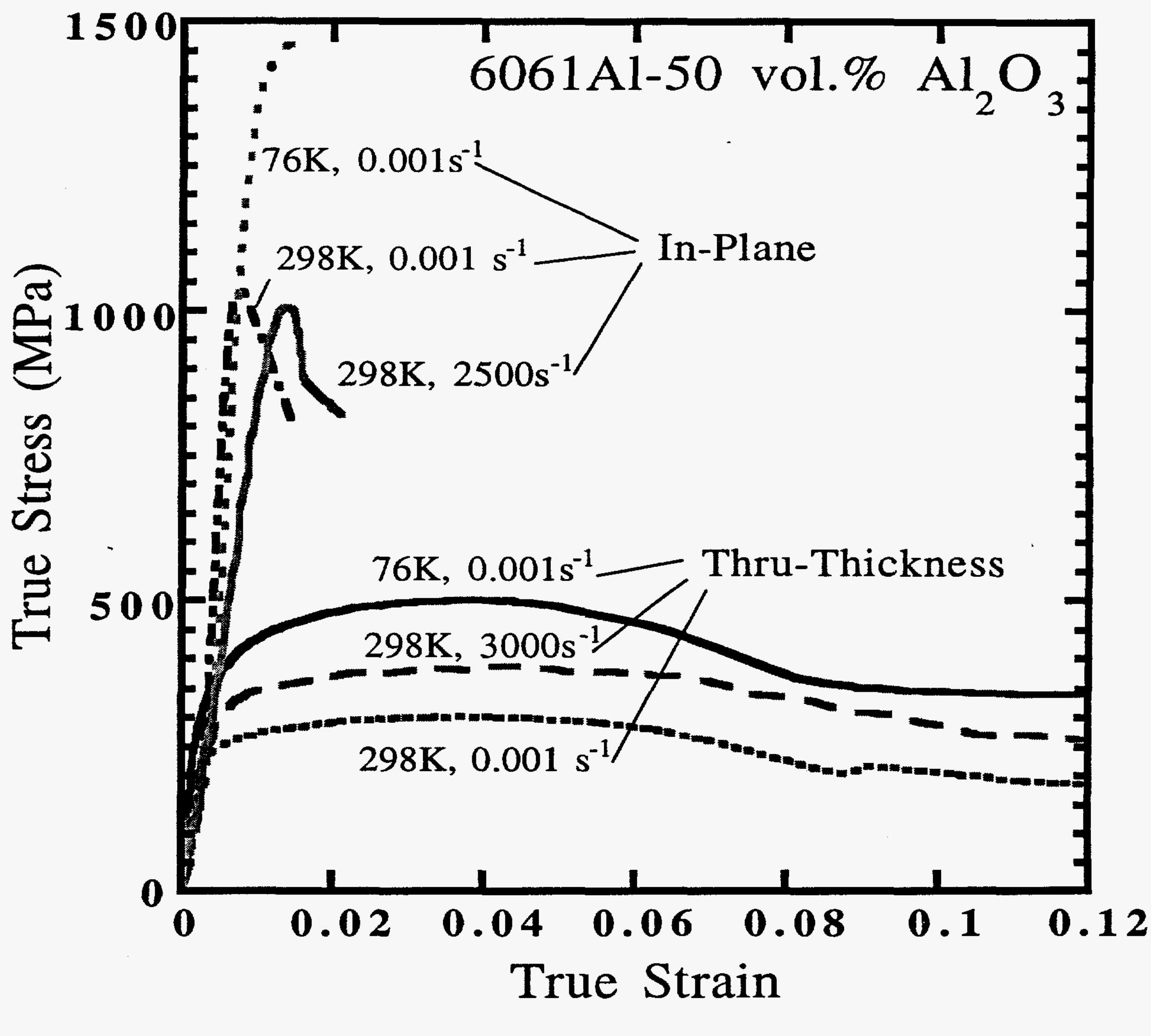

Fig. 1. Stress-strain response of 6061Al-Al_2O_3 MMC in the in-plane and thru-thickness directions as a function of rate and temperature.

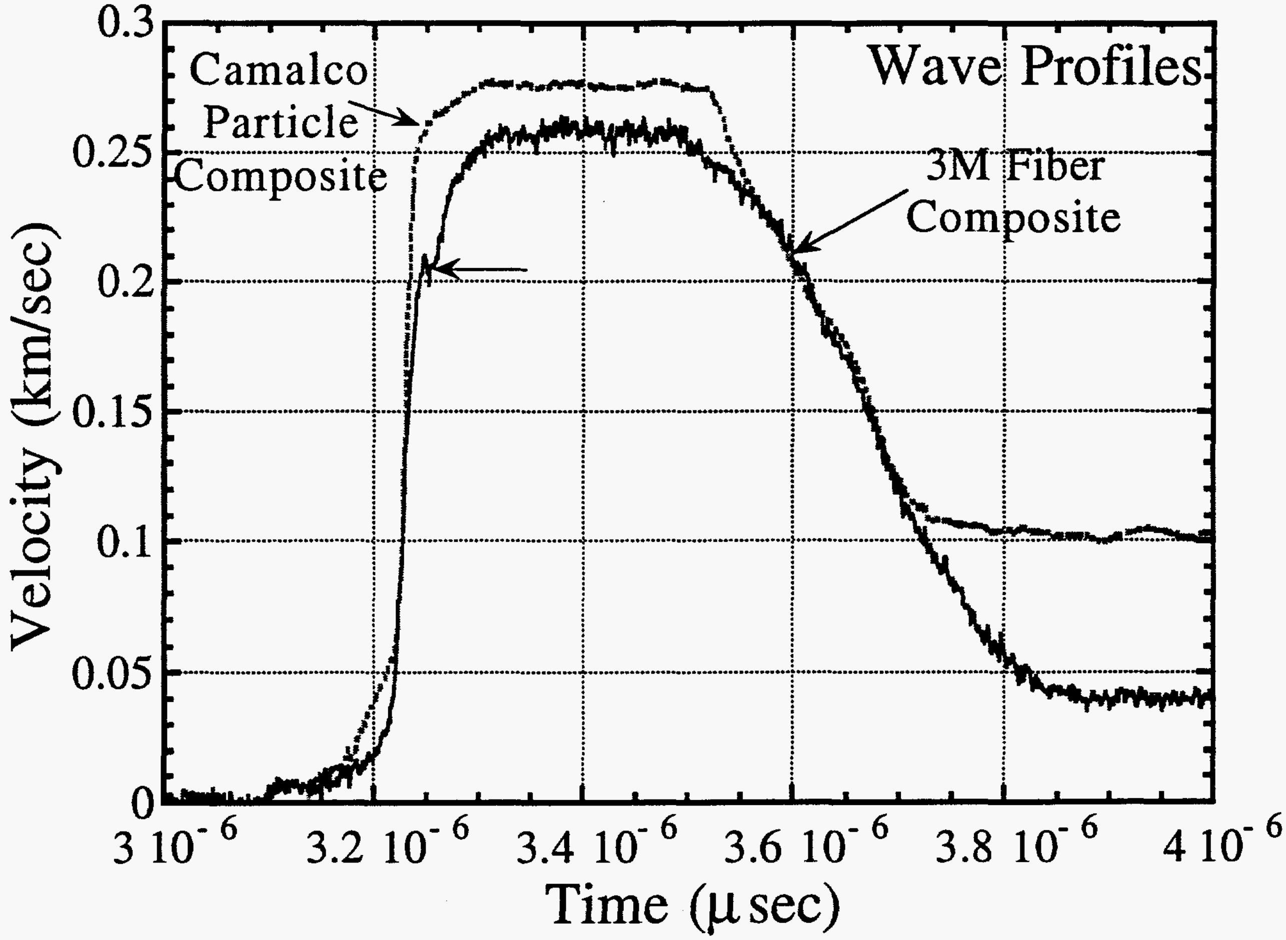

Fig. 2. Wave-profiles for spherical particle and 3M fiber MMC's.

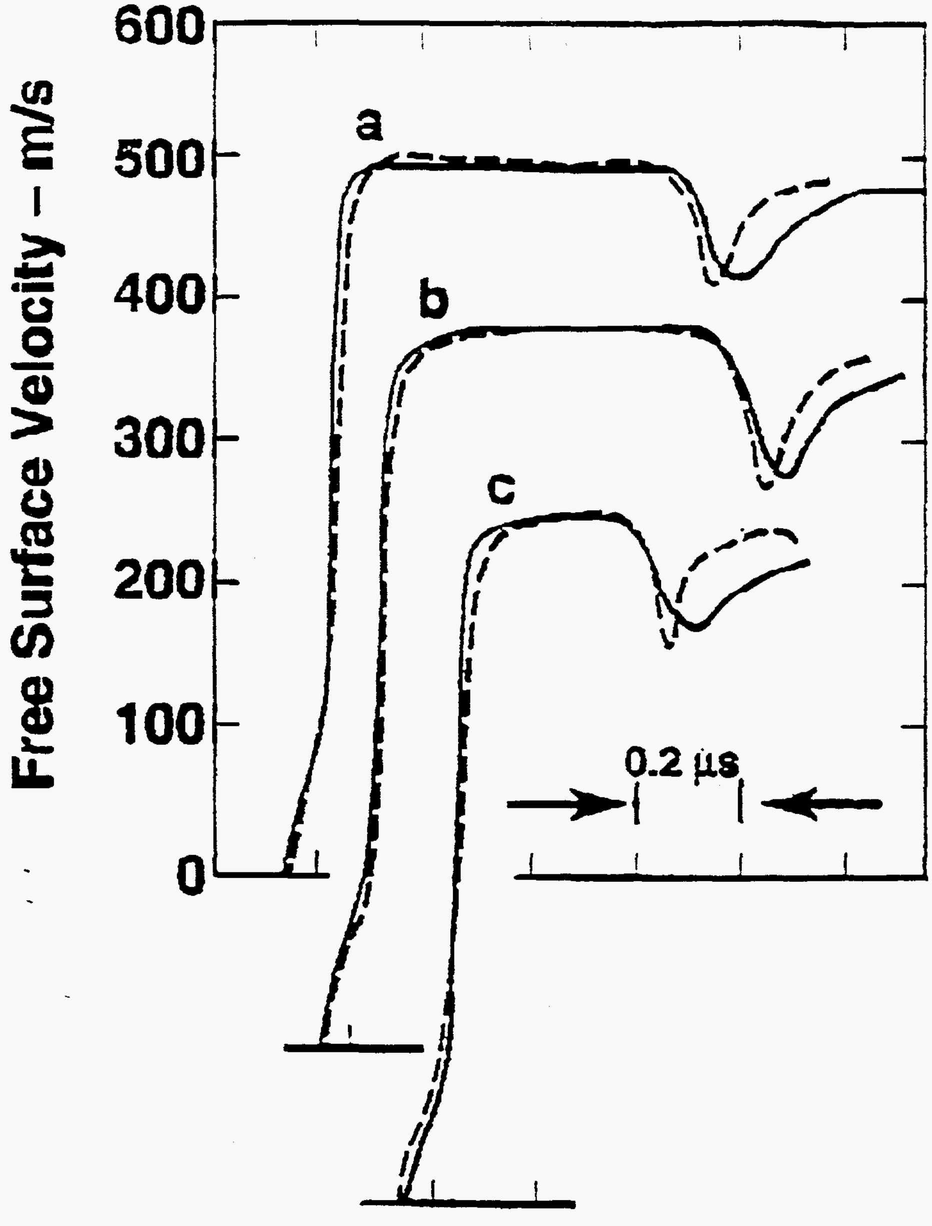

Fig. 3. Spall traces and model simulations of the spallation response of three different particle-reinforced 6061-T6 Al composites.