Fundamental Issues and Applications of

Shock-Wave and High-Strain-Rate Phenomena

EDITED BY

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Proceedings of the 2000 International Conference on
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Shock-Wave and High-Strain-Rate Phenomena
(EXPLOMET' 2000)

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Foreword: John S. Rinehart Awards: 2000

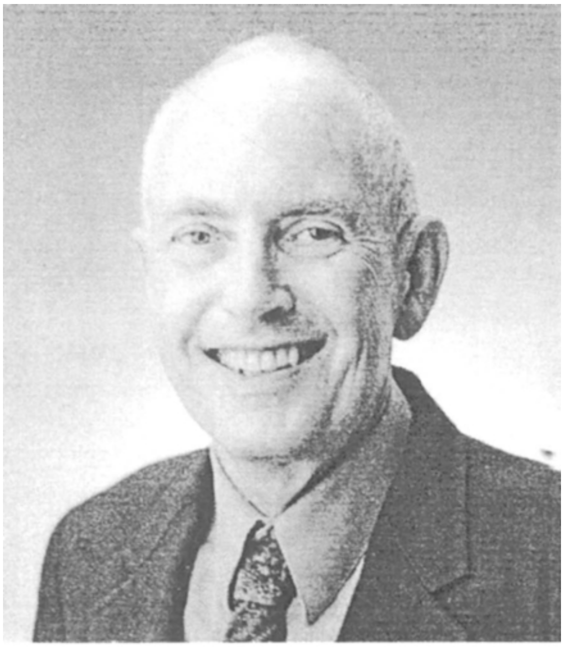
The John S. Rinehart Award was established at EXPLOMET™ '90 as a continuing, quinquennial recognition of outstanding, international efforts and innovative, creative, and applicable contributions in the science and technology of dynamic effects or processes in materials: explosive/shock welding, forming, compaction, synthesis, hardening, fracture and a host of related effects involving high-strain-rate phenomena. The award is named after a true pioneer, John Rinehart, who witnessed and actively contributed to this broad field for over 40 years, culminating in such notable, published testaments as *Behavior of Metals Under Impulsive Loads, Explosive Working of Metals,* with John Pearson, and *Stress Transients in Solids;* in addition to more than 130 scientific and technical articles.

The original Rinehart Awards were presented to Dr. A. A. Deribas and Dr. M. L. Wilkins at EXPLOMET™ '90. They, together with Dr. J. S. Rinehart, constituted a selection committee for the EXPLOMET™'95 awards. The co-recipients of the John S. Rinehart Award for 1995 were Dr. Rolf Prümmer and Dr. Akira B. Sawaoka. This evolving selection committee named Dr. Don Shockey and Dr. Don Curran, both of SRI International, as the co-recipients of the John S. Rinehart Award for 2000.

It is with regret that we must report the death of Dr. Rinehart some months before the EXPLOMET™ 2000 Conference. We honor his memory by dedicating this volume to him.

Don Shockey, the son of a steelworker, was born in 1941 in rural Pennsylvania near Apollo. A standout high school athlete, he was awarded a football/track scholarship by Grove City College (PA) where he captained both teams, became interested in materials science, and received a BS in metallurgy in 1963. Choosing academics over athletics at graduation, he enrolled at Carnegie-Mellon University and received MS and Ph.D. degrees in materials science in 1965 and 1968. His doctoral thesis on fracture in ceramics led to post-doctoral appointments at the Ernst-Mach-Institut and the Institut für Werkstoffmechanik in Freiburg, Germany, where he met and worked with Don Curranon supersonic crack propagation. In 9171 he joined SRI and teamed with Don

Curran and Lynn Seaman to develop the NAG fracture concept of shock-wave-induced fracture. In his 29 years at SRI, he has published over 100 papers on deformation and fracture of materials under dynamic and static loads and continues to lead research efforts in ballistic protection, advanced fractography, and aging system life extension. A Fellow of the American Society of Materials and an SRI International Fellow, Dr. Shockey is an authority on the physics and material aspects of dynamic fracture, fragmentation, and shear bands.



Don Curran was born in 1932 in Aurora, Illinois, grew up in the midwest, and received his BS in Physics from Iowa State University in 1953. He received his MS in 1956 and Ph.D. in 1960 from Washington State University, and was one of WSU's first graduates in the discipline of Shock Physics. His Ph.D. thesis topic involved experimental and theoretical studies of high pressure phase transitions in metals. His thesis advisor was Professor William Band, who imbued him with the spirit of adventure and fun that is associated with scientific discovery. He went to work for George Duvall at SRI International after receiving his MS, and in 1958 returned to WSU to pursue a Ph.D., while spending summers at SRI. He credits George Duvall for demonstrating how rigorous science can be accomplished on-time and on-budget. In 1961 he left for Europe, spending 5 years at the Norwegian Defense Research Establishment near Oslo, Norway, and 3 years at the Ernst Mach Institute in Freiburg, Germany, where he met Don Shockey, this year's co-awardee. In 1970 he returned to SRI International, where he began to contribute to the dynamic fracture program led by Troy Barbee, Richard Crewdson, and Lynn Seaman. During the past 30 years at SRI he has led and contributed to the development of the NAG (Nucleation And Growth) family of mesomechanical failure models for solids. He has published over 60 papers in Shock Physics. He is a Fellow of the American Physical Society, and is past chair of the APS Topical Group on the Shock Compression of Condensed Matter.

Fundamental Issues and Applications of
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K.P. Staudhammer, L.E. Murr, and M.A. Meyers (Editors)

Our Careers in Dynamic Material Failure

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Continuously throughout our 30-year professional careers, world events have provided interesting and challenging problems in the field of dynamic failure that required the boundaries of fracture science to be expanded. Missile defense in the early 1970s, the energy crisis later in the decade, a major armor/antiarmor initiative in the 1980s, and lightweight ballistic protection for personnel and aircraft in the 1990s required advances in fracture science from the continuum mechanics approaches of the 1960s. New approaches were required to treat microstructure, fully plastic fracture, crack nucleation, multiple cracks, and shear localization. We feel fortunate to have had such stimulating technical problems to address during our careers and recount these opportunities in this retrospective. We conclude by describing two current dynamic failure problems and speculating on the next advances in failure physics.

1. INTRODUCTION

One evening at the Third International Conference on Fracture in 1973, as we were just starting our careers, Figure 1, we sat in a beer garden in Munich with the distinguished scientist Tony Kelly, who had constructed a phase diagram, Figure 2, that governs a scientist's professional career.

Figure 1. The authors in 1973 at the reception of the Third International Conference on Fracture in Munich, Germany.

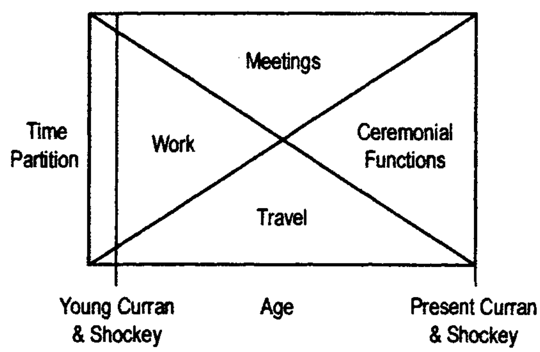

Figure 2. Phase diagram for a career in science.

The diagram shows that young scientists initially devote their time primarily to technical research. But as time goes on, meetings and travel cut increasingly into research time. In Figure 2, note that there is a critical point beyond which real work is replaced entirely by travel and meetings. Beyond this critical time, even travel and meetings give way to increasing amounts of ceremonial functions, such as the award ceremony at this Explomet 2000.

In this short retrospective, we tell how we traveled from left to right on the above diagram over the last 30 years (and also how we have fought to warp the above diagram to move the critical point significantly to the right).

2. OUR FIRST COLLABORATION

We first met in 1968 at the Ernst-Mach-Institut (EMI) in Freiburg, Germany. Don Curran had been there for a year after a five-year stint in Norway, and Don Shockey came on a post-doc from Carnegie-Mellon University. EMI, under the leadership of Prof. Frank Kerkhof, was very active in the relatively young field of Linear Elastic Fracture Mechanics and in measuring the limit velocities of cracks in glass and ceramics, using an innovative ultrasonic technique. The two Dons set out to prove that supersonic cracks could be produced.

We teamed up with new friend and colleague, Siegfried Winkler, and conducted our first collaborative dynamic experiments [1,2]. By focusing a large impulse laser in the interior of a (transparent) KCl crystal, we vaporized a quantity of material at the focal point and, with the resultant plasma, drove (100) cleavage cracks at speeds an order of magnitude faster than the fastest elastic waves. Figure 3 is a dark-field micrograph of a supersonically-formed fracture surface in a still-intact specimen. The smooth sphere at the center is where the plasma was produced.

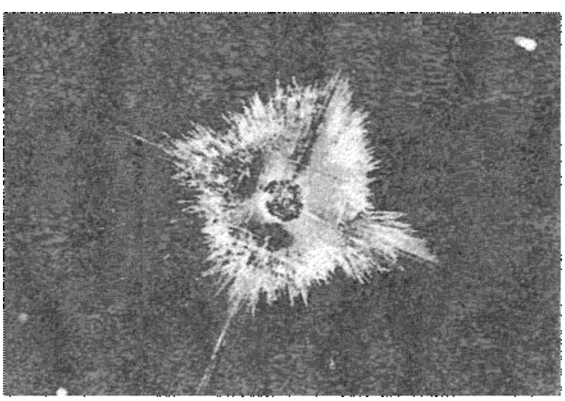

Figure 3. Cracks that ran supersonically in a KCI crystal.

We measured the crack velocity by gathering some of the transmitted laser light with lenses and directing it around the room with a series of mirrors to get an appropriate delay time, and then back through the side of the specimen to get a snapshot of the running crack about 80 ns after energy deposition. The preshot laser adjustments were made with the help of Winkler's ever-present cigarette, as he blew smoke into the beam to make it visible. The experiment was conducted in total darkness, and just before the shot, we would all sit down to ensure that we didn't get in the way of the beam's complicated path around the room. On one occasion, Winkler called out the "sit" command, which was followed in quick succession by the laser pulse, a crack, and a cry of pain and surprise. One of us had sat down on some glass laser accessories.

Our three years in Germany researching high rate material failure were a lot of fun, but if we had been asked then if we expected to make a career in dynamic failure of materials, we would probably have felt it unlikely. Were there really enough dynamic failure problems to occupy our time for the next 30 years? As it turned out, world events in the ensuing 30 years provided a continuous stream of interesting and challenging problems and uninterrupted opportunities for dynamic failure research. In the following pages, we recount some of these events and research projects.

3. MISSILE DEFEAT AND THE NUCLEATION AND GROWTH (NAG) APPROACH TO FRACTURE

By 1971 we had returned to the United States and taken positions at Stanford Research Institute in Menlo Park, California. A pressing problem for the Department of Defense at that time was defending against intercontinental ballistic missiles. To protect the United States against enemy attack, the DoD needed to know if America's nuclear weapons, detonated in the upper atmosphere in the vicinity of an incoming ICBM, would damage the missile enough to prevent it from accomplishing its intended destructive purpose. Specifically, a way was needed to relate the size of a nuclear weapon, the distance from the target, and the damage to the target.

3.1 How Nuclear Explosions Damage Space Targets

Reentry vehicles can be damaged and killed by high-energy x-rays emitted from the exploding nuclear device. Traveling relatively unattenuated through the upper atmosphere, the x-rays impinge on and are absorbed by the target, rapidly heating the skin.

The rapid deposition of energy generates shock waves that reflect from component boundaries and intersect one another to produce short-lived tensions. The tensions can cause various levels of fracture damage, depending on the magnitude and duration of the pulse. The challenge to fracture physicists was to develop a method to predict the extent of fracture damage, knowing the size of the nuclear weapon, its proximity to the target, and the nature of the material of the target components.

Since it was not practical to perform actual upper-atmosphere experiments using nuclear weapons and ICBMs, the algorithm was sought by performing underground nuclear tests at the Nevada Test Site, laboratory simulation tests using nonnuclear loading sources, and computations based on theory. The Defense Nuclear Agency directed the attention of many teams of talented scientists and engineers to this problem.

We joined a team at SRI that was using a gas gun to generate shock waves and fracture damage in simple model materials, Figure 4.

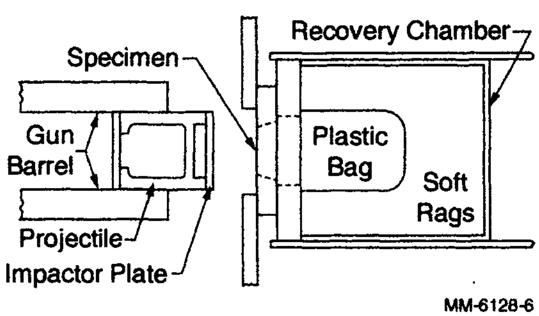

Figure 4. Gas gun plate slap experiment.

By accelerating thin disks of copper and aluminum and iron against hockey-puck-shaped specimens of like materials, the team produced controlled one-dimensional-strain shock waves that simulated the loading conditions expected from x-ray impingement in heat shield and missile component materials.

When the targets were sectioned after impact, the damage was seen to consist of a population of voids in the interior of the copper and aluminum specimens and a population of cracks in the iron specimen, Figure 5. The voids and cracks occurred in a distribution of sizes, and their numbers and sizes became monotonically smaller with distance from a central plane. The question was how to describe these observations in a quantitative manner, relate the data to stress history, and develop predictive equations for damage.

The breakthrough idea was to treat fracture as a metallurgical phase change. Phase transition kinetics had been widely studied and quantitatively described in the metallurgical community as a nucleation and growth process. Troy Barbee reasoned that shock-wave-induced fracture had similar characteristics, except that the driving force was stress instead of temperature. Experiments were devised to vary the two important parameters, stress and stress duration, systematically and independently. This was done with the plate slap experiment, Figure 4, by prescribing the plate thicknesses and the impact velocities. A range of damage could be produced from no damage to full spall.

Lynn Seaman took the first steps to extract damage rate equations by calculating the stress histories experienced by the specimens and correlating the damage. Lynn and the two Dons, with the help of various SRI colleagues, would develop the failure nucleation and growth (NAG) concept and apply it to a wide range of failure problems over the next twenty years [3-11].

Rate equations for void and crack nucleation and growth derived from plate impact tests were validated for the x-ray scenario, using results from underground nuclear tests. The NAG approach was then used to add confidence to damage assessment algorithms.

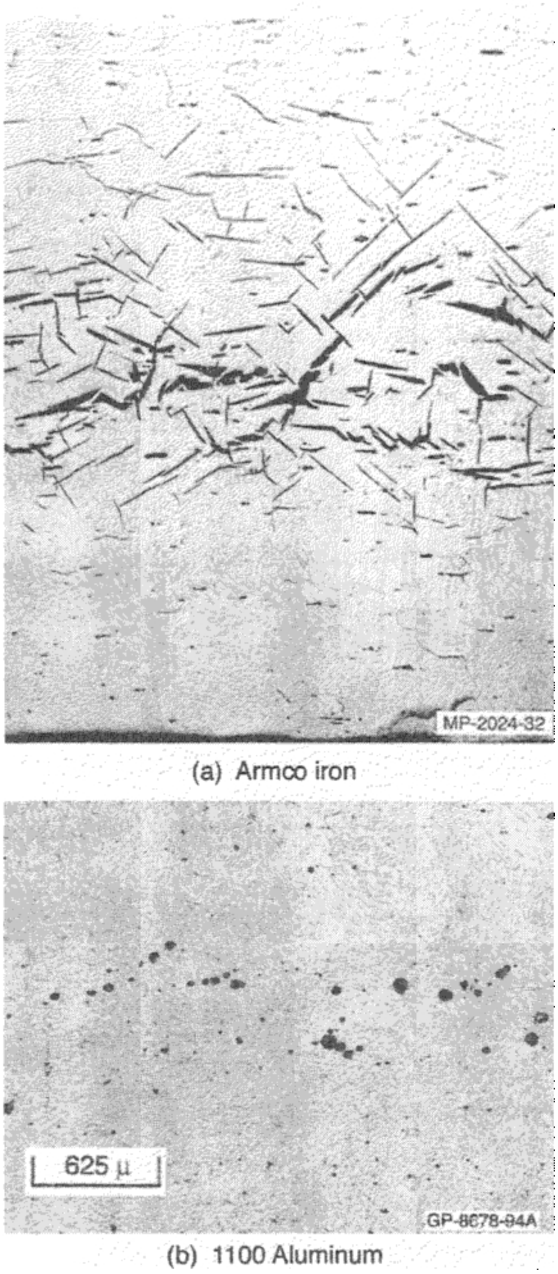

Figure 5. Ductile and brittle microfailure on polished cross sections of plate slap specimens.

3.2 Wide-Ranging Applications of NAG

The NAG concept was found to have universal application. It was used to predict penetration of armor, modified to treat adiabatic shear bands (the dominant failure mode under high-rate compression loads) to predict fragment populations from exploding ordnance, and applied to fracture under static loads. For the nuclear power community trying to solve the crack arrest problem in reactor pressure vessels, NAG was used to compute crack propagation by treating the microstructural failure processes occurring at the tip of a macrocrack.

We learned three important lessons in formulating the NAG approach to fracture that have guided our research ever since. First, always examine the damage; second, design clever experiments to invoke and stop damage at several stages of development; and third, perform computational simulations to gain insight into the damage evolution process.

4. ENERGY CRISIS

In the latter 1970s, the energy crisis brought other dynamic fracture problems to the fore, including *in-situ* explosive fracturing of tight geologic formations to stimulate gas and oil wells, ensuring the safety of nuclear power plants, and understanding particle impact damage on solar panels and turbine components.

4.1 Recovery of Oil from Shale

The U.S. Energy Research and Development Administration with support from the Bureau of Mines and the Geological Survey sponsored research to make untapped fossil fuel reserves commercially feasible. Although very large quantities of oil are contained in the shales of Utah, Colorado, and Wyoming, techniques were needed for recovery. One scheme was to fracture the shale formation *in-situ* with propellants placed in well boreholes, thereby increasing the permeability and allowing conversion of kerogen to shale oil by appropriate down-well thermal processing. The effort included field experiments, laboratory tests, and computer simulation studies by many research teams. The NAG approach was used with iterative computer simulations to help specify the parameters of propellant loading techniques that would produce desired crack patterns. [12-13].

4.2 Nuclear Power Plant Safety

By the mid-1970s, more than a hundred nuclear power plants had been built in the United States (it is noteworthy that no plant has been built in the United States since 1974). To ensure their safe operation in light of the well-known embrittling effect of neutron irradiation on pressure vessel steel, the Nuclear Regulatory Commission required the plants to be designed based on the minimum toughness. Initially, this meant the toughness of the steel had to be measured at the highest loading rate. Because of the considerable ductility of pressure vessel steel, especially at reactor operating temperatures, very large specimens (up to 12 inches in width) were required to get plane strain conditions, and this required innovations in dynamic crack initiation test techniques.

Somewhat later, it was found that the arrest toughness and not the initiation toughness defined the lower bound of the toughness versus temperature curve. Therefore, procedures to measure the toughness associated with a rapidly propagating and arresting crack needed to be developed.

A final dynamic fracture problem was finding a way to measure valid plane strain toughness values on small, Charpy-type specimens that could be placed in the limited space within a reactor, receive the neutron dose representative of other reactor components, and removed periodically and tested to monitor the extent of embrittlement.

As part of the nuclear power safety effort, we worked with others in the research community to help relate microstructural fracture at the tip of a macrocrack to fracture toughness parameters.

4.3 Particle Impact Damage on Solar Cells and Gas Turbines

Another dynamic fracture problem related to the energy crisis was particle impact damage and erosion of solar panels and turbine engines. Ceramics were being considered as low-cost alternatives to super alloys for stators, rotors, and other high-temperature engine components, because of their high strength at elevated temperatures, low density, low coefficient of thermal expansion, and high oxidation resistance.

A major problem, however, was the large dependence of strength on flaw size and distribution. New flaws introduced by impacting particles during service could reduce strength and make lifetime prediction uncertain.

Thus, we needed to understand the phenomenon of impact damage and develop a quantitative description of cracking that could be used to predict the properties and lifetimes of components in service. Many research groups worked on determining the effects of particle size and velocity on impact damage, categorizing and quantifying the damage, and obtaining threshold conditions for various fracture modes.

We constructed a small pneumatic gas gun to accelerate spheres of steel or tungsten carbide up to several millimeters in diameter against flat surfaces of ceramics at velocities up to 300 m/s to investigate the effects of surface oxidation, temperature, and transformation toughening. We and others measured the threshold conditions for permanent deformation and the various cracking types, Figure 6, and showed how the ring cracks, cone cracks, radial cracks, and lateral cracks grew in number and size with increasing velocity [14-17].

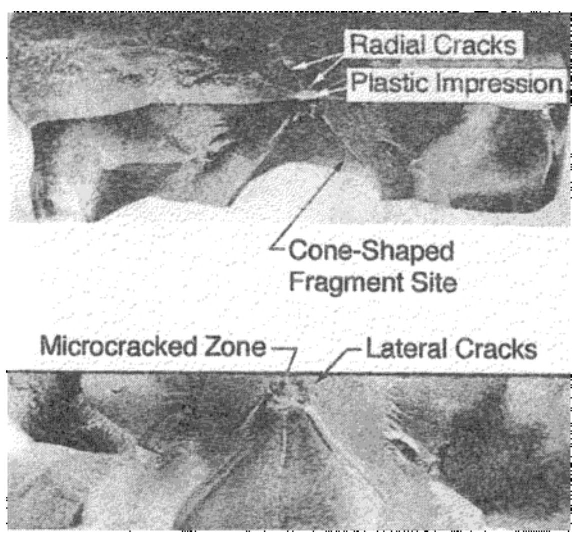

Figure 6. Particle impact damage in Si_3N_4.

5. CONTINUUM FRACTURE MECHANICS

While we firmly believed all along that the great advances in fracture mechanics were to be achieved by considering a material's microstructure, we confess to occasionally taking a continuum approach. One such case was our work to extend classical static fracture mechanics to treat a crack loaded by a short stress pulse produced, for example, by a laser or a thin impactor.

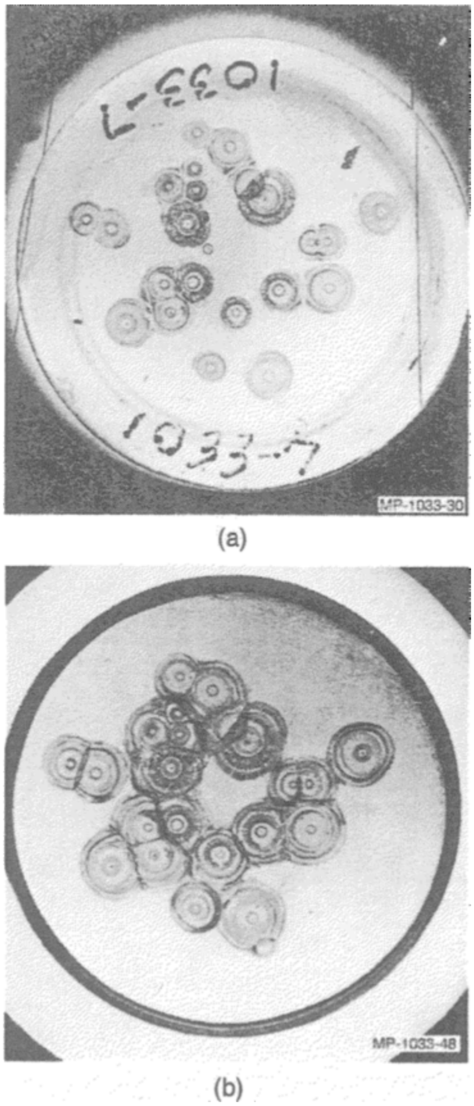

Figure 7. Internal cracks in polycarbonate produced in a plate slap experiment (a) and after a second shock load (b).

5.1 Short Pulse Fracture Mechanics

While performing plate slap experiments on polycarbonate, we produced a specimen containing incipient spall damage consisting of 48 circular penny-shaped internal cracks, which were easily observed in the transparent material, Figure 7(a) [18]. We had the idea of measuring the dynamic fracture toughness of this material at shock wave loading rates by putting the specimen back in the gas gun and performing another plate slap experiment. We performed three such experiments, each at a higher velocity. No cracks grew in the first two experiments, but all cracks above a certain size grew in the third experiment, Figure 7(b). We used the critical crack size and the stress in the shock wave to compute a toughness of 2.2 + 0.2 MPa$\sqrt{m}$ at a stress intensification rate of 10^7 MPa$\sqrt{m}$/s, which is about 60% of the static value.

More interesting though, was that this toughness value predicted that the larger cracks should have grown at the lower stress in the second experiment. They didn't, and that led our colleague, J. F. Kalthoff, to investigate the instability behavior of cracks under short pulse loads [19]. The result was Short Pulse Fracture Mechanics, a modification of classical Griffith-Irwin fracture mechanics that modifies the instability criterion to include time, a necessity when the pulse length, T_o, is comparable to the time required for a wave to run the length of a crack, Figure 8 [20-22].

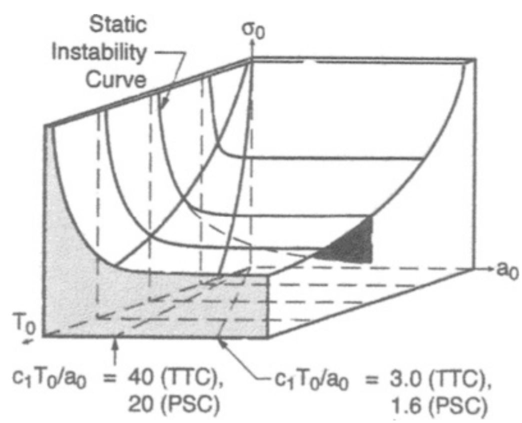

Figure 8. Instability diagram for cracks loaded by a short stress pulse. (TTC and PSC are through-thickness and penny-shaped cracks.)

5.2 The Temperature at the Tip of a Rapidly Propagating Crack

With Walter Klemm, we made simultaneous measurements of the dynamic stress intensity factor K_I^{dyn} and the dynamic fracture toughness K_{ID} in a high-strength steel to investigate the relation between energy delivered to and energy absorbed by rapidly propagating cracks. Values of K_I^{dyn} were obtained intermittently during the propagation history by the shadow optical method of caustics from high-speed photographs of the moving crack tips. Values of K_{ID} were calculated from temperature maxima recorded by thermocouples near the crack path. The results indicated that for fast-running cracks, the change in energy available at the crack tip can be significantly less than the energy absorbed in crack extension, suggesting that the then existing dynamic energy balance methods for determining dynamic fracture toughnesses may provide erroneous values [23].

6. ARMOR AND SHEAR BANDS

Throughout the 1970s and 1980s and into the 1990s, the Army was interested in developing new armor materials and designs, and in predicting penetration and back-of-the-armor debris.

6.1 Shear Bands

We saw our first shear band in 1974, when we sectioned and etched a plate of electroslag remelted steel that had been penetrated by a projectile, Figure 9. The white-etching, high-hardness bands bewildered us at first, before we learned that they had been observed and fully explained by Zener and Holloman in 1944 as thermal-mechanical instabilities, which occur when thermal softening overcomes work hardening [24].
In the ensuing years, we developed experiments to produce shear bands in controlled numbers and sizes, Figure 10, and from the data we developed equations that described their nucleation and growth. The confined exploding cylinder experiment allowed bands to nucleate and grow a certain extent before the confinement arrested them, allowing their numbers and lengths to be assessed as a function of explosive power and strain rate. The test was inspired by the fragmenting grenade and the interrupted plate slap tests.

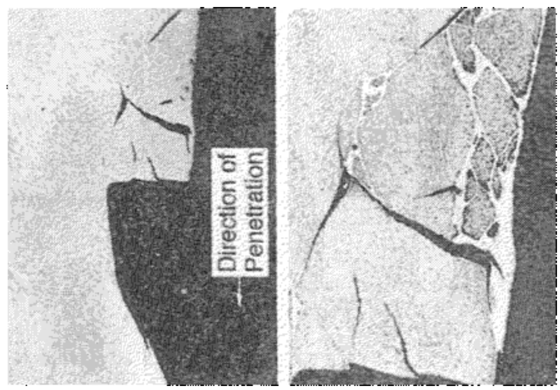

Figure 9. Shear bands in steel adjacent to hole produced by a penetrator.

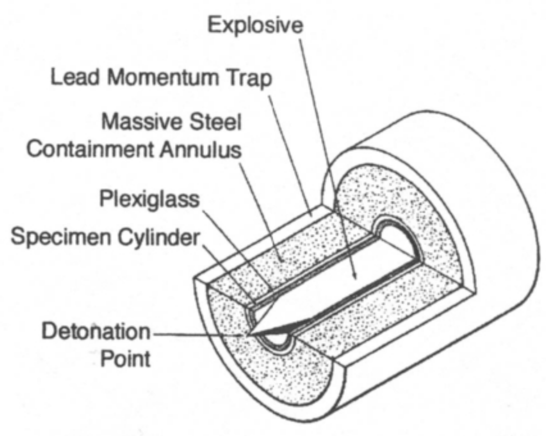

Figure 10. Contained exploding cylinder experiment that allows shear bands to nucleate, grow, and arrest at prescribed stages of development.

The test also allowed microstructural effects rather than structural stress raisers to dictate where and how shear bands formed, and hence provided an opportunity to understand the effects of material variables on shear band behavior. We found that shear bands nucleated and grew with little regard for grains, inclusions, second phase particles, and the like, but rather behaved as if the material were a homogeneous continuum [25,26]—a shattering result for a materials scientist (who likes to feel mechanical behavior can be controlled by controlling microstructure).

We performed orthogonal machining experiments to produce discontinuous chips and used an infrared camera to measure the temperatures associated with shear bands [27]. Our colleague J. H. Giovanola constructed a Hopkinson torsion bar, applied a photoresist grid on the gauge section of a yoyo specimen, and measured the evolution of shear strain from homogeneous to localization, establishing the critical conditions of shear strain and shear strain rate for shear banding [28].

Shear banding remains a rewarding field for research.

6.2 Back-of-the-Armor Debris

A tank armor problem of great interest and intimidating challenge was how to predict the spray of fragments that emanated from the rear surface of an armor plate, Figure 11. Of interest were the number, size, velocity, and trajectory of the fragments. Using the NAG approach, we were able to make some progress in this area, although the problem is hardly solved. It is a challenging problem for newcomers to the field.

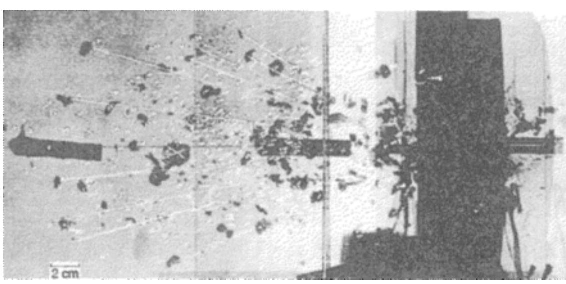

Figure 11. Triple flash x-radiograph showing fragment spray from armor when impacted by a long rod.

6.3 Ceramic Armor

In the late 1980s, ceramic armor was of great interest and computational models were needed to design armor structures and predict penetration. It was understood that ceramic tiles or blocks functioned best if they were confined by steel plates, but no model existed to design confinement or predict performance. Examination of ceramic targets partially penetrated by long tungsten alloy rods showed that a comminuted zone was produced in the ceramic at the leading edge of the advancing rod, and that this finely divided material had to get out of the path of the rod for the rod to continue to penetrate, Figure 12 [29]. Confinement inhibited this and forced the ceramic fragments to flow out through the hole being produced by the rod, absorbing rod energy and furthermore eroding the advancing rod. We named this comminuted zone the Mescall zone, after John Mescall of the Army Materials and Mechanics Center, who was first to deduce the zone from his computations.

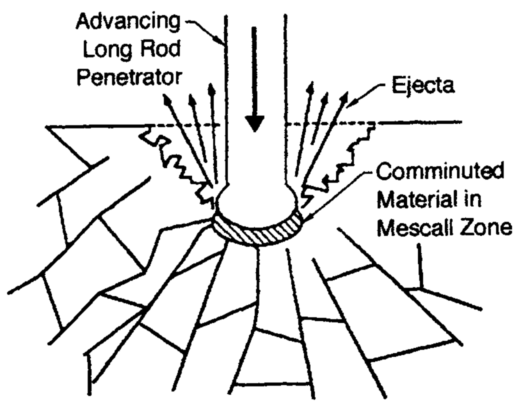

Figure 12. Comminuted material in the Mescall zone at the leading edge of an advancing penetrator in a confined block of ceramic.

To generate experimental data regarding the comminution energy and the friction and flow of finely fragmented ceramic, we designed a buried explosive charge experiment, Figure 13, in which an explosive charge is detonated within a cavity machined in the ceramic, generating a triangular pulse that moves radially outward [30]. The particle velocity at several radii out from the charge is measured, and the deformed and fractured ceramic is recovered for posttest microscopy. From the particle velocity histories, we derived displacement histories, circum-ferential strain histories, and reduced velocity potentials. From the recovered ceramic, we obtained radial distributions of microfracture and other damage. A single experiment provides data and recovered ceramic from a wide range of well-characterized loading conditions. The experimental data were used to support development of the FRAGBED model for ceramic comminution under penetration conditions [31].

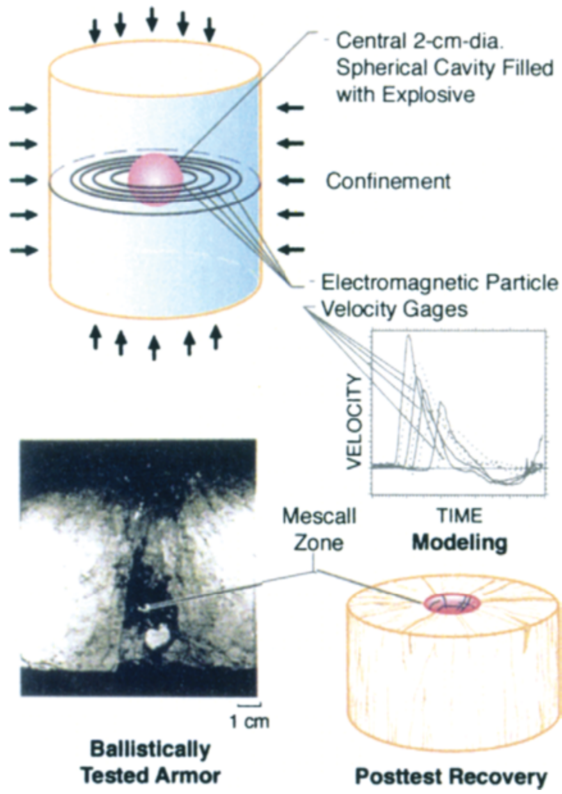

Figure 13. Buried explosive charge experiment to investigate material failure in the Mescall zone.

6.4 Hypervelocity Impact

Attempts to defeat armor in the 1980s and 1990s led to a revival in interest in hypervelocity impact. Studied extensively in the 1950s and 1960s because of the micro-meteorite threat to space vehicles and weapon development, the field had been dormant for several decades.

The steel plate in Figure 14 shows that virtually every conceivable damage mode can be invoked by hypervelocity impact [32]. Brittle cracks extend inward from the base of the crater; the cracks follow adiabatic shear bands; cross hatched patterns of adiabatic

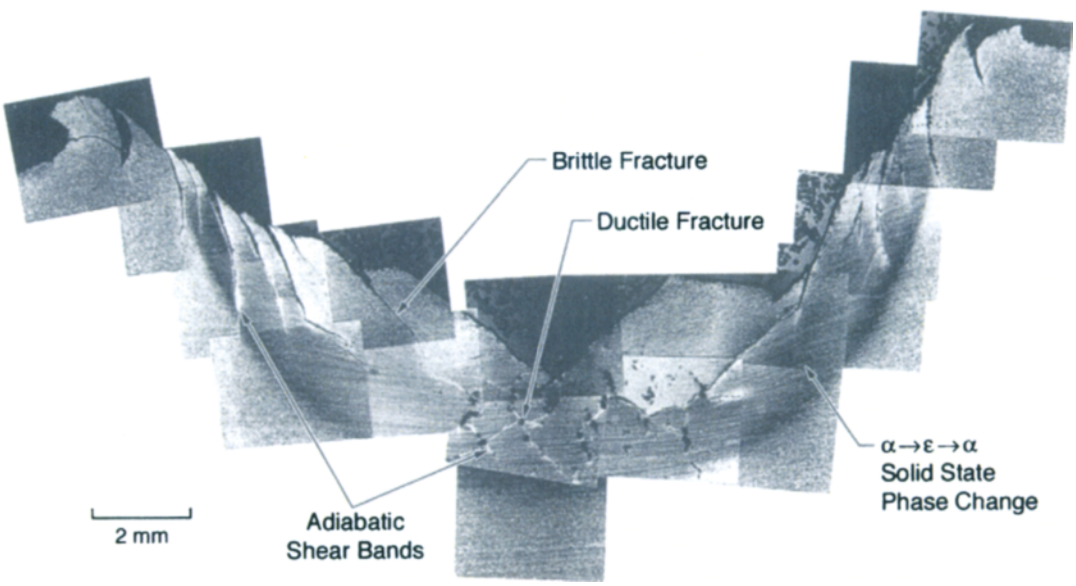

Figure 14. Polished and etched cross section in a steel plate through a crater produced by impact with a water-filled polycarbonate sphere at 6.03 km/s.

shear bands beneath the crater exhibit ductile fracture at intersections; the dark-etching region is the alpha-to-epilson pressure-induced solid state phase change; and a portion of material ejected from the crater was likely melted and perhaps vaporized (or would be at higher velocities). A very interesting and complicated material failure example.

The disintegration behavior of projectile rods when impacting plates at velocities above 10 km/s was largely unexplored. The two primary difficulties preventing experimental studies were the lack of a technique for accelerating a projectile to velocities above 10 km/s and the lack of a procedure for recovering the projectile remains after impact for examination.

Many researchers are actively engaged in overcoming these obstacles (see proceedings of the Hypervelocity Impact Symposia, for example [33]). We attacked the problem by using an exploding foil facility at the Lawrence Livermore National Laboratory to drive an impactor plate, by using a reverse ballistics test arrangement to allow projectile recovery, and by placing soft copper witness plates in the path of the expected debris [34, 35].

Experiments on steel, aluminum, and lead rods with Kapton foils at 13 km/s showed that rear portions of the rods receive no damage; material some distance from the impacted end sustains mechanical damage in the form of plastic flow, shear localization, and tensile fracture; and that melting and vaporization near the impacted end depended on velocity and material.

From the sizes of the craters on the witness plates, we obtained values for a cratering parameter containing the masses and velocities of the debris fragments that formed the craters. By combining the cratering parameter with rough estimates of the fragment masses, we estimated the fragment velocities. By measuring the thickness and extent of the coating on the witness plates, we obtained a bound on the amount of material vaporized by the impact.

Thus, a capability for computing the disintegration behavior of material under hypervelocity impact conditions, in general, must include mathematical models for nucleation, growth, and coalescence of voids and shear bands as well as adequate high-pressure equations of state for melting and vaporization. Existing NAG models for void and shear band evolution at lower velocities appear capable of describing behavior at hypervelocities because the morphology and phenomenology of mechanical damage are similar.

7. CURRENT DYNAMIC FRACTURE PROBLEMS

At the beginning of the new millenium, we find ourselves quantifying and developing ways to interpret fracture surfaces, engineering lightweight ballistic barriers for body armor and commercial transportation systems, helping formulate the technical basis for stewardship protocols for America's nuclear weapon stockpile, developing antiterrorist technology, and helping the National Ignition Facility project understand source debris. We briefly describe the first two efforts.

7.1 Understanding Dynamic Fracture Phenomenology with Fractography

Two goals of dynamic fracture research yet to be achieved are a reliable model for microfailure coalescence and a better understanding of how microstructure features affect microfailure. A new fractographic investigative technique [36], proven in fracture situations under static loading conditions, promises to provide information essential to accomplishing these goals.

With T. Kobayashi, we are quantifying the topographies of conjugate fracture surfaces and analyzing the mismatch pattern when the topographs are juxtaposed to computationally reconstruct the fracture event, illustrate microcrack nucleation, growth, and coalescence, pinpoint the underlying microstructure features, and provide data for microfailure models, Figure 15. When applied to spall surfaces, the technique should reveal and help quantify the evolution of microfailure and enable formulation of a mechanistic model for microfailure coalescence. It will also enhance the reliability of nucleation and growth models—hence providing a complete physics-based spall model [37]. Furthermore, by implicating fracture nucleation sites, growth paths, and ligaments on the fracture surfaces and examining their chemistry and microstructure, we seek an ability to design materials having tailorable dynamic failure characteristics.

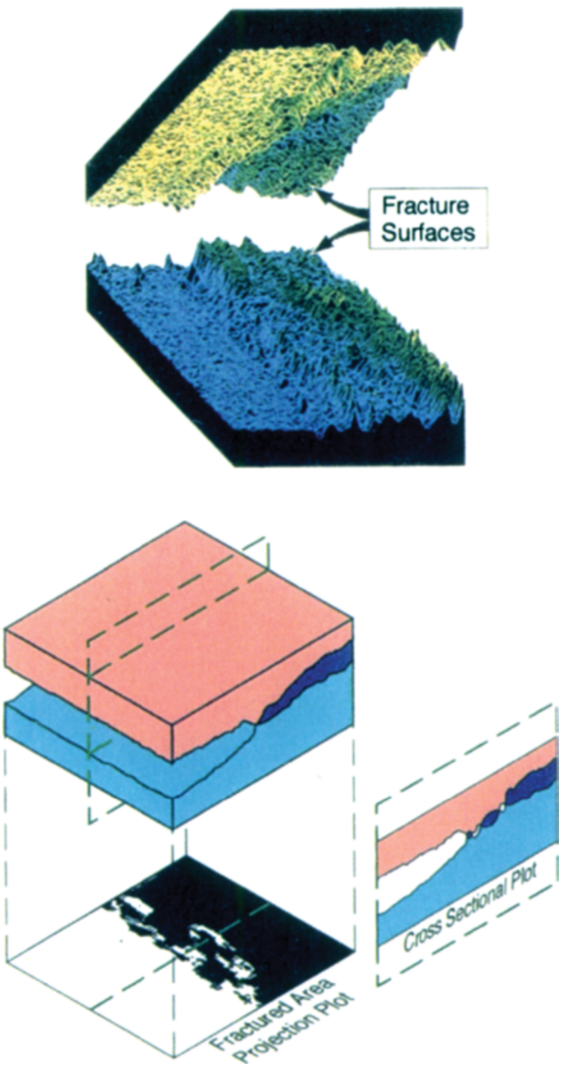

Figure 15. Fracture surface topography analysis to generate coalescence data and model spallation.

7.2 Lightweight Fabric Barriers to Engine Fragments on Commercial Aircraft

On rare occasions, a rotor disk of a main propulsion engine on a commercial aircraft fails and defeats the containment structure in the nacelle, showering a section of the fuselage with engine fragments. As part of a Federal Aviation Administration program to avoid catastrophic consequences, we are designing and evaluating barriers from high strength polymer fabrics such as Zylon that can be installed within the fuselage walls to prevent fragment penetration, Figure 16 [38].

We are developing a finite element model of the fabric that treats the deformation and failure response of individual yarns as well as the undulating geometry and interyarn friction when the yarn is woven into a fabric. To assist barrier design, computational simulations are performed with variations of fabric material and mesh, number of layers,

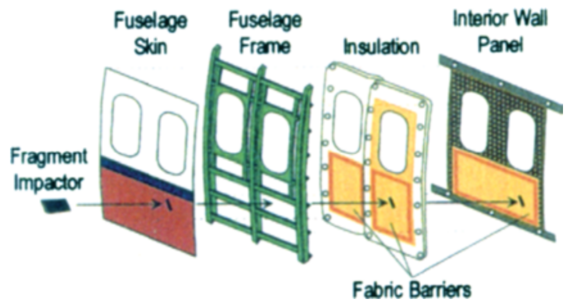

Figure 16. Exploded view of the fuselage wall in a commercial jet liner showing the location of ballistic fabric.

and fastening to the fuselage. Then barriers are constructed and evaluated by accelerating fragment simulators in a gas gun. The data are used to evaluate and improve the model, and another computational/ experimental iteration is carried out. The most promising barrier designs are tested full scale, Figure 17.

Figure 17. Full-scale testing of engine fragment barriers.

8. FUTURE DYNAMIC FAILURE PROBLEMS AND CHALLENGES

We have little doubt that interesting and challenging dynamic failure problems will continue to emerge in the coming years. Evident on the horizon already are the needs to treat electronics, lighter weight ballistic protection for soldiers and peace officers as well as for combat vehicles and commercial transportation, assurance against rapid crack propagation in gas pipelines (preventing large lengths of pipe from rupturing with potentially incendiary and poisonous/polluting consequences), expert testimony in industrial explosions and high-speed transportation accidents, bullet forensics, and more. Ubiquitous needs exist for improved algorithms for predicting dynamic failure response, designing structures and materials to resist dynamic loads, and improved instrumentation, sensors, and techniques for monitoring and recording dynamic failure.

A particular challenge with high payoff in the near term is to solve the inverse fracture problem, the deduction of prior events that led to fracture by examining the final state—a most exciting and basic fracture problem that requires a treatment of the deformation and microfailure events occurring in the process zone of the crack tip. Such a solution will be of great assistance to the materials scientist in developing microstructures with improved failure resistance and to the failure analyst in determining the root cause of an accident. The solution will elevate fractography to a quantitative, three-dimensional, objective science and constitute a leapfrog advance in the current state of practice.

Two thirds of the problem has been solved: there exist models for nucleation of cracks, voids, and shear bands, and there exist models for their growth. A reliable model for the final stage of the fracture process, coalescence, however, has eluded researchers to this point. Part of the difficulty has been the lack of a method for obtaining data on the coalescence of neighboring microfailures. This deficiency can be overcome with the help of FRASTA [35], which enables the process of coalescence to be reconstructed in three-dimensional microscopic detail from the topography of conjugate failure surfaces.

By extending NAG to NAGAC (nucleation and growth and coalescence) of microfailures, a failure analyst can examine a fracture surface and determine the history of the failure (how long the component operated before an observable crack formed, how fast the crack propagated, and did it accelerate or decelerate or stop during its propagation). The analyst can also determine the loading conditions under which the fracture occurred and hence determine if the component operator exceeded operation protocol.

Success in solving problems like this will further our understanding of why things break, how things break, and how to keep them from breaking, or conversely, how to break them efficiently. This understanding, in turn, will allow us to design safer structures and operate them more economically.

Thus, the field of dynamic fracture provides opportunities for the graduate student and young engineer to solve important problems that affect the safety and economy of the world society—an exciting and rewarding prospect. The future for the fracture physicist is bright.

9. ACKNOWLEDGMENTS

Many, many colleagues and collaborators, too many to mention here by name, contributed to the efforts to solve the problems described in this retrospective. However, our friend and SRI colleague Lynn Seaman deserves special mention.

We are also grateful for the financial support over the past 30 years from many agencies and companies, especially the Air Force Office of Scientific Research, Air Force Weapons Laboratory, Army Research Office, Defense Advanced Research Projects Agency, Defense Threat Reduction Agency, Department of Energy, Electric Power Research Institute, Federal Aviation Administration, National Aeronautics and Space Administration, and the Office of Naval Research.

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Preface

This book contains the proceedings of EXPLOMET™ 2000, International Conference on Fundamental Issues and Applications of Shock-Wave and High-Strain-Rate Phenomena, held in Albuquerque, New Mexico, 2000; the fifth in the EXPLOMET™ quinquennial series which began in Albuquerque in 1980. EXPLOMET™ 2000 was a smaller conference than EXPLOMET™ 95 but still larger than the original conference held in 1980.

The book is divided into five major sections with a total of 85 chapters. Section I deals with materials issues in shock and high strain rates while Section II covers shock consolidation, reactions, and synthesis. Materials aspects of ballistic and hypervelocity impact are covered in Section III followed by modeling and simulation in Section IV and a range of novel applications of shock and high-strain-rate phenomena in Section V.

Like previous conference volumes published in 1980, 1985, 1990, and 1995, the current volume includes contributions from fourteen countries outside the United States. A significant fraction of the Chapters contain students either as the principal author or co-author. As a consequence, we hope this book will serve as a global summary of current issues involving shock and high-strain-rate phenomena as well as a general reference and teaching component for specialized curricula dealing with these features in a contemporary way.

The International Conference on Fundamental Issues and Applications of Shock-Wave and High-Strain-Rate Phenomena held in Albuquerque, New Mexico, U.S.A., and hosted by Los Alamos National Laboratory, was also co-sponsored by the Laboratory as well as the University of Texas at El Paso, The University of California, San Diego, and the U.S. Army Research Office, Materials Science Division (Grant No. DAAD19-99-1-0326).

Like the previous, 1995 EXPLOMET™ Conference Proceedings also published by Elsevier Sciences, this volume contains original, camera-ready manuscripts which did not require extensive revisions or re-typing. However, some papers were re-formatted to fit the template requirements and numerous patches were inserted for titles and headings to make a more uniform appearance. It is a pleasure to acknowledge the help of Faye Ekberg of the UTEP Department of Metallurgical and Materials Engineering in this endeavor as well as her assistance along with graduate student Lola Norton in handling the bulk of the conference registration duties. A special thanks is also extended to Josie Staudhammer who contributed to the overall program development and organized the companion program, co-hosted by Pat Murr.

Over the past twenty years, the EXPLOMET™ Conferences have created a family of participants who not only converse every five years but who have developed long-standing interactions and professional relationships which continue to stimulate new concepts and applications particularly rooted in basic materials behavior. We can only hope that this volume will serve as a testament to these efforts and set a tone for the role of these issues in the new millennium.

Karl P. Staudhammer
Lawrence E. Murr
Marc A. Meyers

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Section I

Materials issues in shock and high strain rates

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Fundamental Issues and Applications of
Shock-Wave and High-Strain-Rate Phenomena
K.P. Staudhammer, L.E. Murr, and M.A. Meyers (Editors)

Chapter 1

Elastic - plastic impact (some persistent misconceptions)

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The first rational model of elastic-plastic impact was presented about 37 years ago (J. W. Taylor and M. H. Rice, 1963). They showed that the magnitude of the then mysterious "elastic precursor" is simply the dynamic yield stress; and their model eliminated the mythic "plastic waves"; an incorrect part of the earlier literature. They showed that impact of one flat solid on another produces uniaxial elastic waves traveling with the longitudinal wave speed, and containing both shear and dilatational strain energies. The shear stresses larger than the yield stress get absorbed by plastic deformation; the hydrostatic stresses do not. Thus the uniaxial wave soon becomes two waves; one of lower amplitude travelling at the elastic longitudinal wave speed, and the other of higher amplitude travelling at the slower speed of pressure waves. Both waves are elastic. There are no "plastic waves", although references to them still appear in the literature.

Several misconceptions (of more, or less, persistence in each case) regarding elastic-plastic impacts include: 1. Elastic and plastic deformations can be treated as if they are equivalent (they are not equivalent since they are conservative, and non-conservative, respectively; 2. Plastic deformation is rate independent; 3.There is an equation-of-state for plastic deformation (not valid); 4. Impact is a hydrodynamic process; 5. Dislocation effective masses are a function of velocity (this fallacy is based on incorrect solutions of the equations of motion; 6. Dislocation multiplication is a kinetically zero order process (wrong! Koehler's multiplication process is first order); 7. The expression for the plastic deformation-rate contains a multiplication-rate term (not true because the displacements associated with dislocations are finite); 8. Dislocations can propagate supersonically (the equations that indicate this are incorrect, as are existing molecular-dynamic simulations).

INTRODUCTION

Few subjects are as deceptive as plastic deformation at low deformation rates, and the deceptions become more complex as the rates are increased. As stresses are applied to solid materials, the initial response is linear elastic, and well-behaved, and relatively simple. An observer is lulled into a sense of well-being. Then, a level of stress is reached, called the yield stress, and the behavior becomes anything but well-behaved, as its complexity increases markedly.

Below the yield stress, the causes and effects are connected by Hooke's Law which is linear and applies to all classes of solids. Combining it with Newton's Laws allows both static and dynamic problems to be accurately described. Elastic states can be established which are independent of the loading path used to reach them. Above the yield stress, this pastoral scene changes dramatically. Metals behave very differently from semiconductors; and from insulators. Sometimes the behavior is related to intrinsic chemical bonding; sometimes not. Nonlinearity prevails. There are no plastic states; hence, no equations of state. Loading rates become important. Instead of being invariant, internal configurations at all levels of aggregation change as deformation proceeds.

Because of the major differences in the qualitative aspects of the behavior, attempts to apply the concepts and procedures of the theory of elasticity to plastic behavior have led to many misleading, and sometimes false, conclusions. This has been particularly true in the arena of elastic-plastic impact.