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13. ABSTRACT ***(Maximum 200 Words)***

A novel high-strain-rate and high temperature experimental set-up was developed to investigate failure of advanced materials. Experiments were performed on preheated Ti-6Al-4V specimens, at temperatures in the range 25-550 ^{0}C, to determine the role of thermal activation on dynamic stress induced inelasticity and damage. Interferometric techniques were employed to record the free surface velocity of the target plates. The experimental results show that thermal activation overcomes the role of rate dependence in the material constitutive behavior. The Hugoniot Elastic Limit (HEL) and spall strength of Ti-6Al-4V significantly decrease with temperature despite of the high strain rates, about 10^5 s^{-1}, used in the tests.

Microscopy studies, performed on recovered samples, show that temperature substantially reduces the strain inhomogeneity leading to microvoid formation and that a change in void nucleation site occurs. A completely reversible shock-induced phase transformation $\alpha \rightarrow \omega$ be present in the tested Ti-6Al-4V. Evidence of this phase transformation is observed in the velocity histories upon unloading of the first compressive pulse. The phase transformation is controlled by a combination of thermal and stress driven mechanisms.

Two other activities were completed under this grant, the development of software for finite element analysis of failure in brittle and layered materials, and the development of dynamic fracture experiments with full field measurements by means of speckle techniques. The new software accounts for crack initiation and propagation, finite deformation and surface roughness effects.

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AN INVESTIGATION ON HIGH TEMPERATURE BEHAVIOR OF LAMINATE AND NANOSTRUCTURED COMPOSITE MATERIALS

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Abstract

Planar impact experiments were performed on preheated Ti-6Al-4V specimens, at temperatures in the range 25-550 ^{0}C, to determine the role of thermal activation on dynamic stress induced inelasticity and damage. Measurements in this high temperature and high strain rate regime were possible by modification of the standard plate impact facility to include heating capabilities.

A symmetric planar impact configuration was employed to achieve high compressive and tensile stresses in the specimens. The targets were heated by a magnetic field generated by current flow on a coil surrounding the specimen. Interferometric techniques were employed to record the free surface velocity of the target plates. The experimental results show that thermal activation overcomes the role of rate dependence in the material constitutive behavior. The Hugoniot Elastic Limit (HEL) and spall strength of Ti-6Al-4V significantly decrease with temperature despite of the high strain rates, about 10^5 s^{-1}, used in the tests.

The damage mechanism remains the same at high and room temperatures, i.e., microvoid nucleation, growth and coalescence. Microscopy studies, performed on recovered samples, show that temperature substantially reduces the strain inhomogeneity leading to microvoid formation and that a change in void nucleation site occurs. A completely reversible shock-induced phase transformation $\alpha \rightarrow \omega$ be present in the tested Ti-6Al-4V. Evidence of this phase transformation is observed in the velocity histories upon unloading of the first compressive pulse. The phase transformation is controlled by a combination of thermal and stress driven mechanisms.

Two other activities were completed under this grant, the development of software for finite element analysis of failure in brittle and layered materials, and the development of dynamic fracture experiments with full field measurements by means of speckle techniques. The new software accounts for crack initiation and propagation, finite deformation and surface roughness effects.

1. High Temperature Testing of Advanced Materials

Understanding material response at high temperatures and high strain rates is essential to the development of models describing dynamic failure of advanced materials. Such models are of crucial importance to many applications. For instance, crack arrest in engineering structures, failure of turbine engine blades, foreign object impact on satellites and aircrafts, automotive crashworthiness and military applications such as projectile deformation and armor penetration. Our current understanding of basic properties like plastic flow or dynamic fracture strength in the high temperature and high strain rate regime is very limited. This is the case because of the scarcity of experimental studies with the needed spatial and temporal resolution to identify damage and failure mechanisms.

Plate impact experiments offer unique capabilities for the dynamic characterization of advanced materials. The stress amplitudes and deformation rates obtained in these experiments allow the identification of damage and material instabilities, Espinosa and Nemat-Nasser (2000).

This report describes the experimental technique developed for shock impact testing at high temperature and summarizes the variation of HEL and spallation with temperature in Ti-6Al-4V. Microstructural analyses that provide insight into the deformation mechanisms of the shocked material are also discussed.

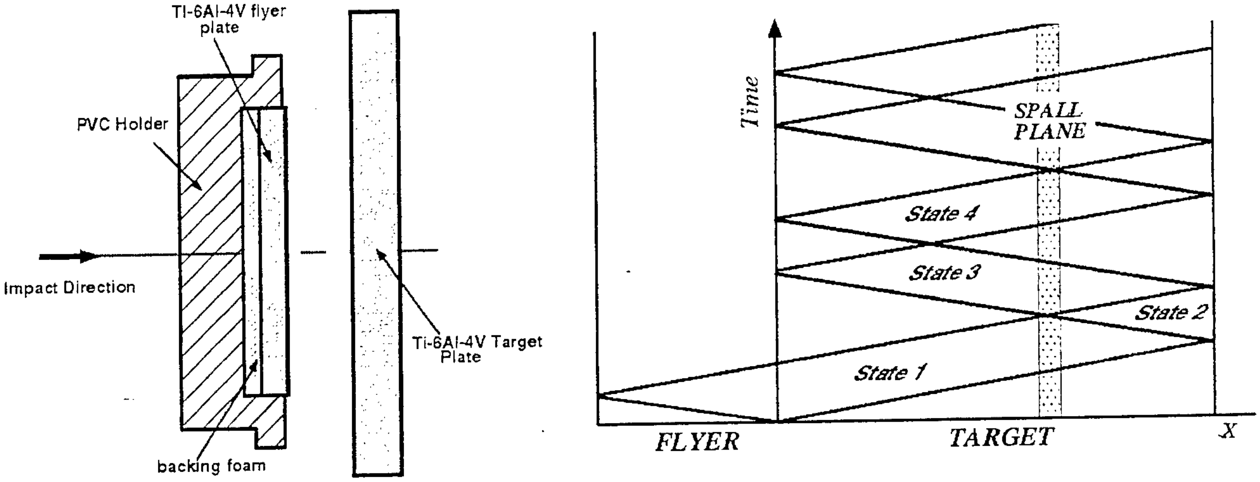


Figure 1: a) High temperature experimental configuration, b) Lagrangian X-t diagram for a symmetric impact.

Experimental Technique

The selected experimental configuration is a symmetric planar impact or spall experiment, see Figure 1a. The elastic wave fronts and their interaction are easily understood by examining the time-distance (t-X) Lagrangian diagram shown in Figure 1b. At impact, plane compression waves are produced in both the flyer and the specimen (state 1). The reflection from the foam-flyer interface unloads, almost completely, the compressive wave resulting in compressive pulse duration equal to the round trip travel time through the flyer thickness. When the compressive pulse reaches the rear surface of the specimen, a reflected wave is generated. This wave unloads the compressive pulse (state 2). Tensile stresses are generated when the two unloading waves, one from the flyer and the other from the specimen back surface, meet in the central part of the specimen (state 3). This location is named spall plane and it is where the target is expected to fail. By the time the tensile pulse reaches the flyer-specimen, interface separation takes place and the pulse reflection causes compressive stresses (state 4). For the reported experiments, the thickness of the targets is close to 8 mm for all specimens with a corresponding half thickness for the flyers. In this way, the spall plane is located near the middle of the target.

Tested Material

Hot-rolled plates of Ti-6Al-4V, provided by Dr. Wells from the Army Research Laboratory, were used in this investigation. No heat treatment was performed in the samples prior to testing. A metallographic examination showed that the starting material had a microstructure consisting of equiaxed and acicular α-phase (90 %) and a small amount of intergranular β-phase (10%). The nominal α grain size varied from 8-15 μm with and aspect ratio of 2-10. The β-grain size was less homogeneous with a grain size varying from 5-20 μm. It was also possible to observe that acicular β-phase is oriented in the rolling direction. The described microstructure is typical of annealing follow by a hot roll processing, Donachie (1988). The target and flyer plates were all machined from the provided plates in such a way that the impact axis was perpendicular to the rolling direction. The hardness was measured to be 35.6 RC.

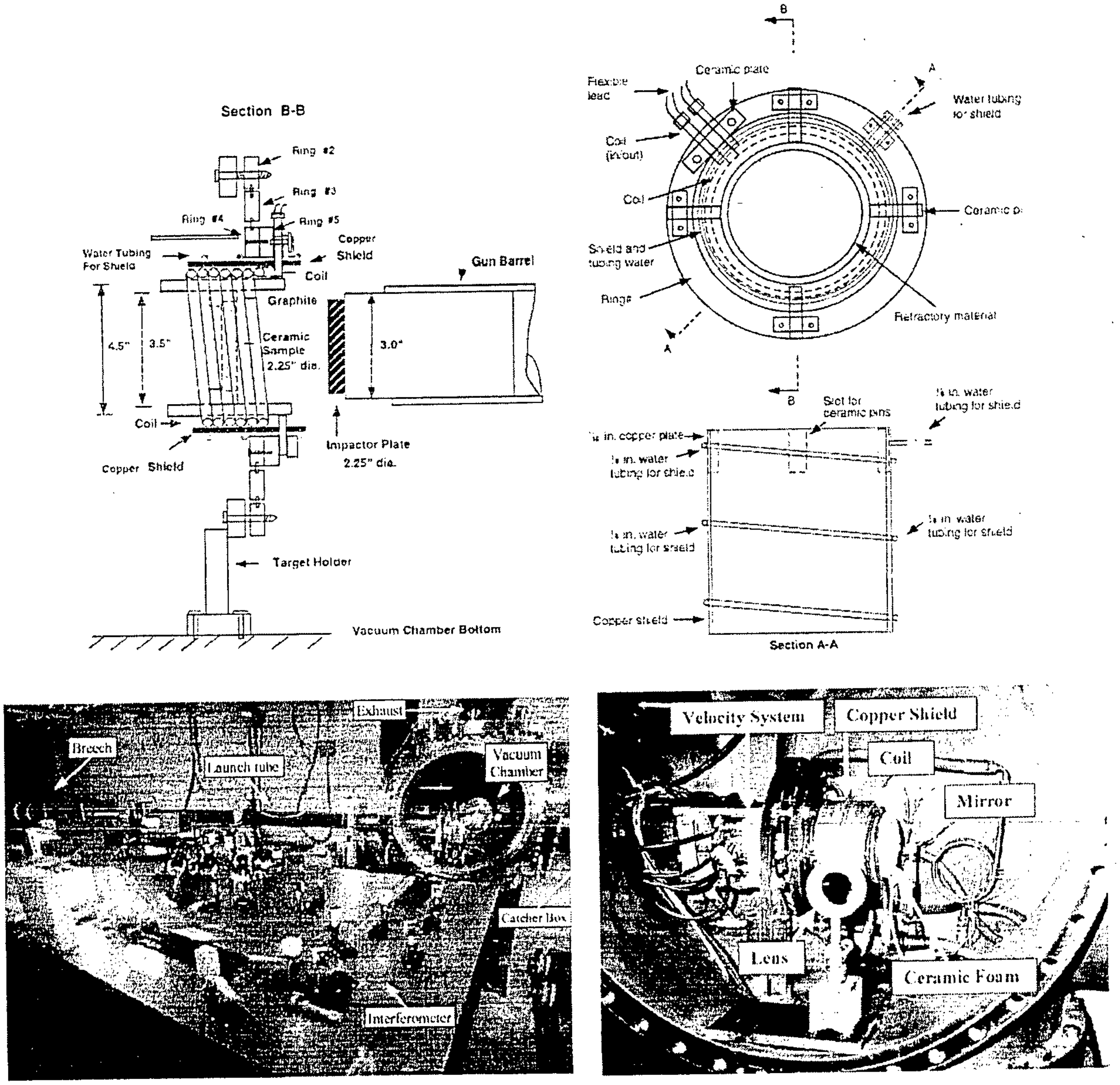


Figure 2: Experimental set-up, schematics and photographs.

Experimental Results and Discussions

A summary of performed impact experiments is presented in Table 1. Table 2 summarizes measured dynamic properties such as HEL, spall strength and dynamic yield stress as obtained from the experimental data. A discussion of the equations employed in the calculations is given in Arrieta, 1999. A summary of velocity histories is shown in Figure 3.

Shot No.	**Temp.** [^{0}C]	**Impactor thickness** [mm]	**Target thickness** [mm]	**Impact Velocity** [m/s]	**Normal Stress** [GPa.]
98-0924	22	3.60	7.6	251	3.46
98-1210	298	3.51	7.79	272	3.57
98-1210	315	3.54	7.62	417	5.45
99-1008	513	3.58	7.61	594	7.45

Table 1: Summary of experimental parameters

Shot Number	**Preheat Temperature** [^{0}C]	**Strain Rate** [s^{-1}]	**Transient Strain**	**HEL** [GPa.]	**Dynamic Yield Stress** [MPa]	**Spall Strength** [GPa]
98-0924	22	1.47×10^5	0.0135	2.77	1402	5.10*
98-1210	298	1.61×10^5	0.0153	2.11	917	----
99-0602	315	2.27×10^5	0.0239	2.105	914	4.47
99-1008	513	3.26×10^5	0.0356	1.98	858	4.30

* Reported in literature, Mebar et.al (1987)

Table 2: Summary of High Temperature Experiments

It is well know that the Hugoniot Elastic Limit (HEL) and therefore the Dynamic yield stress increases with strain rate at constant temperature. Moreover, experiments performed by Lee and Lin (1998) show a drop in Dynamic Yield Stress with temperature when the strain rate is maintained to a constant value of about 10^3 s^{-1}. The experimental results presented in this investigation show that the HEL and its associated value, the Dynamic Yield Stress, drop significantly with temperature, when the strain rate is about 10^5 s^{-1}, see Figure 3. This data agrees quite well with the previously cited results from Lee and Lin (1998).

From Table 2 and the data reported by Lee and Lin, it is possible to infer that both strain rate and temperature have an effect on the constitutive behavior of Ti-6Al-4V. However, the effect of strain rate, on the dynamic yield stress of Ti-6Al-4V, is secondary when compared to the effect of temperature. Thus, the rate of thermal softening prevails over the rate of work hardening under shock deformation in the elevated temperature regime.

The effect of temperature on the spall strength of Ti-6Al-4V has been observed to be similar to the one manifested on other metals, such as aluminum and magnesium, Kanel et al., 1996. The progressive reduction of spall strength with temperature is shown in Figure 3. The measured reduction in the rate of change of the spall strength with temperature appears to be related to the increment of plastic flow favored by the increase in thermal activation. The presence of a $\alpha \rightarrow \omega$ phase transformation at approximately 2.2 GPa, may play a role in the formation of defects that promote microvoid formation and, therefore, reduction in the spall strength. The present results indicate that the spall strength reduction saturates with temperature, in a similar fashion to the dynamic properties, regardless of the presence of stress driven secondary phases.

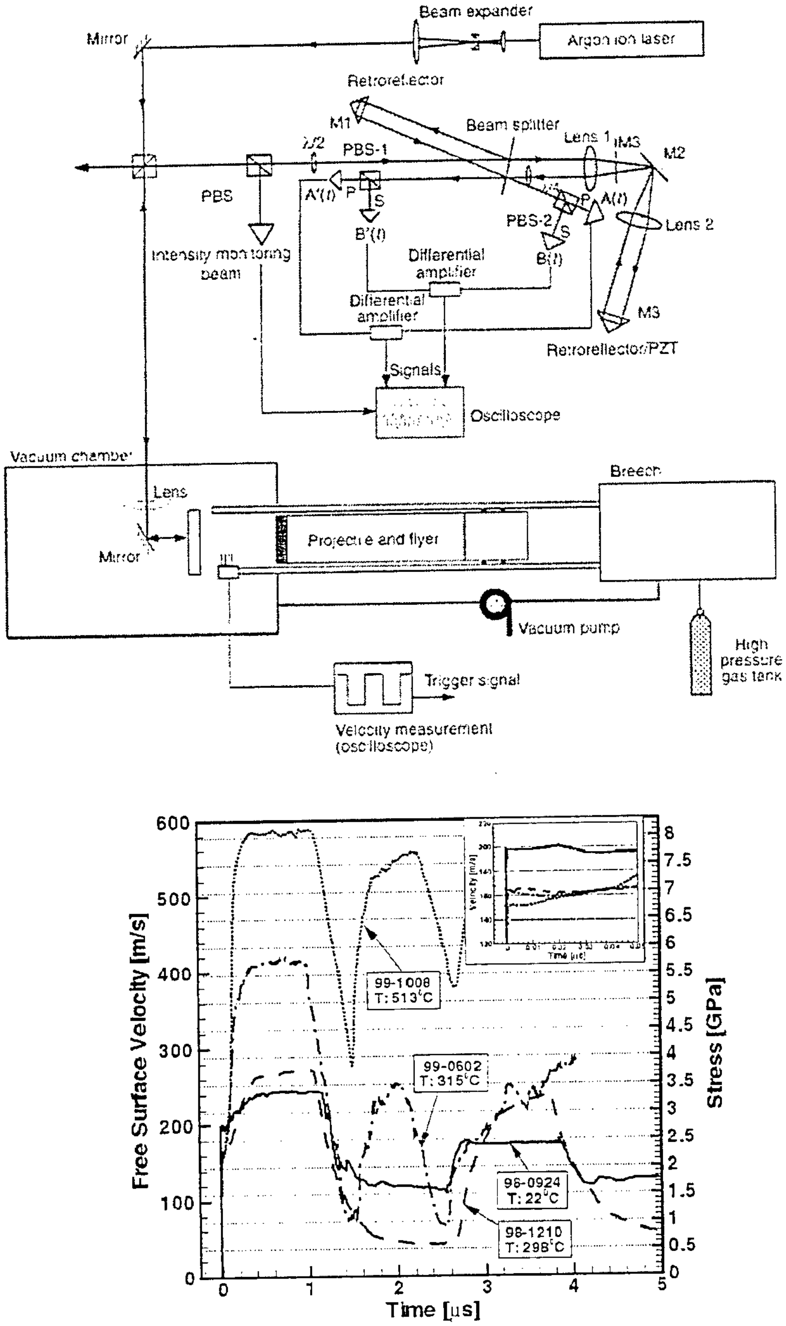


Figure 3: a) Interferometer; b) summary of velocity histories from room and high temperature experiments.

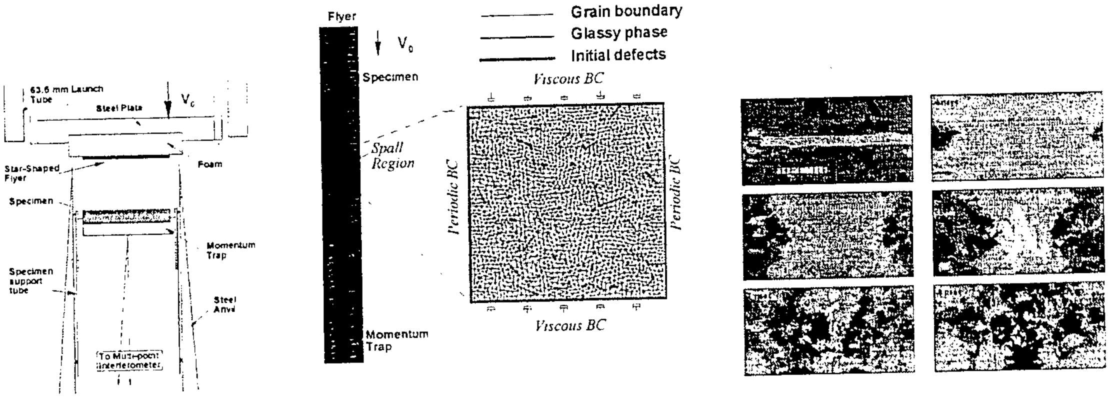
According to our results a shock-induced phase transformation $\alpha \rightarrow \omega$ occurs at room temperature in Ti-6Al-4V when a peak stress of 3.46 GPa is achieved. The transformation is suppressed by thermal activated mechanisms at about 300^0C and 3.57 GPa. It reappears at the same temperature and a higher stress level, namely, 5.45 GPa. Therefore, temperature and strain rate play opposite roles in the generation of the $\alpha \rightarrow \omega$ shock-induced transformation in Ti-6Al-4V. A possible cause is the competition between thermally activated deformation mechanisms, such as slip, which is favored by high temperature and low strain rates, to a thermal deformation mechanisms, such as twining, that is more favorable at high strain rates and stress levels.

By SEM analyses performed on the recovered samples, a correlation among the changes in wave profile with stress induced damage on the target plates has been established. In all cases, damage in the form of microvoids has been observed. Damage at stress levels bellow complete spallation of the material is usually overseen. Room temperature experiment provided experimental evidence that damage at stress levels below 3.5 GPa occurs in Ti-6Al-4V, even though a pull-back signal is not present. The reported damage in Ti-6Al-4V as a function of temperature is useful for future formulations of void nucleation and growth models where the onset of inelasticity, defined as the stress threshold at which damage starts, is a relevant variable, see e.g., Curran et al. (1981). The dramatic changes in wave profile, due to thermal activation, reinforces the need for including the effect of thermal activation on deformation mechanisms in future modeling of void nucleation and growth when the material is preheated or heated by plastic deformation and/or friction.

2 Grain Level Modeling of Impact Soft-Recovery Experiments

Characterization of material behavior under well-defined loading and boundary conditions at high strain rates, were performed to gain insight into the failure of materials under various multiaxial loading conditions. Specimen recovery was obtained to assess failure modes by means of microscopy studies. Information on crack initiation and its kinetics was obtained through interferometrically measured velocity histories, Espinosa et al., 1997, 1998, 2000. The concept of pressure-shear impact with soft-recovery of brittle materials was established and its limitation identified. In parallel with this effort, computational models were developed to account for multi-body contact, finite kinematics of deforming bodies, thermo-mechanical coupling and mesh adaptivity, Espinosa et al., 1998. Finite deformation models for ductile materials were developed using viscoplastic laws including hardening and thermal softening. To capture discrete fragmentation in brittle solids, cohesive fracture laws were embedded in an extended finite element formulation (X-FEM), Espinosa et al., 1998.

In the past, only continuum models were used to describe material behavior. With advances in computational capabilities, massively parallel computers, utilization of more sophisticated models become feasible. Using a parallel version (MPI) of the developed X-FEM code, representative volume elements (RVE) of ceramic microstructures were analyzed for both normal impact soft-recovery experiments and pressure-shear soft recovery experiments. The numerical simulations were based on a 2-D stochastic finite element analysis. The model incorporated a cohesive law to capture microcrack initiation, propagation and coalescence, as well as crack interaction and branching, as a natural outcome of the calculated material response. The stochasticity of the microfracture was modeled by introducing a Weibull distribution of interfacial strength and toughness at grain boundaries. This model accounted for randomness in grain orientation, and the existence of chemical impurities and glassy phase at grain boundaries. Representative volume elements (RVE) of ceramic microstructure with different grain size and shape distributions were considered to account for features observed in real microstructures (Fig. 4). Normal plate impact velocity histories were used not only to identify model parameters, but also to determine under what conditions the model captured failure mechanisms experimentally observed. The analyses showed that in order to capture damage kinetics a particular distribution of grain boundary strength and detailed modeling of grain morphology are required. *Simulated microcrack patterns and velocity histories have been found to be in a good agreement with the experimental observations only when the right grain morphology and model parameters were chosen.* It has been found that the addition of rate effects to the cohesive model resulted in microcrack diffusion not observed experimentally, Zavattieri and Espinosa, 2001a.



(a) (b) (c)

Figure 4: (a) Schematic of the experimental configuration, and (b) computational cell considered in the analysis including a description of microcracking at grain boundaries using interface elements. (c) Evolution of the crack pattern and y component of the stress for one of the cases.

Grain level micromechanical analyses of ceramic microstructures subjected to dynamic compression-shear loading conditions were also performed. The investigation consisted of a combined experimental/numerical approach in which bulk and surface material properties were examined by means of pressure-shear impact experiments. The model incorporated a cohesive law to capture microcrack initiation, propagation and coalescence. Surface roughness was also included in the analysis to capture the time dependent frictional behavior of the various interfaces. The ceramic model accounted for randomness in grain orientation, the existence of chemical impurities and glassy phase at grain boundaries, thermo-elastic anisotropy, visco-plasticity and surface characteristics. Model parameters identified in the simulation of normal impact were employed. The model for the steel anvil plates accounted for finite deformation visco-plasticity, thermal softening and strain hardening. Representative volume elements (RVE) of ceramic microstructure and anvil plates were considered to account for features observed in the experiments. Pressure-shear impact velocity histories were used not only to identify inelasticity, but also to determine dominant failure modes. Simulated velocity histories have been found to be in a good agreement with the experimental observations when bulk *and* surface features were included in the analysis. *It was demonstrated that the velocity histories measured in pressure-shear experiments performed on hard ceramics provide mostly information on the time dependent frictional behavior of the specimen-anvil interfaces.* Bulk ceramic properties did not affect the velocity history in any significant way. A methodology for bridging between micro- and macro-scales was achieved by using the developed model, Zavattieri and Espinosa, 2001b.

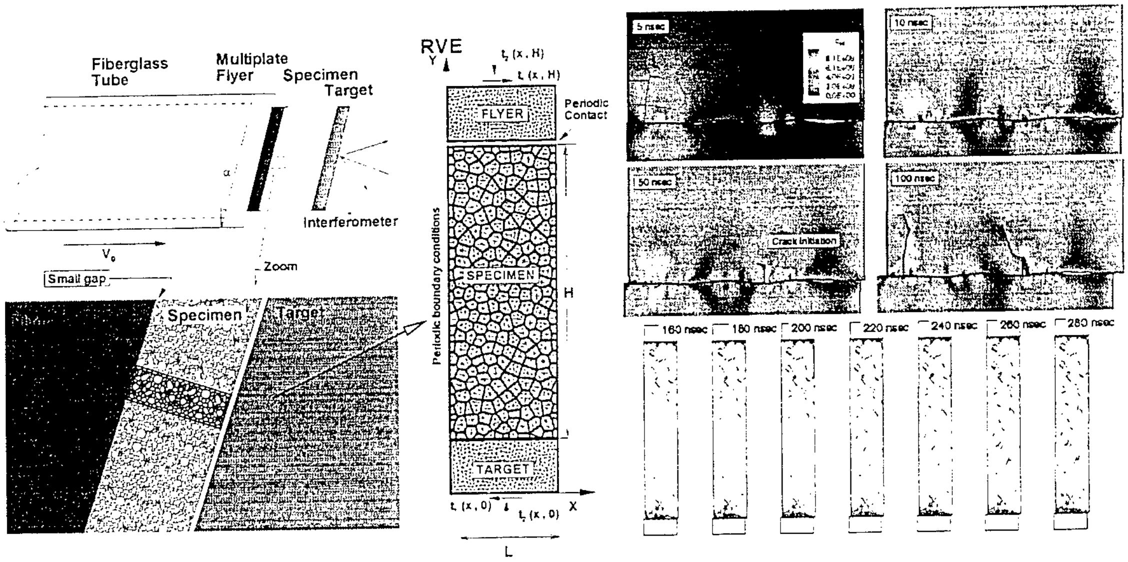


Figure 5: (a) Schematics of the experimental configuration and the RVE (b) Evolution of the crack pattern for full scale simulation.

3. Novel experimental techniques with high-speed photography and full field measurements

Espinosa and his students developed a stored energy Kolsky bar apparatus for compression-shear high strain rate testing of materials with specimen recovery. The apparatus was used to investigate dynamic friction, Espinosa et al, 2000a and b, dynamic torsion of nano-coatings, Espinosa et al, 2000c, and dynamic fracture of ceramics, Espinosa and Barthelat, 2001.

The apparatus, Fig. 6a, is composed of two 1-inch (25.4 mm) 7075-T6 aluminum alloy bars. The so-called incident, or input bar, is 90.5 in (2.3 m) long and the so-called transmission, or output bar, is 75 in (1.9 m) long. Each bar is supported by a series of re-circulating fixed-alignment ball bearings (*INA KBZ16PP*) minimizing the friction resistance on the supports and allowing the bar to rotate and translate freely in both directions. The compression/tension and shear loading pulses are produced by the sudden release of the stored elastic energy. This requires both torsional and compression/tension actuators. The axial part of the elastic energy is produced by means of a hydraulic double acting actuator (*Enerpac RD 166*), which applies a compressive or tensile load at one end of the incident bar. Its capacity is 35 kip (*150 kN*). The torsional part of the elastic energy is achieved by means of a hydraulic rotary actuator (*Flo-Tork 15000-180-AICB-ST-MS2-RKH-N*) located along the incident bar. It is connected to the bar by a 3/8" steel key. Its capacity is 15,000 lb·in. (*1700 N·m*). The sudden release of the stored energy is achieved using a clamp positioned between the rotary actuator and the specimen. The design of the clamp is crucial for good results. The clamp must be able to hold the desired torque and compression/tension force without slippage, and release the stored energy rapidly enough to produce a sharp-fronted stress pulse traveling towards the specimen.

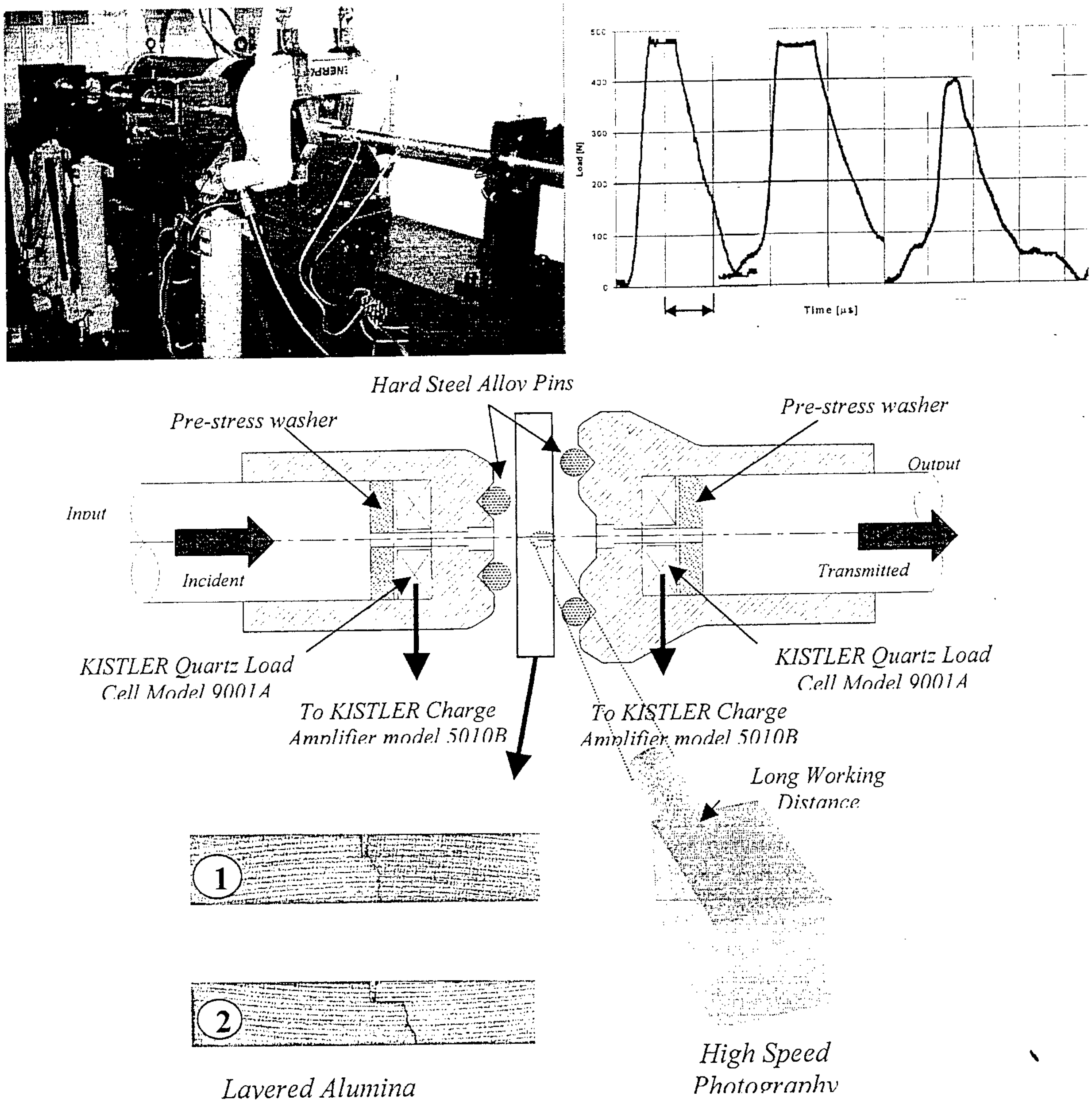


Figure 6: Photograph of designed and manufactured kolsky bar (top left); load histories measured for multilayered ceramic samples (top right); set-up for dynamic fracture experiments with high-speed photography (bottom).

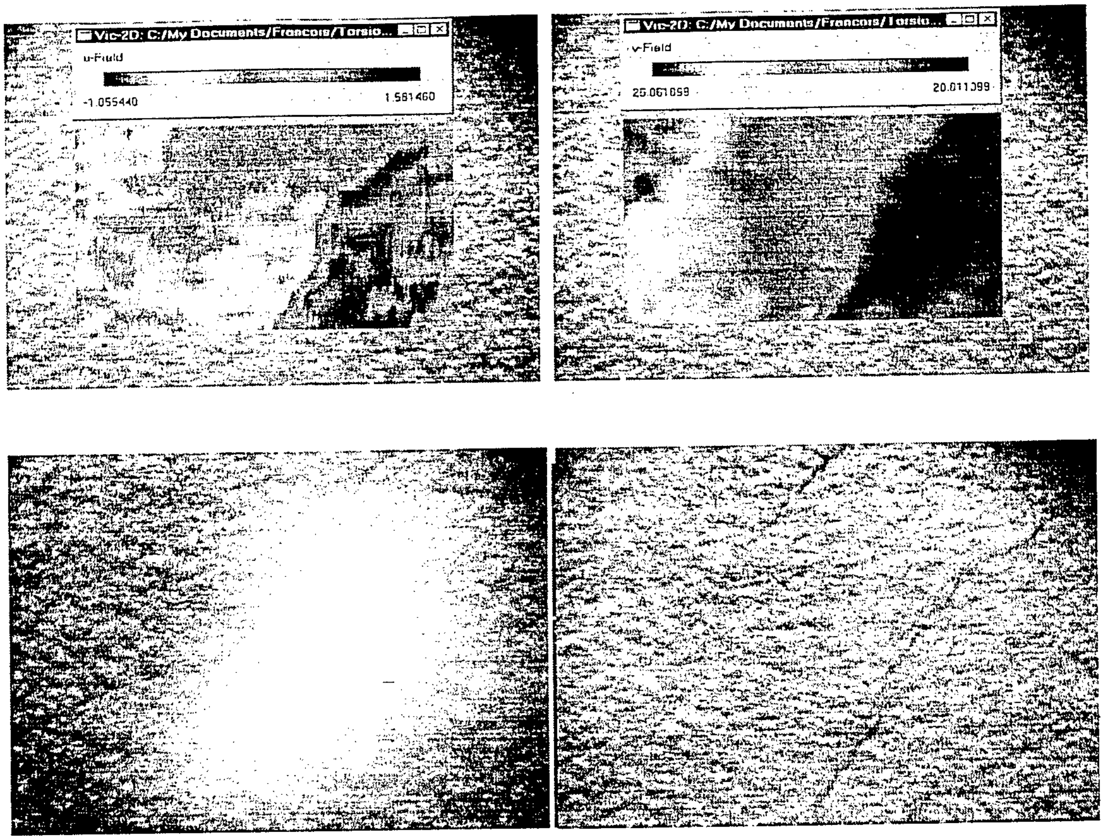


Figure 7: Contours of horizontal and vertical displacement fields as obtained by image correlation of speckle patterns on sample surface.

The Kolsky bar was also used to conduct dynamic fracture studies of ceramics, see Fig. 6b. In these experiments, real time incident and transmitted loads were measured with quartz crystals and high frequency amplifiers (Kistler C78497). Crack tip deformation was identified employing high-speed photography (Cordin Model 220-8 Camera system and Model K2 long distance microscope) and a speckle cross-correlation technique. The correlation was performed using the software VIC-2D 2.0 (Correlated Solutions, 1998). Excellent resolution was found when the speckle size and illumination conditions were properly chosen. Fig. 7 shows displacement contours in which displacement jumps, due to the presence of microcracks, are clearly observed even before the microcracks are visible on the surface of the sample. The experiments showed the fracture toughness of the layered alumina ceramic is not rate dependent and that the failure mode remains the same as in quasi-static fracture.

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Transitions:

Planned ( )   Occurred in FY (2000)

Customer	Result	Application
Geroge Gazonas, Army Research Laboratory, Aberdeen Proving Ground, Maryland 21005-5066 TE: 410-2784616 e-mail: gazonas@arl.army.mil	Provide a new code for the prediction of material microcracking and pulverization when subjected to dynamic loads. A multiple-plane microcracking model and a continuum granular model were integrated to the software LS-Dyna	The customer is interested in having software for design of multilayered armor utilizing advanced ceramics and ceramic composites.

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Customer	Result	Application
Jerry LaSalvia, Army Research Laboratory, Aberdeen Proving Ground, Maryland 21005-5069 TE: 410-3060745 e-mail: jlasalvi@arl.army.mil	A novel dynamic fracture test for the study of nanostructured materials was developed using a modified Kolsky bar apparatus.	The customer will used the developed set up to screen fracture resistance of materials under well-defined dynamic loading conditions.

New discoveries, inventions or patents: None

Honor and Awards: NSF-Career, 1996; ONR-YIP, 1997; ASME service award, 1997, 2001, Fellow of the American Academy of Mechanics, 2001.