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14. ABSTRACT

The objective of this DURIP project was to acquire a new high-performance digital imaging system for visualization and quantitative characterization of high-speed dynamic fracture in advanced composite materials and flow instabilities in nanomanufacturing processes. Full-field dynamic stress analysis of fracture required high spatial resolution while ballistic processes needed ultrahigh-speed imaging. Observations of jet motion and instabilities in nanofiber manufacturing required flexible frame rate and long time (high frame number) videography. As a result of thorough market search, a system of three cameras was selected and acquired, including ultrahigh-spatial resolution Model 550-24 rotating mirror CCD camera by Cordin, ultrahigh-speed Model 214-8 image-intensified gated CCD camera by Cordin, and flexible, ultrahigh-frame number HG-100K color CMOS camera by Redlake. The cameras have overlapping resolution, recording rate/length, and sensitivity performance characteristics. This unique, state-of-the-art ultrahigh-resolution/speed imaging system will be used for quantitative experimental characterization of impact fracture and ballistic performance of novel advanced laminated composites with nanofiber-reinforced ply interfaces and for observation of electrohydrodynamic jet instabilities in electrospinning process.

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EXECUTIVE SUMMARY

High-speed imaging is required for observation and analysis of fast dynamic processes, such as impact fracture and ballistic performance of advanced materials, dynamic deformation and instability development in structures, or hydrodynamic instabilities in jets. These dynamic processes occur at different time scales and their analysis requires imaging systems with different frame rates, spatial resolutions and magnifications, and different frame number capabilities.

The objective of this DURIP project was to acquire a new ultrahigh-performance digital imaging system for visualization and quantitative characterization of high-speed dynamic fracture in advanced composite materials and flow instabilities in nanomanufacturing processes. Full-field dynamic stress analysis of fracture required high spatial resolution while ballistic processes needed ultrahigh-speed imaging. Observations of jet motion and instabilities in nanofiber manufacturing by electrospinning required flexible frame rate and long time (high frame number) videography. As a result of a thorough market search, it was concluded that no single camera was capable of satisfying these conflicting requirements. A system of three cameras was selected and acquired. The system included an ultrahigh-spatial resolution Model 550-24 rotating mirror CCD camera by Cordin, an ultrahigh-speed Model 214-8 image-intensified gated CCD camera by Cordin, and a flexible, ultrahigh-frame number HG-100K color CMOS camera by Redlake. These cameras have overlapping resolution, recording rate/length, and sensitivity performance characteristics. Together, they represent a unique, state-of-the-art ultrahigh resolution/speed imaging system for quantitative observation and analysis of dynamic processes.

This system will be used in multiple research projects of relevance to DoD. These include time-resolved quantitative characterization of impact-induced fracture and ballistic penetration of novel lightweight polymer composites with interfaces nanoreinforced by continuous nanofibers. This new class of nanoengineered structural materials currently under development at UNL showed remarkable improvements in static and fatigue fracture resilience, at a negligible increase of weight. A recently demonstrated delay in the initiation of impact fracture holds high promise for ballistic applications. Quantitative dynamic characterization, modeling, and optimization of these materials will be performed with the help from the newly acquired experimental system. The system will also be used for observation and time-resolved characterization of instabilities in the electrospinning process used to produce aligned high-performance and functional continuous nanofibers for the next generation structural supernanocomposites. This will lead to the development of new integrated nanomanufacturing technologies for economic nanofiber and nanocomposite fabrication. Furthermore, the imaging system will be used for characterization of dynamic failure and friction in armor ceramics.

As a result of this project, significant enhancement was achieved in UNL's research and educational infrastructure on advanced nanomaterials and nanomanufacturing. Multiple current and pending projects will benefit from the new imaging system. Numerous graduate students and postdoctoral researchers in Nebraska will gain opportunity to study and characterize a broad variety of ultra high speed processes of relevance to DoD. These researchers will be available for employment by the DoD and the private sector. Due to the universal nature of the proposed equipment, the new imaging system will also establish broad new research capabilities beneficial to a variety of future DoD projects by the researchers from Nebraska.

1. Statement of the Objective

High-speed imaging is used for observation and analysis of fast dynamic processes. Typical processes of relevance to DoD and PIs research include dynamic impact fracture and ballistic performance of advanced materials, dynamic deformation and instability development in structures, or hydrodynamic instabilities in jets. These dynamic processes occur at different time scales and their analysis requires imaging with different frame rates, spatial resolutions and magnifications, and different frame numbers (recording durations). The objective of this DURIP project was to acquire a new high-performance digital imaging system for visualization and quantitative characterization of high-speed dynamic fracture in advanced composite materials and flow instabilities in nanofiber manufacturing processes.

2. Equipment Selected and Purchased

The dynamic processes above require imaging systems with different sets of capabilities. Full-field dynamic stress analysis of fracture requires ultrahigh-spatial resolution imaging. Ballistic processes in advanced composites require ultrahigh-speed imaging. Observations of jet motion and instabilities in nanofiber manufacturing by electrospinning require flexible frame rate and long duration (high frame number) microvideography. As a result of a thorough market search, it was concluded that no single camera was capable of satisfying these conflicting requirements.

A system of three cameras was selected and acquired. The system included an ultrahigh-spatial resolution Model 550-24 rotating mirror CCD camera by Cordin, an ultrahigh-speed Model 214-8 image-intensified gated CCD camera by Cordin, and a flexible, ultrahigh-frame number HG-100K color CMOS camera by Redlake. These cameras have overlapping resolution, recording rate/length, and sensitivity performance characteristics. Together, they represent a unique, state-of-the-art ultra-high resolution/speed imaging system for quantitative observation and analysis of dynamic processes. A brief description of individual cameras and their unique capabilities is given below.

Cordin Model 550 High-Speed Digital Rotating Mirror Camera

High spatial resolution digital imaging at 1 million or more frames per second is needed for the analysis of many dynamic processes. The latter frame rate corresponds to the typical time scale and sampling rate of several existing dynamic material testing techniques that can be greatly improved with the addition of a high-resolution high-speed digital imaging system. A careful market research has revealed that currently only rotating mirror CCD camera systems have the capability for high-resolution imaging at 1 million or more frames per second. A selected Model 550-24 High Resolution Rotating Mirror CCD Camera System by Cordin includes 24 cameras synchronized for imaging at 1.5 million frames per second. Rotating mirror technology in which metallic substrate mirrors are driven at speeds near their exploding point, allows to control mirror speed and electronic sensor camera interface for proper image capture and sequencing and recording a large number of electronic image data files arriving at time ranges down to the microsecond or even sub microsecond level. The Cordin 500 series rotating mirror electronic sensor cameras deliver undivided light from the object or event being studied to a series of electronic sensor cameras and memory storage circuits. The rotating mirror and optics does the distribution of light to different sensors in sequence and also determines the exposure time and recording rate. The interframe or picture capture rate is determined by the speed of the rotating mirror. Electronic sensors are more sensitive than high speed film and there is no beam splitting or light division so pictures can be taken down to the sub microsecond exposure level that are far superior in resolution and dynamic range to images recorded with an MCP intensifier. It should be noted, however, that for exposure times below hundreds of nanoseconds are not possible with this camera. Cordin is the only supplier of rotating mirror electronic sensor cameras with such high performance parameters.

Special characteristics of the Cordin Model 550 rotating mirror CCD camera together with special software make it possible to get a pre triggering function. This feature is especially useful in those circumstances where the operator wants to see a number of frames of the subject under investigation prior to the time when a trigger signal can be easily obtained. Unlike with film cameras the Model 550 will be recording light from the event on its sequence of frames over and over with the CCD sensor cleared just before each new frame is to be recorded. This means that in the moments before a sequence is recorded there are images on all of the sensors of the camera that are then either reset to prepare a given frame for a new picture or transferred to electronic processing and storage for later retrieval. Software then allows a pre- selected number of these frames to be saved that occurred prior to the actual event trigger. When the event under study occurs and a trigger to record is given to the camera the pre specified number of frames recorded prior to the trigger instant are then saved rather than deleted and processes as part of the frame sequence of the event.

The Model 550 camera offers also an extended interframe time feature, the camera can be synchronized with a laser and the camera also has alignment software that allows subpixel alignment of frames for easier analysis. This is the only camera in the world that offers all these unique features and also high-speed exposure times with excellent picture quality and 10 bit actual dynamic range.

In summary the Model 550 Digital Rotating Mirror Camera System has 24 high resolution (1K x 1K) individual separate frames with no MCP intensifier to limit resolution and dynamic range. The light is not split each frame receives the full light. The pre triggering function offers availability of frames before the camera was actually triggered. These features are all available only in the Cordin Rotating Mirror Digital Camera systems and in no other high-speed photography system.

Cordin Model 214-8 Image-Intensified Gated CCD Camera System.

Our imaging needs further required ultrahigh-speed imaging at 10 million or more frames per second, which is needed for our effort to develop new ballistic impact experiments. A thorough market research has revealed that Cordin Model 214-8 Image-Intensified Gated CCD Camera System is capable of imaging at 10 million frames per second. In this type of cameras, an optical system divides the image across multiple channels, thus yielding ultimate temporal resolution, at the expense of some loss in spatial resolution and sensitivity. Individual channels are activated in sequence to give a series of images separated by very short time intervals. The Model 214-8 records 8 frames with the minimum interframe/exposure time of 25 nanoseconds. The above ultrahigh speed and ultrasmall interframe time are ideal for the planned ballistic experiments.

Negotiations with Cordin allowed us to purchase both cameras described above along with the operating software, PCs, light sources (one digital delay/pulse generator and four PL250DR flash lamp systems), and camera stands/carts as a single package.

Redlake Model HG-100K High-Speed Color CMOS Camera

A digital camera system capable of making high-resolution movies of moving objects at speeds above 1000 frames per second is needed for visualization and motion analysis of the electro-spinning processes currently under study at UNL. In addition to the high speed, a resolution of 1K 1K or better, a capability of 1000 or more frames in a single movie record, and software supporting video making and two- and three-dimensional particle velocity and trajectory analyses are necessary. We found through market research that MotionXtra HG-100K High-Speed Color CMOS Camera produced by Redlake, the leading CMOS imaging system manufacturer, had the required specifications (1.5Kx1K resolution at 1000 frames per second and number of single-shot frames expandable with memory size). The camera was supported by the most comprehensive line of motion analysis software developed for the Redlake Motion series of digital cameras. We also found that the Redlake digital imaging products were sold only through their regional representatives/distributors. The sales representative for the region including Nebraska was Imaging Dynamics in Plymouth, MI. Our negotiation with Imaging Dynamics resulted in a significant academic discount such that we could purchase a HG-100K Color CMOS Imager with 4GB memory (sufficient for 2400 single-shot frames), special lens package of our need (a 60 mm f/2.8D macro lens, a 50 mm f/0.95 high-speed lens, and a 16-160 mm zoom lens), a set of four Arrilite Halogen 120VAC lamps, a Variable Friction Magic Arm Camera Set, and installation and training. For all the digital imaging systems we have looked into, this was the only one that satisfied our current needs, had the cost within the available budget, and could be easily upgraded (with more memory) for other high-speed motion analyses. A control computer for this camera was acquired separately.

3. Research Projects to Use The New Equipment

The following current and pending research projects will critically benefit from the new high-speed imaging capabilities.

Novel Advanced Composites for Lightweight Ballistic Armor Applications (PIs - Y. Dzenis, R. Feng)

The described high-performance imaging system will substantially enhance our current research on "Development and Characterization of Novel Lightweight Nano-Micro Composites with Superior Ballistic Protection Capabilities". The following is a description of the main thrust of the proposed research and the new important research components that will be developed using the requested high speed imaging system.

Background. Advanced polymer composites are commonly utilized in applications in the form of laminates with plies of unidirectional fiber composites. Combination of plies with fibers oriented in different directions (lamination) is used to overcome weakness of unidirectional composites in transverse-to-fiber direction. Delamination is the usual failure mode for laminates subjected to impact and fatigue loadings that are typical for military applications. Improvement of ballistic protection characteristics of multifunctional structural components such as body or vehicle armor requires advanced polymer matrix composites with superior resistance to impact-induced delamination/failure. Previous attempts to improve delamination resistance lead to substantial increases in weight of composite structures, taking away from the major advantage of advanced polymer composites-their lightweight and high specific properties.

Approach. A new approach to improve delamination resistance of advanced composites has been recently proposed at UNL (first U.S. patent awarded in 2001; other patents pending). Strong continuous polymer nanofibers are used as nanoreinforcement at the interface between the plies. Nanofibers are able to reinforce laminate interfaces without substantial reduction of in-plane properties. Each laminate interface can be reinforced by nanofibers without substantial increase in weight. The nanofiber mat is attached to one side of a conventional preimpregnated unidirectional lamina (prepreg) prior to lamination. The nanofibers are flexible and conform to the shape and distribution of the primary reinforcing fibers at the interface, as the resin flows. Some of the nanofibers orient perpendicularly to the interlaminar plane so that they contribute to both shear and peel stress resistance. Nanofiber reinforcement both arrest matrix crack propagation and suppress crack induced delamination. Delamination at edges is reduced by reduction of the mismatch of properties and by the elimination of the singular plane between the plies.

Recent Results. In the last several years, large improvements have been demonstrated in static and fatigue interlaminar fracture toughness of the new composites. Hundreds of percent increases in Mode I (peel) and Mode II (shear) static fracture toughness and orders of magnitude reductions in fatigue crack propagation rates have been recorded with only 0.5-1% weight increase. Attempts have been also made to evaluate dynamic fracture toughness under impact loadings. The latter is critical for potential ballistic protection applications. However, limited by the dynamic testing instruments available at UNL, it was only possible to demonstrate the delay in dynamic fracture initiation as a consequence of nanofiber reinforcement.

Need for High Speed Imaging Equipment. The full proof of concept of impact-resilient toughening requires comprehensive quantitative evaluation of crack initiation and propagation. To this end, we need to improve substantially the dynamic testing facilities, develop new techniques for precise time-resolved measurements, conduct in-depth experimental and theoretical studies on the micro and nano mechanisms governing dynamic fracture in these new composites, and use the results to optimize the materials structure and nanomanufacturing processes. These closely integrated issues will be addressed with the help from the new equipment.

Proposed Use of Equipment in Impact Experiments. Loading configuration currently used in the work on dynamic fracture testing of composite interface includes a cylindrical steel projectile launched by a gas gun impacting a long cylindrical bar of the same material and placed between the projectile and the specimen. It serves as an elastic wave-guide both for delivering the impact load and for probing the dynamic loading at the bar-specimen interface through the strain gauge sensor on the bar. Depending on whether the bar is centered with the interface or located on one side of the specimen, the loading condition ahead of the pre-crack, can be mode I (peel) or predominantly mode II (shear). The loading duration is typically ~30 us. The commercial crack propagation gauges tried so far have turned out to be inadequate for capturing the needed details of crack propagation process. To overcome this difficulty, the PIs propose to use the high-speed photographic instrument during the experiments to obtain time-resolved visualization of cracking process and measurements of mode I and II crack propagation speeds in addition to the strain gauge measurement of loading history. An electronic delay/time unit will be triggered as the incident wave passes the strain gauge. The flash light and camera will then be activated by the delay/time unit in a designed time sequence to achieve synchronization. Both diffused and painted specimen surfaces will be tried to find a surface treatment optimized for the high-speed photography. In conjunction with modeling and simulation, the measured cracking speeds and far-field loading history will allow us to determine the mode-I and mode-II dynamic fracture toughness parameters of the composites. Also, because the digital photographic data from the camera are actually time-resolved speckle-grams, we will in future work perform speckle interferometry analysis to obtain full-field measurements. Based on experimental observations of fracture mechanisms and progression, models of hierarchical fracture at nano- and micro-scales will be developed.

Proposed Hopkinson Bar-Based Experiments. A modified split Hopkinson torsion bar device is available at UNL. In addition to the usual torsion driver, the apparatus has an axial loading unit that can generate dynamic tensile loading. Dynamic mode-I and mode-II fracture experiments can be developed based on this device. The results will provide the experimental data for dynamic loading in the time scale of hundreds of microseconds. Such measurements complement those from the impact experiments described above, in which the dynamic loading is in the time scale of tens of microseconds.

The mode-I test will use a dynamic tensile pulse of ~400 us with a rise time less than 100 us. The specimen will have a rectangular cross section and a Teflon pre-crack embedded on one side. The specimen assembly will then be sandwiched and glued between the input and output bars. The mode-II test uses dynamic torsional pulse of ~500 us. The specimen cross section will have two equal-sized islands of sample material. They will be located axisymmetrically and in such a way that the fiber direction is normal to the edge facing the shearing motion driven by the applied dynamic torsion. The rest of the cross section will be covered with a thin Teflon sheet. Pure mode-II loading can be achieved and the orientation mismatch is expected to be small during the period of crack initiation and early stage of crack propagation. Furthermore, combined dynamic compression and torsion loading can be generated with this Hopkinson bar device. Hence, the effects of closed crack surface friction on mode-II toughness can also be examined. In either mode I or mode II experiment, both the far-field motion and remote load will be determined from the stress wave profiles in the bars, which are measured with the strain gauges on the bars. Time-resolved speckle interferometry will be used in the specimen gauge section to measure the evolutions of local strain fields and the histories of crack propagation.

Ballistic Impact Experiments with Time-Resolved Visualization. A series of rod-to-plate ballistic impact experiments will be also conducted to evaluate the ballistic performance of the intact composite plates with and without nanoengineered interface. The projectile will be launched by a gas gun. The projectile velocity right before the impact will be measured using a line-laser occlusive sensor. High-speed photography will be used to obtain time-resolved visualization of the penetration event. The photography process will be triggered by the signal from the impact velocity detector.

Nanomanufacturing of High-Performance Nanofibers for Next Generation Supernanocomposites (PI - Y. Dzenis)

The described high-performance imaging system will also tremendously enhance our research on "Novel Continuous Carbon Nanofibers for the Next Generation Lightweight Structural Nanocomposites". The following is a description of the main thrust of this research and the new important research components that will be developed using the requested high speed imaging system.

Background. A strategic goal of the U.S. Air Force is to be able to deliver munitions to targets anywhere around the globe from the United States in 55 minutes. This will require very high speeds and novel, very lightweight and temperature resistant materials. Nanoscale materials technology has been recognized as critical for the defense needs in the 21st century. Nanocomposites are promising emerging materials for structural and functional applications due to unique properties of their nanoscale constituents. However, the currently available nanocomposites based mostly on nanoparticles lack the high strength and stiffness required for structural applications. The advent of high-performance fibers and their introduction to advanced composites produced a revolution in the area of lightweight structural materials in the last decades. Further dramatic improvement of fiber properties is expected with the reduction of their diameters into the nanometer range. Superstrong nanofibers can lead to new, revolutionary levels of performance of composites. A spectacular example of the emerging nanofibrous material is carbon nanotubes (CNTs). CNTs have been recently shown to possess extreme mechanical and physical properties. However, applications of CNTs in composites are hindered by the difficulties with their processing, alignment, and achievement of high volume fractions in composites.

Approach. In this project, a new class of high-performance reinforcement, i.e. continuous carbon nanofibers suitable for applications in structural composites will be developed and demonstrated. A new nanomanufacturing technology based on the electrospinning technology will be further advanced and utilized. Continuous carbon nanofibers will be produced from polyacrylonitrile (PAN) precursors. The nanofibers will be characterized by a variety of analytical and thermomechanical techniques. Effects of processing and carbonization parameters on nanofiber geometry, molecular structure, and properties will be studied. The project will build upon the recent pioneering experimental and theoretical work on electrospinning by the PI. In particular, newly developed methods of controlled nanofiber deposition and alignment (patents pending) will be utilized to produce oriented nanofiber assemblies (sheets and yarns) with high volume fractions of nanofibers. The alignment of nanofibers in these assemblies will enable their stretching during the thermomechanical treatments. This will, in turn, produce continuous nanofibers with extreme orientation and thermomechanical properties.

Use of High-Speed Imaging System. Nanomanufacturing component of the project above will critically benefit from the proposed equipment. Fabrication of high-performance nanofibers relies on our ability to control the electrospinning process. It has been recently shown that the electrospinning process is driven by electrohydrodynamic instabilities. In particular, 'bending' instabilities appear to be most prevalent, but 'splaying' instabilities are also often observed. A substantial effort on understanding and modeling of these instabilities is currently under way by the PI. Recently, several rigorous electrohydrodynamic models of all major subprocesses of the electrospinning process have been developed, i.e. jet initiation, steady state spinning, rectilinear axisymmetric and nonaxisymmetric jet instabilities, and 'bending' instabilities. In a model of steady state electrospinning, the motion of a charged weakly conductive viscous jet in the electric field was considered. A general three-dimensional model included electric forces, pondermotive forces, viscous forces, and surface tension. It was found that the stable jet exists in the radius range less than a critical value defined by the dielectric properties and surface tension of the fluid. The process of jet initiation was analyzed as an electrical break-up of a charged meniscus. The surface shape was defined by the balance of the hydrostatic pressure, surface tension, and electric forces resulting from interactions of the electric field with free charges and dielectric polarization of the fluid. An asymptotic solution of this complex coupled problem was obtained analytically. Conditions for jet initiation were analyzed. These mathematical models substantially improve our understanding of this complicated process.

The focus of the current research at UNL is on the instabilities and their effects on resulting nanofiber orientation and deposition on substrates. Direct nanofiber deposition onto various substrates is being studied. The accomplishments to date include development of a new numerical model of jet motion and its application for the development of methods of nanofiber alignment (patents pending). The model explicitly incorporates jet instabilities. The model was already used to analyze the effect of field and other parameters on nanofiber orientation on the substrate. High-speed observation capability will allow us to comprehensively test and further improve these models. Partial validation was performed by comparisons with experimental observations of nanofiber distributions on the substrate. However, better, quantitative model validation should be based on direct time-resolved observation of instability developments and quantitative measure their time evolution. Such an observation requires high-speed videography. The long recording time available with the new system, coupled with the ultrahigh spatial/temporal resolution will allow us to see thinner jet segments and image temporal evolutions of consecutive hierarchical jet instabilities. Their captured time evolution will allow us to measure the intervals between the instability events and to compare them with the theoretical predictions. Several other new techniques of nanofiber alignment and controlled deposition currently under development at UNL will greatly benefit from such direct observations. New experimental capability and data will provide invaluable information for further model development and validation and for the development of controlled integrated nanomanufacturing processes. Of special interest to the projects described above will be the observations of interactions of jet instabilities with various substrates used in direct deposition of nanofibers onto composite prepregs.

Impact. This basic project will produce a body of knowledge for the development of a new family of advanced nanoreinforcing materials, i.e. high-performance continuous nanofibers for the next generation lightweight structural nanocomposites. These nanofibers will be produced at a reasonable cost compared to other high-performance nanomaterials, such as carbon nanotubes. Nanofiber continuity will also dramatically reduce the cost of their handling and processing into nanocomposites. Utilization of newly developed methods of nanofiber alignment will make possible fabrication of nanofibers with superhigh properties by applying appropriate thermomechanical treatments under tension. In addition, these will enable fabrication of nanocomposites with high volume fractions and complex nanoreinforcement architectures. Controlled fabrication of complex layered and graded nanofiber assemblies and membranes will be enabled. The resulting continuous nanofibers, assemblies, and nanocomposites will be usable in many DoD and civilian applications.

Dynamic Characterization of Armor Ceramics (PI - R. Feng)

Research on "Polycrystal Modeling of Ceramics Subjected to High Strain Rates and Pressures" will also critically benefit from the proposed equipment. The objectives of the research work are to develop analytical and computational methods for analyzing impact-loaded engineering ceramics taking into account the effects of polycrystalline microstructures, elastic anisotropy of the crystals, and material damages due to microplasticity and microfracture. Realistic three-dimensional polycrystalline structure model based on Voronoi tessellation and material models for nonlinear anisotropic crystal elasticity, intragranular microplasticity and intergranular microfracture have been developed and implemented into the ABAQUS codes. Model simulations have been conducted to study the micromechanical nature of inelastic deformation and failure in ceramics deformed under high confining stresses.

So far, the model parameters have been well calibrated with the data from the plate-impact uniaxial-strain compression experiments on SiC. However, the loading condition varies dramatically during a real ballistic impact. In particular, model validation for various confinement conditions is import to establishing the usefulness of the model prediction for armor applications. The uniaxial-stress compression condition in the split-Hopkinson pressure bar experiment is a good contrast to the uniaxial-strain condition in the plate impact experiment. A ceramic specimen is expected to fail under a sufficiently large unconfined dynamic compression. A photographic recording of the geometric evolution and surface cracking of the specimen during the failure process is a very good overall measure of the failure process. Model simulations to match such experimental data will validate both the constitutive description and microstructural model for the material. Other dynamic loading conditions with intermediate confinement may be achieved in the combined dynamic compression-shear experiment developed recently by the PI using the Hopkinson torsion bar technique.

If the high-speed photography instrument is acquired, new experiments will be conducted on SiC and other ceramics using the Hopkinson pressure and torsion bar devices available in Feng's laboratory. With the pressure bar setup, a series of specimens will be tested under various loading conditions to induce different degrees of damage in the material. During each experiment, synchronized sequential pictures of the specimen will be taken along with the usual strain gauge measurements. A corresponding model simulation will then be carried out using the measured loading condition. The computed specimen response, deformation and surface failure evolution will be compared with the measurements. The validation for the model prediction of frictional resistance and shear dilatancy during damage evolutions under different levels of confinement will be based on a series of combined pressure-shear experiments using the modified torsion bar setup. The specimens will have pre-fractured surfaces matched in conformal engagement. During each experiment, synchronized sequential pictures of the specimen surface (sputtered with paint) will be taken. The combination of time-resolved strain gauge measurements of the stress waves in the bars and photographic measurements at the specimen interface will allow us to determine when, how and under what condition frictional sliding, interfacial shear dilatancy and off-interface cracking start and evolve. Since the levels of compression and shear can be independently controlled and compressive stress as high as several GPa can be achieved in such an experiment, the results will be very useful for validating the model performance under various confinement conditions and for optimizing the model parameters. In summary, the results of these new experimental efforts based on the proposed high-speed imaging system are expected to lead to a well-contested material model for use in the design and optimization of the armor structures involving ceramics.

Intelligent NDE of Advanced Composite Joints (PI - Y. Dzenis)

Research on "Fatigue Fracture Analysis and Development of Fundamentals of Predictive NDE of Adhesive Composite Joints" will also benefit from the new equipment. The objective of the research is a detailed fatigue analysis of fatigue damage and fracture in adhesive composite joints and development of fundamentals for predictive nondestructive evaluation of their fatigue life. Adhesive joint technology has been recently recognized as critical for the development of automated low-cost fabrication processes for large, highly integrated defense structures. This manufacturing technique significantly reduces the high-cost hand-assembly labor steps in fabricating composite structures. This technology is also critical to the repair of damaged metallic and composite structures and maintenance of the ageing military hardware. Lightweight polymer composite patches can be used to repair major damage by replacing or supplementing the lost load path. Advanced composites are capable of minimizing balance and clearance problems on control surfaces, can be readily formed to complex contours, and can minimize undesirable stiffness increases by tailoring reinforcement to suit the loading configuration. One of the major problems impeding wider use of adhesive composite joints is poor understanding of their fatigue behavior and lack of reliable methods of joint certification for durability.

The base experimental information is being collected from the mode I, II, and mixed mode fracture tests on joints and from ultrasonic experiments. Fracture mechanisms in these tests are analyzed using a recently developed AE analysis method. The results are compared with the on-line video fractography and a host of state-of-the-art high-resolution ultrasonic NDE methods. A regular CCD camera is used in the on-line observations. This research can be substantially enhanced with a high-speed data on crack increments in joints and resulting ultrasonic vibrations. In particular, localized vibrations caused by the rapid release of the elastic energy during the crack increment may be captured and compared with the experimental acoustic emission (AE) observations and modeling. These comparisons can lead to better understanding and detection of various fracture micromechanisms in joints. This can lead, in turn, to better predictive models of fatigue fracture and life.

Development of Full-Field Dynamic Measurement Methods (PI - R. Feng)

The proposed high-speed imaging system will also provide the necessary equipment for doing full-field measurements in PIs planed future work on development and characterization of nanoengineered composites with superior properties for ballistic protection applications. Both the speckle interferometry and the coherent gradient sensing (CGS) based on Moiré deflectometry will be considered. A cylindrical projectile launched by a gas gun will impact the specimen. Depending on whether the symmetric or asymmetric impact is used, the loading condition ahead of the pre-crack can be mode I or predominantly mode II. The traversal time of the impact-induced stress wave in the projectile gives the duration of the impact loading (typically ~30 us). A line-laser occlusive detector will be used to measure the projectile velocity right before impact. The detector output will trigger a time delay unit, which correlates the activations of light source and high-speed camera according to a designed time schedule.

Time-resolved speckle-interferometric measurements will be related to the in-plane strain field. The specimen surface will be diffused or pained. The surface, lighting and magnification will be such that the propagating crack is also visible in the digital pictures permitting the determination of crack propagation speed. A high-power continuous laser acquired from other source will be used for time-resolved CGS technique. The specimen surface in this case will be flat and reflective. During the dynamic cracking process, there will be out-of-plane surface displacement due to the Poisson's effect. When the reflection of the collimated coherent light from the deformed surface passes through two high-density Ronchi rulings (gratings) properly separated and shifted, Moiré deflectometry patterns form. The pattern passing through +1 (or -1) order filter can be related to the out-of-plane component of the strain field. If the cracking is predominantly brittle, the results from either the speckle interferometry or CGS measurements can be used, in conjunction with elastic analysis, to determine the fracture toughness parameters. Each of the techniques has its limitation. The use of both, however, will improve the accuracy of the results. The experiments described above will be conducted on both the specimens with or without nanofiber interfaces and for various fiber orientation combinations between the upper and lower parts. Quantitative comparisons are also expected.

4. Interface with Existing Experimental Facilities

Extensive existing facilities of the PIs will be substantially augmented by the new ultrahigh speed imaging equipment. Prof. Dzenis' Laboratory on Advanced Materials and Nanomanufacturing will utilize the camera in electrospinning research, damage and fracture micromechanics, and nondestructive evaluation research. Prof. Feng's Laboratory for Dynamic Materials Characterization will use the camera to develop new diagnostics techniques for dynamic material testing (dynamic speckle and Moiré interferometries) and time-resolved visualization of damage and failure processes in materials under impulsive loading.

5. Impact of the Proposed Equipment on Research and Research-Related Education

The targeted research is highly innovative. The expected results include: know-how on manufacturing of composites with nanoreinforced interfaces and characterization of their microstructures and properties, new experimental data on the mechanical properties and fundamental delamination/ failure mechanisms in novel hierarchical composites, quantitative evaluation of improved delamination resistance of the new composites under impact loading, theoretical models for nanocomposite optimization and design, and ballistic data and models suitable for materials selection for ballistic protection applications.

The results of this research will provide a fundamental basis for the development of cost effective, impact resilient, microcrack arresting hybrid polymer composites with a high potential for military and commercial applications. Experimental and theoretical studies performed during the course of this project can form a basis for a new direction in composite science and technology, i.e. nanoreinforcement of interfaces. Equally, the development and use of unique dynamic fracture testing techniques will constitute a substantial pioneering effort in dynamic materials characterization and analysis. Strategic career goal of the PIs is to develop strong, competitive research programs in these areas.

The new equipment will substantially enhance our capability to conduct defense-related research in Nebraska. The equipment will be also used for educating graduate and undergraduate students and post-docs. The instruments will be used in the laboratory sessions of Experimental Mechanics and Mechanics of Composites courses. Undergraduate students will be involved through several undergraduate research programs available at UNL. The PIs currently employ as many as 12 Ph.D. and M.S. students and post-docs and support several undergraduate research students. These researchers will be available for competitive employment by the DoD and the private sector.

6. Selected Publications

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[7] Zhang, K. S., Zhang, D. Feng, R., and Wu, M. S. (2005). Microdamage in polycrystalline ceramics under dynamic compression and tension, J. Appl. Phys., 98, online publication 023505-1.

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[13] Xiang-Fa Wu, Yuris A. Dzenis. Electrohydrodynamic instability of thin conductive liquid films. Journal of Physics D: Applied Physics 2005, 38 (16): 2848-2850

[14] Xiang-Fa Wu, Yuris A. Dzenis. Elasticity of planar fiber networks. Journal of Applied Physics 2005, 98(9): Art. No. 093501 (9 pages)

[15] Xiang-Fa Wu, Yuris A. Dzenis. Droplet on a fiber: Geometrical shape and contact angle. Acta Mechanics (In Press)

[16] Xiang-Fa Wu, Yuris A. Dzenis, Kyle W. Strabala. Wrinkling of a charged elastic film on a viscous layer. Meccanica, in press

[17] Xiang-Fa Wu, Goutam Ghoshal, Mikhail Kartashov, Zuleyha Aslan, Joseph A. Turner, and Yuris A. Dzenis. Damage development and ultrasonic NDE of a cross-ply graphite-fiber/epoxy laminate under impulsive loading excited by Hopkinson pressure bar. Composites Science and Technology, in press

[18] Chiew, S.Y., Wen, Y., Leong, K.L., and Dzenis, Y., "The Role of Electrospinning in the Emerging Field of Nanomedicine", Current Pharmaceutical Design, special issue on Nanomedicine and Drug Delivery (invited review), in press

7. List of Participating Scientific Personnel

Principal Investigator: Y. Dzenis

Co-Principal Investigator: R. Feng

Graduate Students:

X. Ren (Ph.D.)

Y. Salkovskii (Ph.D.)

	L. Liu (Ph.D.)
	Y. Chen (Ph.D.)
Post-Doctoral Associate:	X. Wu