Army Research Laboratory

Special Workshop: Kolsky/Split Hopkinson Pressure Bar Testing of Ceramics

by James W. McCauley and George D. Quinn

ARL-SR-144 **September 2006**

NOTICES

Disclaimers

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Special Workshop: Kolsky/Split Hopkinson Pressure Bar Testing of Ceramics

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*National Institute of Standards and Technology, Gaithersburg, MD

14. ABSTRACT
A special workshop on Kolsky Bar/Split Hopkinson Pressure Bar Testing of Armor Ceramics was held in conjunction with the 29th International Conference and Exposition on Advanced Ceramics and Composites, Cocoa Beach, FL, on 27 January 2005. This special report is a collection of the pertinent information from that workshop.

15. SUBJECT TERMS
armor, ceramics, dynamic testing, standardization

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Contents

Foreword

Ceramics are effective armor materials, but laboratory scale tests that can correlate with ballistic armor performance have been elusive. Therefore, there is an urgent need to identify quasistatic and dynamic laboratory scale tests, or ways of interpreting current test data, for materials development, analytical modeling, and materials screening purposes, rather than going to full-blown ballistic tests early in the development of new materials. It is still not at all clear what combination of static and dynamic mechanical properties (figure of merit) control armor performance and how these properties are controlled/influenced by intrinsic (crystal structure, phase transitions, and single crystal elasticity) and extrinsic material characteristics (composition/phase, grain level sub-structure, and microstructure and processing defects).

Further development of armor ceramics would significantly benefit from valid Figures of Merit (FoM) and would certainly facilitate a systematic approach to optimization by processing and microstructure control.

$$FoM_{threat} = \text{fct (property 1, property 2, property n, …)}$$

This appears to be a three-step process (threat dependent):

- Quantify property – material characteristics relationships.
- Validate mechanical property measurements.
- Determine and validate FoM relationship to ballistic performance.

Limited past success in relating dynamic mechanical property measurements to ballistic performance may have been due to using the wrong or incomplete properties or the lack of appropriate standardized tests that lacked reproducibility. Armor ceramic performance can be simplified into two main stages: a dwell phase, where the projectile velocity is nominally zero at the ceramic front face, and a penetration phase. If the projectile is completely stopped at the front surface, this is referred to as "interface defeat." Appropriately configured dynamic compression strength measurements in a Kolsky Bar, also referred to as a Split Hopkinson Pressure Bar (SHPB), have recently been suggested as a very strong possibility for a ballistic performance screening test.[1] Work by James seemed to substantiate a correlation to ballistic performance.[2] In addition, Lundberg et al. suggested that the compressive yield strength modified by the amount of "dynamic plasticity" in armor ceramics correlates well to transitional

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[1]Pickup, I. M.; Barker, A. K. Damage Kinetics in Silicon Carbide. *Shock Compression of Condensed Matter* ***1997***; Schmidt, Dandekar, Forbes, Eds.; 513–516.

[2]James, B. J. Factors Affecting Ballistic Efficiency Tests and the Performance of Modern Armor Systems. *Presented at the European Fighting Vehicle Symposium*, Shrivenham, UK, May 1996.

velocities ("dwell").[3] The technique developed by Pickup and Barker may be a more simple way to predict the amount of dwell in ceramics being evaluated for armor.

Figures 1 and 2 illustrate the Pickup and Barker sample configuration and an illustrative stress/time plot for three SiC materials.

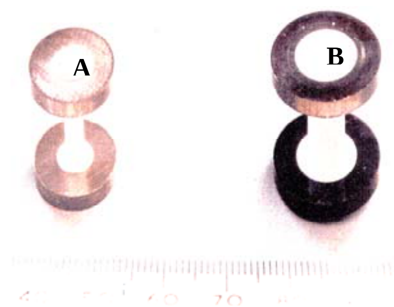

Figure 1. SHPB dumbbell shape specimens with axial confinement.

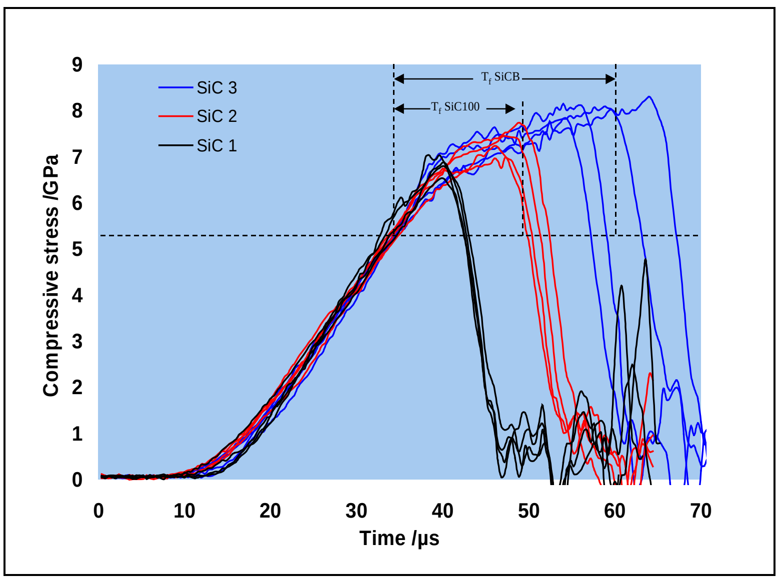

Figure 2. Stress history of SiC B (SiC 3), SiC 100 (SiC 2), and AME SiC (SiC 1).

The characteristic failure times, as reported by Pickup and Barker, are as follows: AME SiC = 12 μs; SiC 100 = 20 μs; and SiC B = 30 μs.

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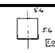
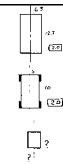
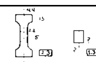
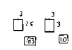
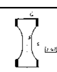
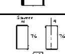
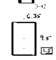
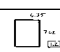
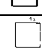
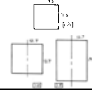
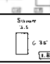
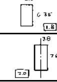
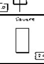
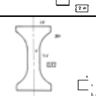
[3]Lundberg, P.; Renstrom, R.; Lundberg, B. Impact of Metallic Projectiles on Ceramic Targets: Transition Between Interface Defeat and Penetration. *International Journal of Impact Engineering* **2000**, *24*, 259–275.

The technical literature for SHPB/Kolsky testing of high performance ceramics has very contradictory information. Compression strengths for similar materials vary substantially between laboratories. Between-laboratory variability (reproducibility) may be as much as 50%. It is not clear how much of this is due to material variability, but it is reasonably certain that much of the variability is due to experimental errors or variations in the testing procedures. Table 1, from George D. Quinn of the National Institute of Standards and Technology (NIST), shows the enormous variability in SHPB specimen geometry and confinement. Figure 3 illustrates exploded views of the specimen geometries listed in the table.

Table 1. Compendium of SHPB sample geometries and confinement. Darker borders represent confinement (George D. Quinn, NIST).

Laboratory	Name	Year	Materials	σ_c (GPa)	n	ε (rate) (1/sec)	ε_f	Bar diameter	Pulse shaper?	Inserts?	Specimen	Camera	Strain gages	Complementary Quasi static data?
ARL	Weerasooriya	2004	SiC-N					25 mm 18 mm	Yes	WC (6% Co)		-	On specimen	-
SWI	Lankford	1981 1981 1989 1989 1989 1989 1998 1998 1998 1998 2004 2004	α - SiC Lucalox Al_2O_3 Compglass RBSN HPSN Pyroceram AD 995 Al_2O_3 JS I Al_2O_3 JS II Al_2O_3 AlN sint. SiC (α?) SiC- N	4. – 6.3 3.5 – 6.0 0.3 – 2.0 2. 0 4.0 – 4.5 2.0 3.5 – 9.0 9.0 6.5 3. – 6. 5. – 7. 4. – 9.	3 4 8 11	$1. \times 10^3$ $1. \times 10^3$ $1. \times 10^3$ $1. \times 10^3$ $3. \times 10^3$ $.5 – 5 \times 10^3$ $1. \times 10^3$ $1. \times 10^3$ $1. \times 10^3$ 5×10^3 5×10^3		?	No	Vascomax 350 (bar material)	 ← some confinement	(Yes, now)	On bars On specimen (according to Staehler, Predebon, Pletka, Subhash 1995)	Yes
Los Alamos	Gray Blumenthal	1989	B_4C / Al cermets 4 compositions	4.3 2.2 2.0 1.3		1 to 2×10^3		12.7 mm	?	WC		-	On specimen	Yes
JHU	Ramesh	2004 2004 2004 2004 2004	α-SiC GS 44 Si_3N_4 AD 995 Al_2O_3 α-sialon SiC-N	2.6 4.0 4.0 4.6 5.1 – 7.2	13 6 8 8 8	$.5 - 2.2 \times 10^3$ $.8 – 2.5 \times 10^3$ $.7 – 2.2 \times 10^3$ $.5 – 2.5 \times 10^3$ 100-500 MPa/μsec		7.1 mm 12.7 mm 7 mm	Yes Yes	WC (3% Co) and collars WC (3% Co) and collars		Yes, High speed	On bars	Yes
DRA - UK	Pickup Barker James	1997 2001	SiC (RB) SiC (sint) SiC – B? (PAD) $Al_2O_3 – 1$ $Al_2O_3 - 2$	6.7 7.3 8.1 4.1 6.1		0.9×10^3		16 mm	?	?		Yes	?	Yes
Cal. Tech.	Subhash Ravichandran	1993 1995	AlN	3.5 – 5.2		$.1 – 5 \times 10^3$		?	Yes	-		-	On bars	-
	W. Chen Ravichandran	1996 2000	AlN AlN	4 – 5	5	$.5 \times 10^3$		12.7 mm 19 mm	Yes Yes	WC WC		-	On bars	Yes
	W. Chen Ravichandran	1997	Macor glass ceramic	.44	5	-	.004	19 mm	Yes	WC		-	On bars and on specimen sleeve	Yes
Univ. Arizona	W. Chen	2003 2004	AD 995 Al_2O_3	2.7 4.3	-	$.3 \times 10^3$ $.3 - .4 \times 10^3$	.015 - .020	19 mm	Yes	WC		-	On bars	-
Univ. Arizona	Frew Forrestal	2002	Macor (Glass ceramic)	.55	5	$.17 \times 10^3$	.012	19 mm	Yes	No		-	On bars	-
Sandia	W. Chen	2001	Indiana Limestone	.10 - .13	9	$.1 - .3 \times 10^3$	-	19 mm	Yes	No		-	On bars	-
UC – San Diego	Sarva Nemet-Nasser	2001	Hot pressed SiC	4.2 – 7	10	$.25 – 1.2 \times 10^3$	~ .01	?	Yes	WC		-	On bars	Yes
UC – San Diego	Shih, Meyers, Nesterencko S. Chen	2000	Hot pressed SiC SiC - B	4.7 5.4	5 6	$.4 - .8 \times 10^3$ $.4 - .8 \times 10^3$		12.7 mm	Yes	SiC/Si_3N_4		-	On specimen	Yes
Georgia Tech	Keller Zhou	2003	4 grades of SHS TiB_2 / Al_2O_3	4.6 – 5.3	4 x 6 ea	$.4 \times 10^3$		19 mm	Yes	WC	? 	-	On specimen	-
NIST	Rhorer, Fields, Levine, Quinn	2005	AD 995 Al_2O_3	4.6 – 5.3		In progress		15 mm	Yes	WC		Yes, High speed	On specimen	-

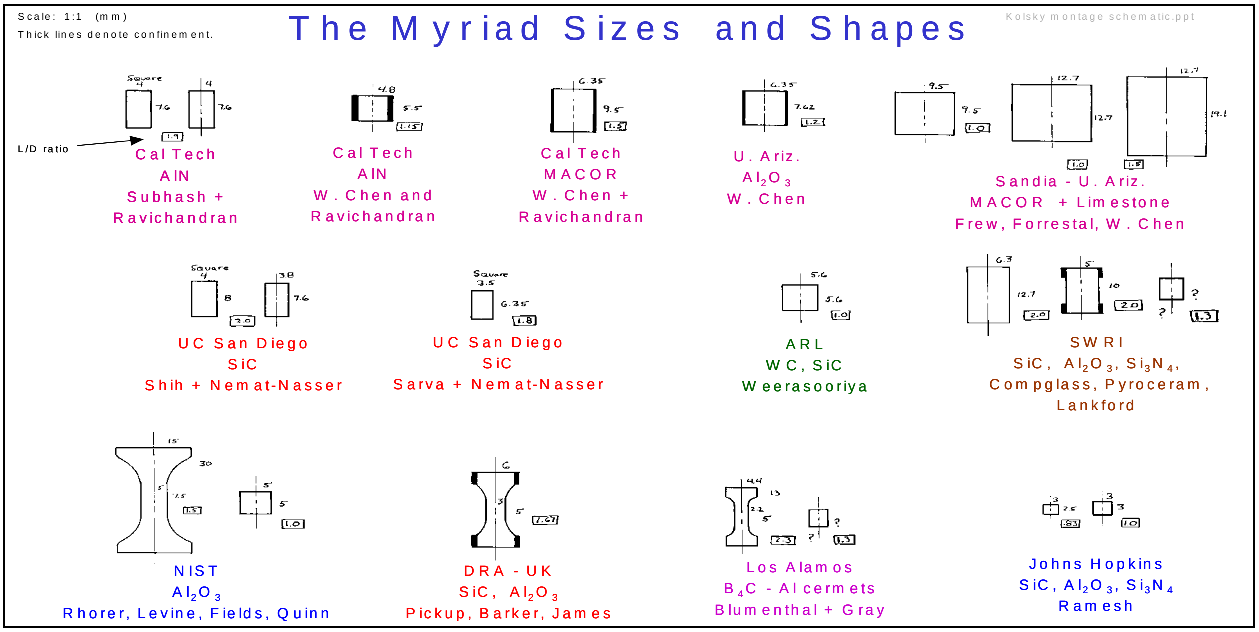


Figure 3. Exploded views of specimen geometry in the table (George D. Quinn, NIST).

An interlaboratory (round robin) test for ceramic materials could help solve many of these problems, but to the best of the author's knowledge there has never been a round robin exercise on an identical batch of ceramic material that quantified the between-laboratory precision using the current state of the SHPB/Kolsky testing procedures.

This workshop was convened to review the Pickup and Barker results and the state of the art and determine the consensus of the leaders of the SHPB/Kolsky technical community for such a round robin exercise.

A round robin could be crafted so as to allow each laboratory to test specimens according to their own preferred procedure, but also a few judiciously chosen common configurations such as a Pickup and Barker dumbbell specimen. In this manner, the current repeatability and reproducibility uncertainties (estimates of precision) could be quantified and also identify key parameters that should be controlled in SHPB/Kolsky testing. This work could pave the way for potential standardization. The ultimate goal would be to improve the state of the art of dynamic compression testing of ceramic materials so that the method could be properly assessed as a mechanical screening test for predicting armor ceramic performance.

This U.S. Army Research Laboratory (ARL) special report is a summary of presentations and discussions that occurred at a special workshop on Kolsky/Split Hopkinson Pressure Bar Testing of Ceramics held 27 January 2005 at the Holiday Inn, Cocoa Beach, FL, in conjunction with the American Ceramic Society 29th International Advanced Ceramics and Composites Conference at Cocoa Beach. The workshop was organized by James W. McCauley, ARL, Aberdeen, MD, and Mr. George D. Quinn, NIST, Gaithersburg, MD, with financial support from

Dr. Douglas Templeton, U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC).

Included in this report is the invitation letter that was sent to selected international experts in the field, summarized minutes of the meeting transcribed by George D. Quinn, and the following PowerPoint presentations given at the workshop:

- Kolsky/SHPB Ceramic Testing of Armor Ceramics, Cocoa Beach, FL, 27 January 2005 – George D. Quinn.
- SPECIAL WORKSHOP, Kolsky/Split Hopkinson Pressure Bar Testing of Armor Ceramics – James W. McCauley.
- Obtaining High-Rate Behavior of Ceramics Using Valid Hopkinson Bar Experiments – Some Personal Observations – Tusit Weerasooriya.
- High Rate Measurements on Ceramics – George D. Quinn and Richard Fields.

This work was supported by Dr. Douglas Templeton, U.S. Army TARDEC Project DC05; JONO 489W81.

Preface

A special workshop on Kolsky Bar/Split Hopkinson Pressure Bar Testing of Armor Ceramics was held in conjunction with the 29th International Conference and Exposition on Advanced Ceramics and Composites, Cocoa Beach, FL, on 27 January 2005. This special report is a collection of the pertinent information from that workshop.

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Invitation Letter to a Special Meeting on Kolsky/SHPB Testing of Ceramic Armor Materials

From: George Quinn <geoq@nist.gov>
Subject: Invitation to a special meeting on Kolsky/SHPB testing of
Ceramic Armor Materials
Cc: joyce.harris@nist.gov

From: Mr. George D. Quinn
National Institute of Standards and Technology

Dear Prospective Attendee,

Dr. James McCauley of the Army Research Laboratory, Dr. Douglas Templeton of the US Army TARDEC, and I would like to invite you to attend a special workshop on **Kolsky/Split Hopkinson Pressure Bar testing of ceramic armor materials**
on Thursday afternoon, January 27, 2005, 1:15 pm - 4:15 pm
in the Holiday Inn, 1300 North Atlantic Avenue, Cocoa Beach, 1300 North Atlantic Avenue, FL (+001 321-783 2271).

The meeting is open by invitation only.
We are **inviting experts such as yourself** who have experience with Kolsky/SHPB testing of ceramic armor materials to participate in this planning meeting.

We also are inviting key industrial and government representatives to attend as observers. There is no fee for this workshop.

The Holiday Inn is about 1 kilometer down the road south from the Double Tree hotel, the main site of the American Ceramic Society's 29th International Conference on Advanced Ceramics and Composites. That meeting has a focused session on "Topics in Ceramic Armor" with sixty papers on ceramic armor. It will conclude at noon on Thursday and the Kolsky/SHPB meeting will be held immediately after lunch on that same day.

The purpose of our meeting is to discuss recent developments and general aspects of Kolsky/SHPB testing of ceramics. What are the repeatability and reproducibility of data for ceramics? What are the advantages of the different specimen types? What is the most important information that can be acquired from such dynamic compression testing? Is Kolsky/SHPB testing a useful tool to help screen new candidate armor materials? Would an interlaboratory comparison study (round robin) be worthwhile? Is there common ground that we may build upon? We are inviting the leading experts who have experience with Kolsky/SHPB testing of ceramic armor materials to share their views. There will be a couple of short informal overview presentations, but we do not plan on having formal technical presentations.

Introduction: Mr. G. Quinn, NIST and Dr. J. McCauley, U.S. ARL, Aberdeen
Brief overview: Kolsky/SHPB testing, Dr. T. Weerasoriya, U.S. ARL, Aberdeen
Brief overview: NIST Kolsky projects. World Trade Center project; U. S. Department of Justice frangible projectile project; and preliminary ceramic test results. Dr. R. Fields, R. Rhorer, Dr. L. Levine, and Mr. G. Quinn, NIST
Discussion: Invited experts
Brief overview: Rules of thumb for round robins, Mr. G. Quinn, NIST
Discussion: Invited experts
Conclusions: Dr. J. McCauley and Mr. G. Quinn

For more information on the American Ceramic Society Conference, see the December issue of the American Ceramic Society Bulletin, or log on to: www.ceramics.org/meetings/schedule.asp and click on: 29th International Conference on Advanced Ceramics and Composites, Cocoa Beach, January 23-28, 2005

We are open to any suggestions on how the meeting should be conducted and the issues that ought to be discussed. Please let me know by January 7, 2005 whether you will be able to attend this important planning meeting

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Gaithersburg, MD 20899 USA
(301) 975-5765
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Minutes of the Meeting

Kolsky/Split Hopkinson Pressure Bar Testing of Ceramics

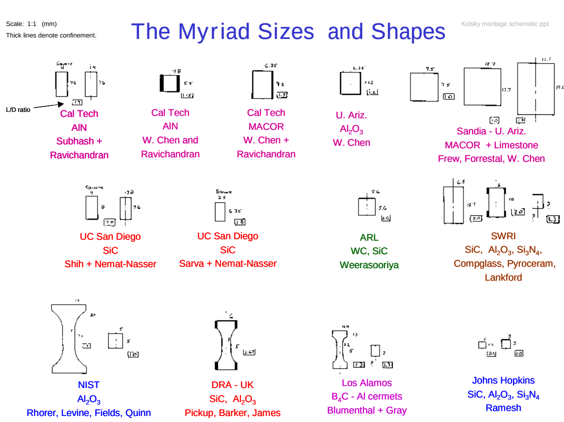
A Special Workshop
January 27, 2005
Holiday Inn, Cocoa Beach, Florida

Organized by: James McCauley, US Army ARL, Aberdeen, MD and
Mr. George Quinn, National Institute of Standards and Technology, Gaithersburg, MD
Supported by: Dr. Douglas Templeton, US Army, TARDEC

1. The meeting started at 1:15 Thursday afternoon, after the last session on ceramic armor had concluded in the morning. Many of the Kolsky/SHPB experts had given papers earlier in the week on their latest work. Attendance was by invitation only in order to keep the size of the group manageable. At least fifty attendees filled the room and extra chairs had to be brought in. An attendance last is at the end of these minutes. Experts who had Kolsky/SHPB or dynamic property testing experience were invited to sit at the front U-shaped ("*round*") table.

2. Each attendee received a sheet of paper with a **scale drawing of the various specimens types** in use for ceramic Kolsky/SHPB testing. The sheet also had a table that listed the materials and testing conditions as well as some peak strengths. The drawing and the table constitute a mini review of the **state of the art**. The drawing and table show a wide variation in techniques and results.

(These were very popular and are included here as Word "pictures." You may cut and paste these, or enlarge them with zoom options. Please let G. Quinn know of any additions or corrections.)



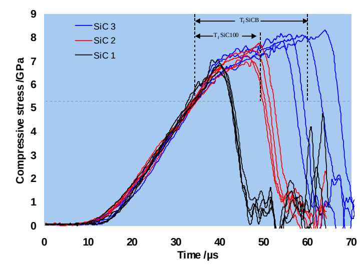
Laboratory	Name	Year	Materials	σ_c (GPa)	n	$\dot{\varepsilon}$ (rate) (1/sec)	ε_f	Bar diameter	Pulse shaper?	Inserts?	Specimen	Camera	Strain gages	Complementary Quasi static data?
ARL	Weerasooriya	2004	SiC-N					25 mm 18 mm	Yes	WC (6% Co)		-	On specimen	-
SWI	Lankford	1981 1981 1989 1989 1989 1989 1998 1998 1998 1998 2004 2004	α - SiC Lucalox Al_2O_3 Compglass RBSN HPSN Pyroceram AD 995 Al_2O_3 JS I Al_2O_3 JS II Al_2O_3 AlN sint. SiC (α?) SiC- N	4. – 6.3 3.5 – 6.0 0.3 – 2.0 2. 0 4.0 – 4.5 2.0 3.5 – 9.0 9.0 6.5 3. – 6. 5. – 7. 4. – 9.	3 4 8 11	$1. \times 10^3$ $1. \times 10^3$ $1. \times 10^3$ $1. \times 10^3$ $3. \times 10^3$ $.5 – 5 \times 10^3$ $1. \times 10^3$ $1. \times 10^3$ $1. \times 10^3$ 5×10^3 5×10^3		?	No	Vascomax 350 (bar material)	← some confinement	(Yes, now)	On bars On specimen (according to Staehler, Predebon, Pletka, Subhash 1995)	Yes
Los Alamos	Gray Blumenthal	1989	B_4C / Al cermets 4 compositions	4.3 2.2 2.0 1.3		1 to 2×10^3		12.7 mm	?	WC		-	On specimen	Yes
JHU	Ramesh	2004 2004 2004 2004 2004	α-SiC GS 44 Si_3N_4 AD 995 Al_2O_3 α-sialon SiC-N	2.6 4.0 4.0 4.6 5.1 – 7.2	13 6 8 8 8	$.5 - 2.2 \times 10^3$ $.8 – 2.5 \times 10^3$ $.7 – 2.2 \times 10^3$ $.5 – 2.5 \times 10^3$ 100-500 MPa/μsec		7.1 mm 12.7 mm 7 mm	Yes Yes	WC (3% Co) and collars WC (3% Co) and collars		Yes, High speed	On bars	Yes
DRA - UK	Pickup Barker James	1997 2001	SiC (RB) SiC (sint) SiC – B? (PAD) Al_2O_3 – 1 Al_2O_3 - 2	6.7 7.3 8.1 4.1 6.1		0.9×10^3		16 mm	?	?		Yes	?	Yes
Cal. Tech.	Subhash Ravichandran	1993 1995	AlN	3.5 – 5.2		$.1 – 5 \times 10^3$		?	Yes	-		-	On bars	-
	W. Chen Ravichandran	1996 2000	AlN AlN	4 – 5	5	$.5 \times 10^3$		12.7 mm 19 mm	Yes Yes	WC WC		-	On bars	Yes
	W. Chen Ravichandran	1997	Macor glass ceramic	.44	5	-	.004	19 mm	Yes	WC		-	On bars and on specimen sleeve	Yes
Univ. Arizona	W. Chen	2003 2004	AD 995 Al_2O_3	2.7 4.3	-	$.3 \times 10^3$ $.3 - .4 \times 10^3$	.015 - .020	19 mm	Yes	WC		-	On bars	-
Univ. Arizona	Frew Forrestal	2002	Macor (Glass ceramic)	.55	5	$.17 \times 10^3$	.012	19 mm	Yes	No		-	On bars	-
Sandia	W. Chen	2001	Indiana Limestone	.10 - .13	9	$.1 - .3 \times 10^3$	-	19 mm	Yes	No		-	On bars	-
UC – San Diego	Sarva Nemet-Nasser	2001	Hot pressed SiC	4.2 – 7	10	$.25 – 1.2 \times 10^3$	~ .01	?	Yes	WC		-	On bars	Yes
UC – San Diego	Shih, Meyers, Nesterencko S. Chen	2000	Hot pressed SiC SiC - B	4.7 5.4	5 6	$.4 - .8 \times 10^3$ $.4 - .8 \times 10^3$		12.7 mm	Yes	SiC/Si_3N_4		-	On specimen	Yes
Georgia Tech	Keller Zhou	2003	4 grades of SHS TiB_2 / Al_2O_3	4.6 – 5.3	4 x 6 ea	$.4 \times 10^3$		19 mm	Yes	WC	?	-	On specimen	-
NIST	Rhorer, Fields, Levine, Quinn	2005	AD 995 Al_2O_3	4.6 – 5.3		In progress		15 mm	Yes	WC		Yes, High speed	On specimen	-

3. George Quinn of NIST began the meeting with a 10-minute introduction. He showed the agenda and stated that the **goals of the meeting** were to:

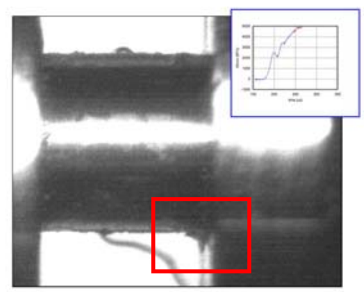
- Discuss the state of the art of ceramic dynamic compression property testing by Kolsky/SHPB testing, and
- Discuss the value of the data for armor applications

Mr. Quinn also mentioned that a the July 2006 Conference on fractography of Glasses and Ceramics will in July 2006 will have special session on fractography of ceramic armor materials. For more information see: http://engineering.alfred.edu/outreach/conferences/fractography/

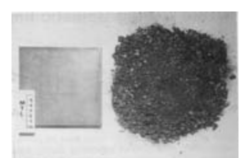
4. **Jim McCauley of US ARL then set the tone for the meeting** with introductory remarks in a 40-minute 12-slide presentation. Jim believes that Kolsky/SHPB test data may play an important role in determining why some ceramics fare better than others in a ballistic environment. What are the combinations of static/dynamic mechanical properties that control performance? Are there figures of merit? How are the mechanical properties influenced by intrinsic and extrinsic material characteristics (grain size, phase distribution, defects, etc)? Jim was particularly keen on some results from DRA, UK which showed dramatic differences in the stress- time behavior of several silicon carbides. The data for Cercom's SiC-B suggested possible dynamic plasticity. If so, then Kolsky/SHPB data may provide good clues as to the source of that material's good ballistic performance and may pave the way for material improvements.



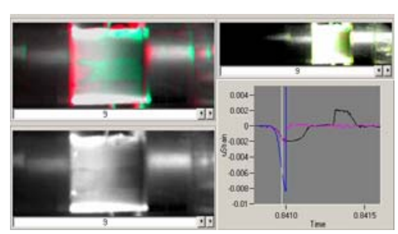
5. **Tusit Weerasoriya of US Army ARL** then gave a 20-minute 19-slide presentation on Obtaining Valid Data- Some Personal Observations. His most recent work on tungsten carbides highlighted some of the issues and problems. The stress in the specimens should be in dynamic equilibrium. Stress concentrations at the edges of cylindrical specimens may be a problem. A swivel-articulating joint may help eliminate any misalignments. Strain gages should be applied to specimens. Data scatter from testing errors must be managed to reveal the real material trends with stain rate.



6. **George Quinn of NIST** then gave a 13-minute 17-slide presentation. He reiterated the goals of the meeting and presented a little about his background with Jim McCauley at Watertown Arsenal in Boston. George discussed work at NIST to refine and standardize test methods such as flexural strength, hardness, and fracture toughness. Some of these methods and standards are in widespread use by the ceramic armor community. George trained and worked with Carl Tracy who developed the dumbbell compression strength test method that is now an ASTM standard. Quinn also trained and worked with Mike Slavin who did some intriguing fractographic analysis of ballistic rubble. There were some similarities to static compression strength test rubble.



7. **Richard Fields of NIST** then gave a 22-minute 24-slide presentation about NIST's Kolsky/SHPB work. The NIST rig had been constructed to support machining studies and featured a high temperature capability, a high speed imaging capability, and even a thermal imaging capability. The rig is now being used to study frangible bullets in a project funded by the Department of Justice and had also been used to study dynamic properties of steels from the World Trade Center September 11th failure investigation. New results on CoorsTek AD 995 alumina cylinders were shown as an example of the NIST capability. Dumbbell specimens will be tested very soon for comparison. Fields mentioned that Dr. Richard Rhorer had started an uncertainty analysis of the Kolsky bar strain



gage output signals. Fields listed some issues that need to be addressed including consistency and uncertainty in Kolsky/SHPB testing.

These Power point introductory presentations ended at 3:00 pm.
The Five Talks will be sent separately as .pdf files

Discussion Phase: Experts and Attendees

The presentations raised serious issues about Kolsky/SHPB testing of ceramics. Why are data so inconsistent? How much of the variability is due to test procedures differences? What are the best ways to analyze the data? Does the data have any value for characterizing ceramic armor? Can the data be used in models?

The attendees had sat patiently through the presentations and now were ready say their piece. Mr. Quinn moderated the ensuing discussion. The discussion was initially limited to the experts at the head table. There were some frank exchanges of views.

Ghatu Subhash pointed out that there are no standards for dynamic property testing and that the perspectives of the materials science community may be different than those of the solid mechanics community. K. T. Ramesh focused the discussion by raising a good point: What is the objective of generating Kolsky/SHPB data? Is it for property and constitutive equation characterization, material development or ranking purposes, or generation of data for modelers? Is it possible to generate data that is satisfactory for all these needs or should attention be focused on one aspect?

This triggered about 30 minutes of discussion, but no consensus was reached. For example, Wayne Chen suggested that Kolsky/SHPB testing could serve as a bridge to estimate real ballistic performance. Then Dennis Grady frankly wondered whether the data has any value at all, since specimens are typically not in stress equilibrium. Tusit Weerasooriya replied by saying he had measured genuine strain rate effects in tungsten carbide. George Quinn then cited Jim Lankford's work at Southwest Research Institute that showed considerable strain rate effects. He said he had spoken to Jim before the meeting. Quinn said that he knew that some of the attendees probably would be critical of some of Lankford's methodology, but Jim's retort would have been that he has been detecting real trends, his customers were happy, and the ballistic event is not neat and tidy either. Sidney Chochron from SwRI added some comments about activities in Europe.

The discussion was then opened up to all attendees. Ray Cutler suggested that testing could focus on studying damage kinetics of a range of materials. Perhaps understanding could come from comparing behaviors. Ian Pickup said that understanding often came from direct comparisons of static compression strength data to dynamic results. Dumbbell specimens had worked extremely well at DRA for both tests. Colin Robertson suggested that dynamic testing was a valuable tool to detect quasi plasticity that may be the key to good ballistic performance.

At this point, Mr. Quinn took an impromptu poll of the experts around the head table:

What is the primary benefit or value of Kolsky/SHPB data?

What is the primary benefit or value of Kolsky/SHPB data?

The answers were:

Ian Pickup	Evaluation of damage kinetics
Dennis Grady	Evaluation of damage kinetics-qualitatively?
Sidney Chochron	Data for numerical modeling, not for material figures of merit
Wayne Chen	Damage kinetics and stress strain constitutive behavior, dwell correlations?
Bazle Gama	Model verification
K.T. Ramesh	Model verification, constitutive equation determination
Ghatu Subhash	Data that is a piece of the larger puzzle
Bill Blumenthal	Not sure SHPB/Kolsky testing has value. What are the basic physics? What are the mechanisms? Are there in fact better approaches? Is Kolsky data really dynamic, or is it just a faster than normal static test?
Tusit Weerasooriya	Data for models

Then other attendees added their comments on the benefit or value of Kolsky/SHPB data:

Mike Normandia	Kolsky/SHPB testing should be seen as one of a suite of tests. One may not be sure it is the best, but no one knows if there is a "best" test. Get constitutive equation data.
Henry Chu	Model data and verification
Colin Robertson	One of a suite of tests that may be applied.
Richard Fields	Detection and characterization of plasticity
Heinrich Knoch	Agrees with Blumenthal. Not sure Kolsky/SHPB has value.
Richard Palicka	Screening test

There then was a general discussion on testing details. There were some positive signs and some consensus.

- There was a general consensus that **high-speed cameras are valuable tools for interpreting test results.** This is an important recent **positive development**. Older testing had no such verification. The advent of cost effective high-speed photography, data acquisition, and computers have dramatically improved the quality of Kolsky/SHPB testing.
- Tungsten carbide inserts are important, but there are nuances and details about their use.
- Most experts agreed that **pulse shapers are essential**.
- **There is growing consensus that strain gages must be applied to the specimens,** since strain estimates from the gages on the bars may give inaccurate results for ceramics. Bill Blumenthal gave a good paper earlier in the conference that discussed strain gage usage in some detail.

George Quinn a gave brief presentation on round robins at 4:00 pm.
It was clear from the discussions and the review of the state of the art that most felt it is premature to talk about formal standardization of Kolsky/SHPB testing of ceramics. There are too many unresolved issues at the moment.
Nevertheless, some Guidelines or Recommendations could be very useful to bring

some consistency to the field. Could a round robin can help clarify a situation like this? Mr. Quinn has had considerable experience and success with round robins. He gave a very brief 8-slide 5-minute overview of round robins. Quinn's **Rules of Thumb** for round robins were shown. These are listed in the accompanying Power Point presentation and are also available in a review article located at:

http://www.ceramics.nist.gov/pubs/pub00002.htm

A brief impromptu survey was taken of the experts at the round table.

Would a ceramic Kolsky/SHPB round robin be a good idea?

Answers:

Ian Pickup	Not sure. It might identify problems. Do static testing too.
Dennis Grady	Cool to the idea. Perhaps see if different people can get similar stress strain curves
Wayne Chen	It may be worthwhile
K. T. Ramesh	No, it is premature
Sidney Chochron	Good learning exercise?
Bazle Gama	Helpful to make standards? Helpful to get useful data
Ghatu Subhash	Not sure. Must think more about it.
Bill Blumenthal	Unsure. What are the criteria of success? Possible value for determining variability due to strain rate.
Tusit Weerasooriya	No, it is premature
Henry Chu	Run a mini round robin first. Just 2 or 3 labs.

These very guarded responses from the experts prompted Dr. Richard Fields of NIST to speak up and suggest that if the experts were unwilling to participate in a round robin, then one wonders whether sponsors should have much confidence in their data.

The meeting concluded at 4:15 when Mr. Quinn stated that he would prepare and distribute minutes of the meeting. There certainly is much to contemplate.

Colin Robertson and Jim McCauley thanked Mr. Quinn for his handling of the meeting.
Jim McCauley and Mr. Quinn thanked the attendees for participating in a lively meeting.

Recorded by:
Mr. George Quinn, NIST

* **

Please see Mr. Quinn's summary comments

and Points of Contact on the next pages.

The list of attendees is on the last page.

Some final comments by Mr. Quinn, February 28, 2005

1. There was no consensus as to whether Kolsky/SHPB data would ever **correlate to ballistic performance.** People are simply not sure. **Nevertheless, many agreed with Mike Normandia's assessment that Kolsky/SHPB data ought to be one of a suite of tests that are used.**

2. Jim McCauley and others strongly believe that Kolsky/SHPB data may furnish critical information about possible dynamic plasticity that may correlate to dwell or other important ballistic phenomena. Jim may be right.

3. Uncertainty in the test data (error, variability due to procedures, etc) may be of such magnitude that genuine material behavior or trends may be missed or masked.

4. The Kolsky/SHPB experts seemed wary of setting guidelines. So for example, there was no consensus on whether dumbbell specimens or simple cylindrical specimens are preferred. On the other hand, the **industrial participants** were very eager to get more consistent procedures. They want to see some progress.

5. There was near universal agreement that the meeting was productive. We did not get bogged down talking about testing nuances. (e.g., lubricated or unlubricated, one strain gage or two or three, pulse shaper details, confined or unconfined, etc.) That was probably for the best. It was better to discuss the general issues. The details can come later..

6. My personal assessment is that some consistency is desperately needed. We have been in this situation before and we have experience in solving problems like this. For example, in the early 1980's there was no consistency in ceramic flexural strength testing procedures. Different laboratories got different results on the same material. We crafted guidelines with some restrictions, but some flexibility in specimen choice, specimen preparation, and other key details. This work evolved into the very successful MIL STD 1942, ASTM standard C 1161, and now world ISO standard, ISO 14705.

We've cleaned up other methods. The most difficult was fracture toughness that was a very controversial property. Affairs were in a terrible mess in the 1990's. We now have ASTM C 1421, several ISO standards, and even a reference material. This work was backed by five major international round robins. This was stunning achievement.

The problems with Kolsky/SHPB testing may seem formidable, but my colleagues and I at NIST are ready for the challenge. We can use our metrological, mechanical engineering, and materials science skills to find technically sound but practical solutions. Some guidelines would be a good start.

Please feel free to contact us.

If you think this work is worthwhile, please do not hesitate to contact Jim McCauley and Douglas Templeton.

Contact information is on the next page.

Points of Contact:

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U.S. Army TARDEC
ATTN: AMSTA-TR-R; MS 263
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douglas.templeton@us.army.mil
templetd@tacom.army

Mr. George Quinn
Ceramics Division
Stop 852
National Institute of Standards and Technology
Gaithersburg, MD 20899
(+001) 301 975 5765
mailto:geoq@nist.gov

The Attendees list is on the next page.

Attendees

Kolsky/SHPB Experts and US Army

Colin Robertson	Advanced Defense Materials, Ltd
Dennis Grady	Applied Research Associates
James McCauley	US Army ARL
Tusit Weerasooriya	US Army ARL
Ian Pickup	DSTL
K. T. Ramesh	Johns Hopkins Univ.
William Blumenthal	Los Alamos
Ghatu Subhash	Michigan Tech.
George Quinn	NIST
Richard Fields	NIST
Bazle Gama	Univ. Delaware
Sidney Chochron	Southwest Research Institute
Wayne Chen	Purdue
Henry Chu	INEEL
Brian Herman	INEEL/Bechtel
Douglas Templeton	US Army TARDEC

Interested Parties and Stakeholders

Mike Normandia	US Army ARL
Jeffrey Swab	US Army ARL
Jerry LaSalvia	US Army ARL
Bryan Leavy	US Army ARL
Sam Martin	US Army ARL
Lisa Prokurat Franks	US Army TARDEC
David Stepp	US Army ARO
William Mullins	US Army ARO
Richard Haber	Rutgers Univ.
Dale Niesz	Rutgers Univ.
Roger Cannon	Rutgers Univ.
Brian McEnerney	Rutgers Univ.
Ryan McCuiston	Rutgers Univ.
Michael Bakas	Rutgers Univ.
Bhasker Paliwal	Johns Hopkins Univ.
John Holowczak	United Technologies
Heinrich Knoch	Wacker/ESK/Ceradyne
James Shih	Ceradyne
Biljana Mikijelj	Ceradyne
Raymond Cutler	Ceramatec
Richard Palicka	Cercom
Thomas Holmes	M-Cubed Technologies
D. Diehl	PPG
David Marchant	Simula

(Note: A handful of attendees did not mark the sign-in sheet.)

Kolsky/SHPB meeting cocoa-04.ppt

Weapons and Materials Research Directorate
U.S. Army Research Laboratory

NIST

Kolsky/SHPB Ceramic Testing of Armor Ceramics Cocoa Beach, FL January 27, 2005

1:15 pm to 4:15 pm

- Introduction — J. McCauley, ARL
- Review Kolsky/SHPB Ceramics Testing — T. Weerasooriya, ARL
- Review NIST Kolsky Projects — G. Quinn and R. Fields, NIST
- Discussion of State of the Art and Issues Pertaining to Ceramic Testing — Invited Experts
- Rules of Thumb for Round Robins — G. Quinn
- Conclusions — J. McCauley and G. Quinn

Introductory Presentation by George Quinn

The objectives of today's meeting are to:

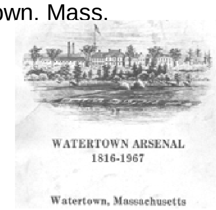
Discuss the state of the art of ceramic dynamic compression property testing by Kolsky/Split Hopkinson Pressure Bar testing.

Discuss the value of the Kolsky/SHPB data for ceramics.

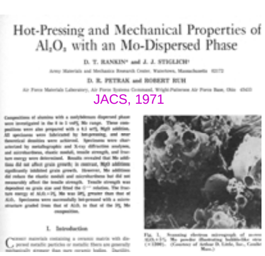
Quinn and McCauley were both in bldg 313N in Watertown Arsenal in the mid 1970's

Mr. George Quinn

1969- 1990
U. S. Army Materials Research Laboratory
Watertown. Mass.



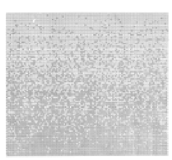
Graded Ceramic-Metal composites for armor


Hot-Pressing and Mechanical Properties of Al_2O_3 with an Mo-Dispersed Phase

D. T. RANKIN and J. J. STIGLICH

D. R. PETRAK and ROBERT RUH

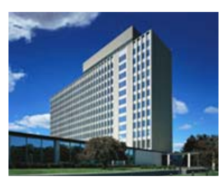
JACS, 1971



Microstructure modeling

Percolation Theory, Phase Connectivity and Topology

1990 - 2005
National Institute of Standards and Technology

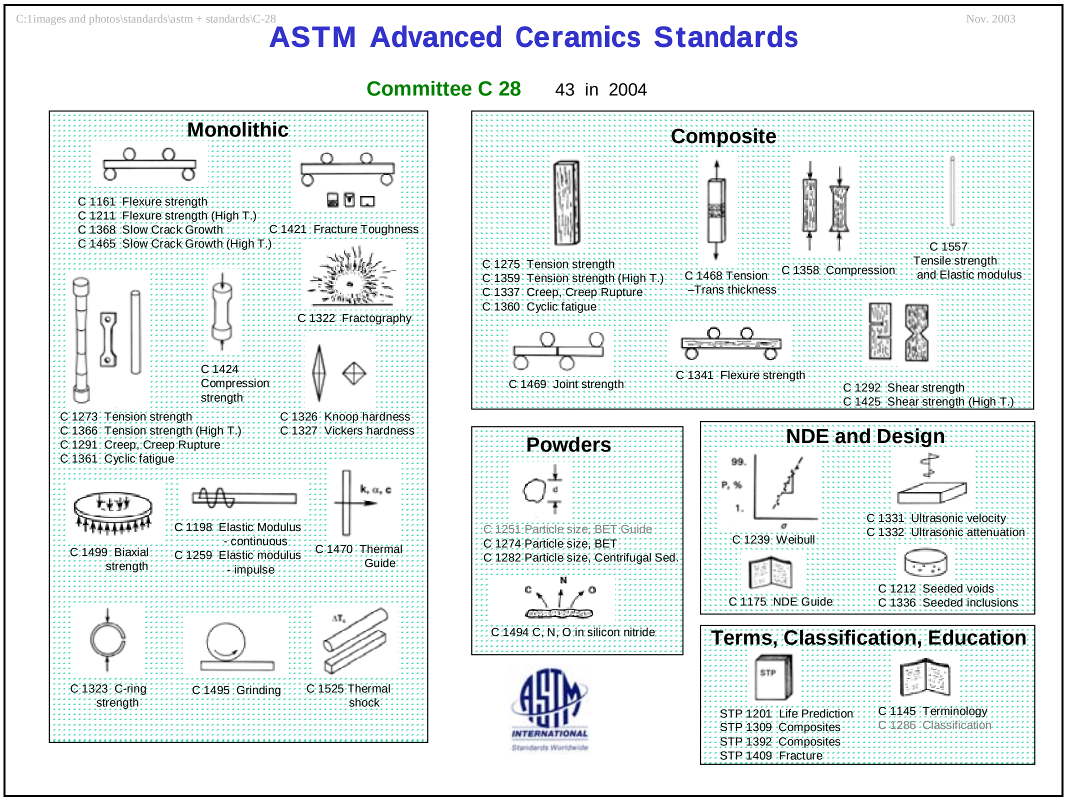


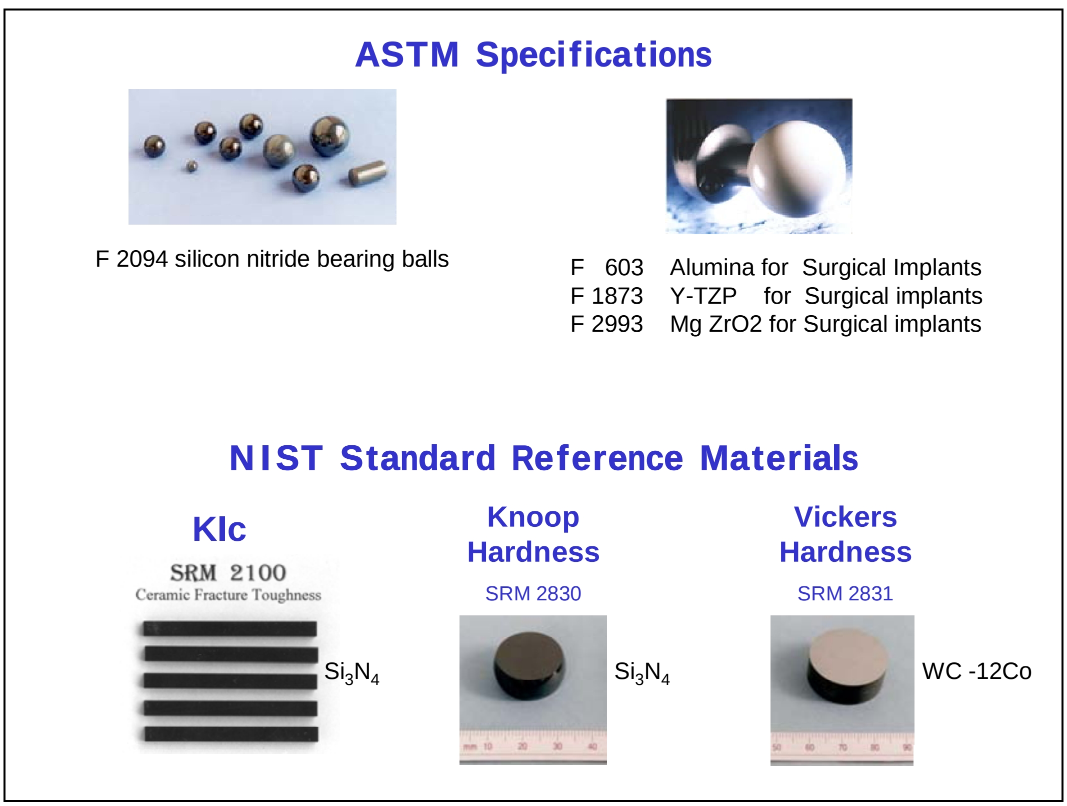
Test Methods and Standards

ASTM INTERNATIONAL Standards Worldwide

ISO

VAMAS


C:1images and photos\standards\astm + standards\C-28
Nov. 2003
ASTM Advanced Ceramics Standards
Committee C 28 43 in 2004
Monolithic
C 1161 Flexure strength
C 1211 Flexure strength (High T.)
C 1368 Slow Crack Growth
C 1465 Slow Crack Growth (High T.)
C 1421 Fracture Toughness
C 1322 Fractography
C 1424 Compression strength
C 1273 Tension strength
C 1366 Tension strength (High T.)
C 1291 Creep, Creep Rupture
C 1361 Cyclic fatigue
C 1326 Knoop hardness
C 1327 Vickers hardness
C 1499 Biaxial strength
C 1198 Elastic Modulus - continuous
C 1259 Elastic modulus - impulse
C 1470 Thermal Guide
C 1323 C-ring strength
C 1495 Grinding
C 1525 Thermal shock
Composite
C 1275 Tension strength
C 1359 Tension strength (High T.)
C 1337 Creep, Creep Rupture
C 1360 Cyclic fatigue
C 1468 Tension –Trans thickness
C 1358 Compression
C 1557 Tensile strength and Elastic modulus
C 1469 Joint strength
C 1341 Flexure strength
C 1292 Shear strength
C 1425 Shear strength (High T.)
Powders
C 1251 Particle size, BET Guide
C 1274 Particle size, BET
C 1282 Particle size, Centrifugal Sed.
C 1494 C, N, O in silicon nitride
NDE and Design
C 1239 Weibull
C 1331 Ultrasonic velocity
C 1332 Ultrasonic attenuation
C 1175 NDE Guide
C 1212 Seeded voids
C 1336 Seeded inclusions
Terms, Classification, Education
STP 1201 Life Prediction
STP 1309 Composites
STP 1392 Composites
STP 1409 Fracture
C 1145 Terminology
C 1286 Classification


ASTM Specifications
F 2094 silicon nitride bearing balls
F 603 Alumina for Surgical Implants
F 1873 Y-TZP for Surgical implants
F 2993 Mg ZrO2 for Surgical implants
NIST Standard Reference Materials
KIc
SRM 2100
Ceramic Fracture Toughness
Si3N4
Knoop Hardness
SRM 2830
Si3N4
Vickers Hardness
SRM 2831
WC -12Co

Any Test Procedure is a series of details

And the Devil is in the details!

- The sounder the technical basis, the easier the job.
- The less sound the technical basis, the more the need for engineering judgment.
- The simpler the procedure, the better.
- Good procedures should be balanced.
  They should be technically rigorous and practical.

The Tangible Benefits

- Better methods give better data.
- Better methods facilitate utilization of new materials
- Better methods establish credibility.

Ceramic Test Methods and Armor Characterization at Watertown Arsenal

Reprinted from the Advances in Ceramics, Volume 22, Fractography of Glasses and Ceramics

Ceramic Fracture During Ballistic Impact

C. Tracy, M. Slavin, and D. Viechnicki

U.S. Army Materials Technology Laboratory
Ceramics Research Division
Watertown, MA 02172-0001

Ceramics have been used as armor materials for more than 20 years, but still little is known about the penetration mechanisms operating during ballistic impact, particularly the role of fracture. Work in progress concerning the fracture of ceramics during ballistic impact for a specific threat and target setup are discussed. Sintered and hot-pressed TiB_2 and SiC were investigated. The microstructures and fracture surfaces of these materials were characterized using optical and electron microscopy. The pertinent elastic and low strain-rate mechanical properties were measured. Fracture surfaces produced during low strain-rate bend and compression testing will be compared with surfaces of ceramic rubble particles produced during high-velocity ballistic impact. Differences in fracture behavior among ceramics will be discussed.

Carl Tracy

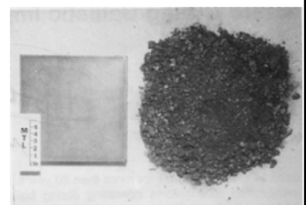
No picture available

Dennis Viechnicki

Table II. Ceramic Material Properties

Property	SiC Sintered	SiC Hot-Pressed	TiB_2 Sintered	TiB_2 Hot-Pressed
Density (g/cm^3)	3.12	3.28	4.55	4.51
Grain size (μm) (intercept length)	4		8	10
Porosity (vol%)	3–4	1–2	1	2
Elastic modulus (GPa)	407	448	551	551
Poisson's ratio	0.16	0.17	0.13	0.11
Compressive strength (GPa)	>5.16	6.29		5.70
standard deviation		0.27		0.17
Average flexural strength (MPa)	326	730	350	398
Weibull modulus	10.8	9.5	11.3	28.7
Fracture toughness (MPa · m$^{1/2}$)	3.01	5.23	8.00	6.69
standard deviation	0.28	0.29	0.26	0.19
Knoop hardness (GPa) (500 gf)	22.4	22.3	20.8	23.0
Relative ballistic performance	0.97	0.83	0.82	1.00

ASTM C 1424 (1999)



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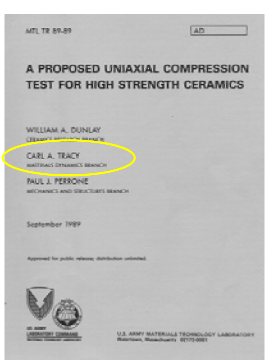
Tracy's Compression Specimens

ASTM C 1424 (1999)


MTL TR 89-89

AD

A PROPOSED UNIAXIAL COMPRESSION TEST FOR HIGH STRENGTH CERAMICS

WILLIAM A. DUNLAY

CARL A. TRACY
MATERIALS DYNAMICS BRANCH

PAUL J. PERRONE
MECHANICS AND STRUCTURES BRANCH

September 1989

Approved for public release; distribution unlimited.

U.S. ARMY MATERIALS TECHNOLOGY LABORATORY
Watertown, Massachusetts 02172-0001

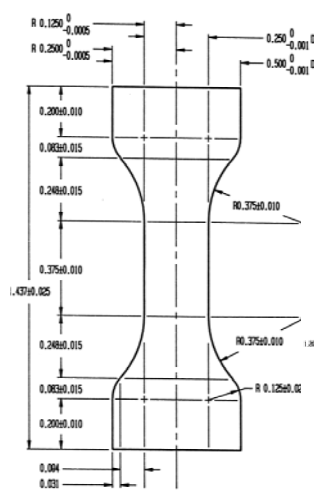


FIG AI-1. COMPRESSION TEST SPECIMEN A. SCALE 1" = 0.25"

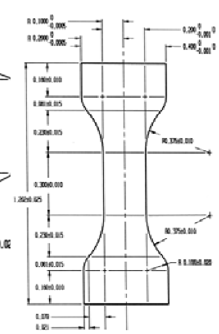


FIG AI-3. COMPRESSION TEST SPECIMEN B. NOT TO SCALE

Watertown Arsenal Ceramic Armor Work

Mescall and Tracy, 1986

Improved Modeling of Fracture in Ceramic Armors

Army Science Conference June, 1986

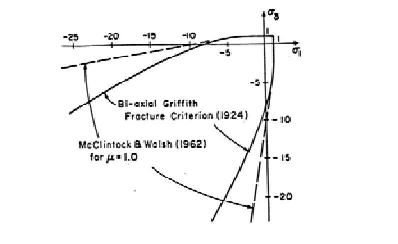


Figure 2: Fracture locus for biaxial stress states in both tension (first quadrant) and compression (third quadrant).

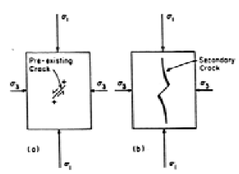


Figure 3: Triaxial compression test of brittle solid containing flaw. Note in Figure 3b the tendency of growing crack to turn toward maximum compressive load and to arrest.

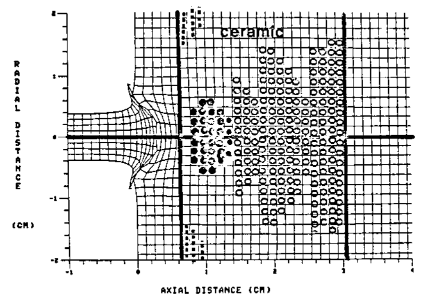
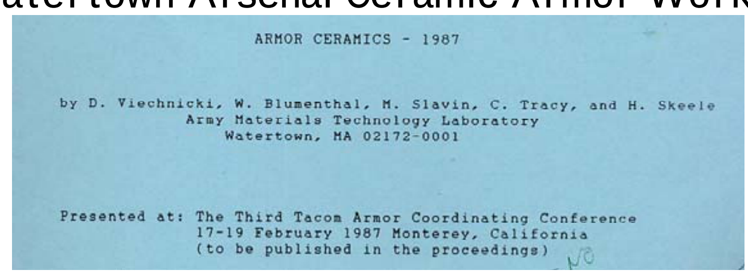


Figure 5: Fracture pattern in ceramic at five microseconds after impact. Closed circles indicate compression failure, open circles hoop tensile failure and squares radial tensile failure.

Watertown Arsenal Ceramic Armor Work



ARMOR CERAMICS - 1987

by D. Viechnicki, W. Blumenthal, M. Slavin, C. Tracy, and H. Skeele
Army Materials Technology Laboratory
Watertown, MA 02172-0001

Presented at: The Third Tacom Armor Coordinating Conference
17-19 February 1987 Monterey, California
(to be published in the proceedings)

TiB2

TABLE II. THE EFFECTS OF PROCESSING AND PROPERTIES ON THE BALLISTIC PERFORMANCE OF TITANIUM DIBORIDE.

PROCESSING TECHNIQUE	HOT PRESSED	SINTERED	HOT PRESSED	SINTERED
MAJOR ADDITIVE OR IMPURITY (wt%)	-	10SiC	10 Ni	10TiC
GRAIN SIZE (um)	10			8
POROSITY (%)	3	[illegible]		1
DENSITY (g/cc)	4.51	[illegible]	4.50	4.55
ELASTIC PROPERTIES				
YOUNG'S MODULUS (GPa)	551	440	502	555
POISSON'S RATIO	0.11	0.110	0.096	0.13
LONGITUDINAL SONIC VELOCITY (km/s)	11.3	10.4	10.7	11.2
SHEAR SONIC VELOCITY (km/s)	7.42	6.82	7.14	7.35
MECHANICAL PROPERTIES				
MODULUS OF RUPTURE (MPa)	398			325
WEIBULL MODULUS	28.7			11.3
COMPRESSIVE STRENGTH (GPa)	5.70			
FRACTURE TOUGHNESS (MPa[m]^1/2)	6.69			8.00
HARDNESS (GPa)	25.0			20.5
FRACTURE MODE	Trans-granular			Trans+inter-granular
RELATIVE BALLISTIC LIMIT	1.00	0.95	0.88	0.75

SiC

TABLE III. THE EFFECTS OF PROCESSING AND PROPERTIES ON THE BALLISTIC PERFORMANCE OF SILICON CARBIDE.

PROCESSING TECHNIQUE	SINTERED	HOT PRESSED	REACTION SINTERED
MAJOR ADDITIVE OR IMPURITY (wt%)	0.4B	2 Al2O3	10 Si, C
GRAIN SIZE (um)	4		Bimodal, grit=100, grain=5
POROSITY (%)	2 - 4	1 - 2	0
DENSITY (g/cc)	3.12	3.28	3.08
ELASTIC PROPERTIES			
YOUNG'S MODULUS (GPa)	408	451	391
POISSON'S RATIO	0.16	0.17	0.17
LONGITUDINAL SONIC VELOCITY (km/s)	11.7	12.1	11.6
SHEAR SONIC VELOCITY (km/s)	7.5	7.6	7.3
MECHANICAL PROPERTIES			
MODULUS OF RUPTURE (MPa)	311	693	
WEIBULL MODULUS	11.0	10.0	
COMPRESSIVE STRENGTH (GPa)	5.16	6.29	
FRACTURE TOUGHNESS (MPa[m]^1/2)	3.01	5.23	
HARDNESS (GPa)	22.4	22.4	16.3
FRACTURE MODE	Trans-granular	Trans+inter-granular	Inter granular
RELATIVE BALLISTIC LIMIT	1.00	0.86	0.71

Al_2O3

TABLE IV. THE EFFECTS OF PROCESSING AND PROPERTIES ON THE BALLISTIC PERFORMANCE OF ALUMINA.

PROCESSING TECHNIQUE	HOT PRESSED	HOT PRESSED	HOT PRESSED	SINTERED
MAJOR ADDITIVE OR IMPURITY (wt%)	1NiO	1 MgO	25 SiC whiskers	6-10 SiO2
GRAIN SIZE (um)				12
POROSITY (%)	1	<1		4 - 6
DENSITY (g/cc)	3.94	[illegible]	3.71	3.51 - 3.55
ELASTIC PROPERTIES				
YOUNG'S MODULUS (GPa)	384	393	354	291 - 276
POISSON'S RATIO	0.234	0.236	0.218	0.22 - 0.24
LONGITUDINAL SONIC VELOCITY (km/s)	10.7	10.8	11.0	
SHEAR SONIC VELOCITY (km/s)	6.20	6.36	6.60	
MECHANICAL PROPERTIES				
MODULUS OF RUPTURE (MPa)			491	281 - 345
WEIBULL MODULUS			5.1	11.3
COMPRESSIVE STRENGTH (GPa)				2.49 - 2.48
FRACTURE TOUGHNESS (MPa[m]^1/2)				3.75 - 2.5
HARDNESS (GPa)				12.4
FRACTURE MODE				Inter-granular
RELATIVE BALLISTIC LIMIT	1.00	0.94	0.91	

State of the Art of SHPB/Kolsky Testing of Ceramics -

Quinn's impressions

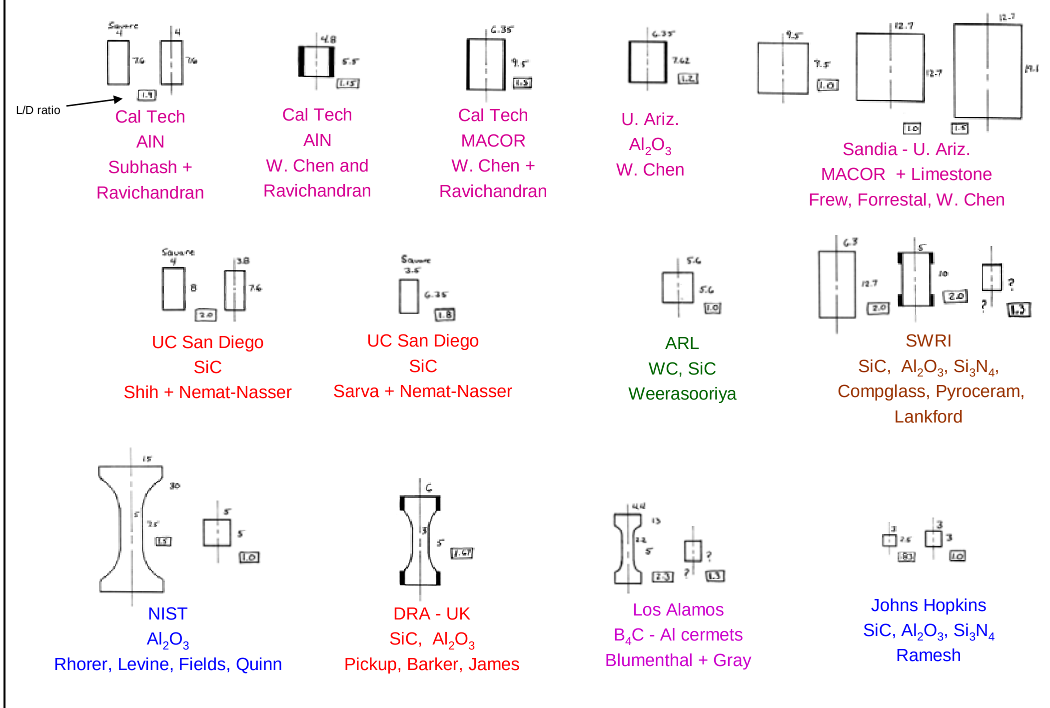
Kolsky/SHPB Ceramic data

Laboratory	Name	Year	Materials	σ_c (GPa)	n	$\dot{\varepsilon}$ (rate) (1/sec)	ε_f	Bar diameter	Pulse shaper?	Inserts?	Specimen	Camera	Strain gages	Complementary Quasi static data?
ARL	Weerasooriya	2004	SiC-N					25 mm 18 mm	Yes	WC (6% Co)		-	On specimen	-
SWI	Lankford	1981 1981 1989 1989 1989 1989 1998 1998 1998 1998 2004 2004	α - SiC Lucalox Al_2O_3 Compglass RBSN HPSN Pyroceram AD 995 Al_2O_3 JS I Al_2O_3 JS II Al_2O_3 AlN sint. SiC (α?) SiC- N	4. – 6.3 3.5 – 6.0 0.3 – 2.0 2. 0 4.0 – 4.5 2.0 3.5 – 9.0 9.0 6.5 3. – 6. 5. – 7. 4. – 9.	3 4 8 11	1. x 10^3 1. x 10^3 1. x 10^3 1. x 10^3 3. x 10^3 .5 – 5 x 10^3 1. x 10^3 1. x 10^3 1. x 10^3 5 x 10^3 5 x 10^3		?	No	Vascomax 350 (bar material)	← some confinement	(Yes, now)	On bars On specimen (according to Staehler, Predebon, Pletka, Subhash 1995)	Yes
Los Alamos	Gray Blumenthal	1989	B_4C / Al cermets 4 compositions	4.3 2.2 2.0 1.3		1 to 2 x 10^3		12.7 mm	?	WC		-	On specimen	Yes
JHU	Ramesh	2004 2004 2004 2004 2004	α-SiC GS 44 Si_3N_4 AD 995 Al_2O_3 α-sialon SiC-N	2.6 4.0 4.0 4.6 5.1 – 7.2	13 6 8 8 8	.5 - 2.2 x10^3 .8 – 2.5 x10^3 .7 – 2.2 x10^3 .5 – 2.5 x10^3 100-500 MPa/μsec		7.1 mm 12.7 mm 7 mm	Yes Yes	WC (3% Co) and collars WC (3% Co) and collars		Yes, High speed	On bars	Yes
DRA - UK	Pickup Barker James	1997 2001	SiC (RB) SiC (sint) SiC – B? (PAD) Al_2O_3 – 1 Al_2O_3 - 2	6.7 7.3 8.1 4.1 6.1		0.9 x 10^3		16 mm	?	?		Yes	?	Yes
Cal. Tech.	Subhash Ravichandran	1993 1995	AlN	3.5 – 5.2		.1 – 5 x 10^3		?	Yes	-		-	On bars	-
	W. Chen Ravichandran	1996 2000	AlN AlN	4 – 5	5	.5 x 10^3		12.7 mm 19 mm	Yes Yes	WC WC		-	On bars	Yes
	W. Chen Ravichandran	1997	Macor glass ceramic	.44	5	-	.004	19 mm	Yes	WC		-	On bars and on specimen sleeve	Yes
Univ. Arizona	W. Chen	2003 2004	AD 995 Al_2O_3	2.7 4.3	-	.3 x 10^3 .3 - .4 x 10^3	.015 - .020	19 mm	Yes	WC		-	On bars	-
Univ. Arizona	Frew Forrestal	2002	Macor (Glass ceramic)	.55	5	.17 x 10^3	.012	19 mm	Yes	No		-	On bars	-
Sandia	W. Chen	2001	Indiana Limestone	.10 - .13	9	.1 - .3 x 10^3	-	19 mm	Yes	No		-	On bars	-
UC – San Diego	Sarva Nemet-Nasser	2001	Hot pressed SiC	4.2 – 7	10	.25 – 1.2 x 10^3	~ .01	?	Yes	WC		-	On bars	Yes
UC – San Diego	Shih, Meyers, Nesterencko S. Chen	2000	Hot pressed SiC SiC - B	4.7 5.4	5 6	.4 - .8 x 10^3 .4 - .8 x 10^3		12.7 mm	Yes	SiC/Si_3N_4		-	On specimen	Yes
Georgia Tech	Keller Zhou	2003	4 grades of SHS TiB_2 / Al_2O_3	4.6 – 5.3	4 x 6 ea	.4 x 10^3		19 mm	Yes	WC	?	-	On specimen	-
NIST	Rhorer, Fields, Levine, Quinn	2005	AD 995 Al_2O_3	4.6 – 5.3		In progress		15 mm	Yes	WC		Yes, High speed	On specimen	-

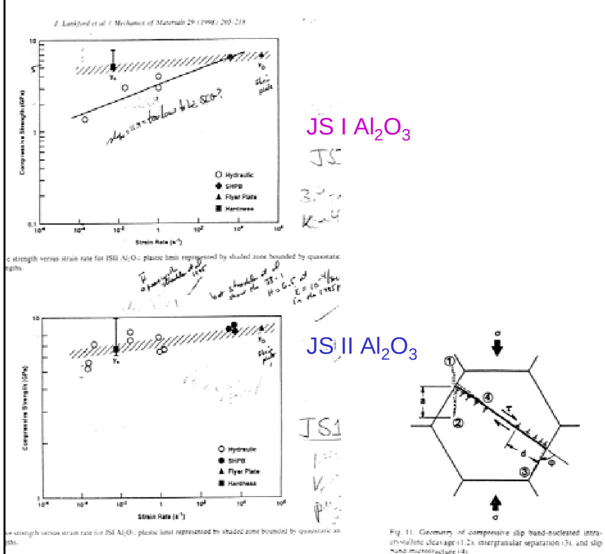
Scale: 1:1 (mm)
Thick lines denote confinement.

The Myriad Sizes and Shapes

Kolsky testing review2.ppt



State of the Art of SHPB/Kolsky Testing of Ceramics - *Examples*



Lankford et al. 1998

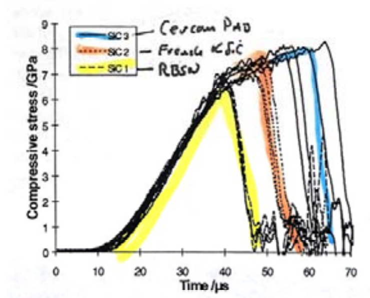


FIGURE 2. SHPB stress histories exhibiting prolonged periods of inelastic behaviour for SiC 2 and SiC 3.

Pickup and Barker 1997

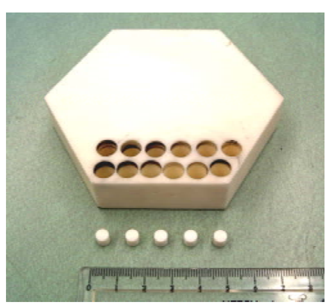
State of the Art of SHPB/Kolsky Testing of Ceramics - *Examples*

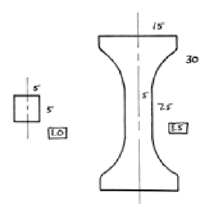
Material	Lab 1 **SWRI** Lankford (GPa) (/sec)	Lab 2 **JHU** Ramesh (GPa) (/sec)	Lab 3 **U. ARIZ.** W. Chen (GPa) (/sec)	Lab 4 **ARL** Weerasooriya (GPa) (/sec)	Lab 5 **NIST** (GPa) (/sec)	Lab 6 **DRA-** Chertsey Pickup Barker, James (GPa) (/sec)	Lab 7 **UCSD** Shih, Meyers, Nesterenko, S. Chen (GPa) (/sec)	**Watertown** **Carl Tracy Static σ_c** **(GPa)**
CoorsTek **AD 995** Al_2O_3	**3.5 – 9** 1×10^3 (strong rate sensitivity)	**4.03** (8) .7 to 2.2 x 10^3	**~ 4.3** .3 x 10^3 (some confinement)	-	In progress	-	-	(AD 94) 3.49 ± 2% 3.59 ± 3%
St. Gobain-Carborundum Hexoloy **α - SiC**	**4.0 to 6.3** .5 to 5. x 10^3 (strong rate sensitivity)	**2.6** .5 to 2 x 10^3	---	-	-	(French version) 7.5 .9 x 10^3		**4.55** ± .43 (9%) (10)
Cercom SiC B			---			**8.17 ± .16** .9 x 10^3 (extended strain to failure, plasticity?	**5.4** (6) .4 to .8 x 10^3	-
Cercom SiC N		**4.9 to 7.1** (100 – 500 MPa/μsec)		In progress				-

Summary: Not much consistency. Problems?

Richard Fields NIST Kolsky Projects

AD 995 Alumina Ceramic Testing





Special Workshop – Kolsky/Split Hopkinson Pressure Bar Testing of Armor Ceramics by *James McCauley*

SPECIAL WORKSHOP

Kolsky/Split Hopkinson Pressure Bar Testing of Armor Ceramics

Holiday Inn, Cocoa Beach, Florida

January 27, 2005

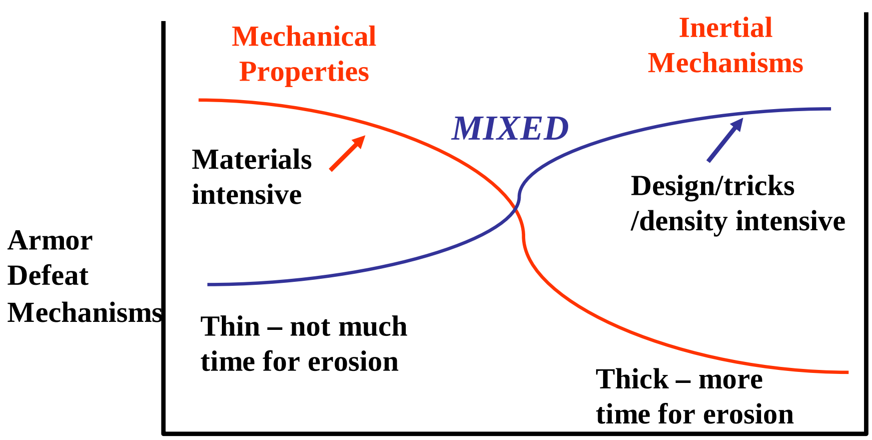
Jim McCauley

Army Research Laboratory, APG. MD

Sponsored by Dr. Doug Templeton, TARDEC, Warren, Michigan

Small caliber | **Medium caliber** | **Large caliber**

Ceramic Damage and Failure Mechanisms



Projectile Kinetic Energy = ½ mv² →

Impact Pressure $\cong$ **fct (v** $(\rho_p \times \rho_t)$ →

Note: bullets of same mass, but different densities can have different impact pressures

Simplified Ceramic Armor Ballistic Impact Event

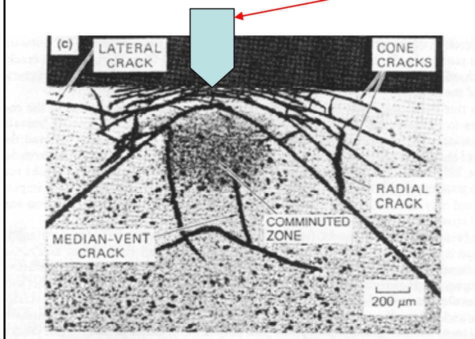


FIG. 8. Sectional views of subsurface cracking pattern in HP Si_3N_4 impacted by 2.4 mm diameter steel spheres at velocities of 56.4 m s^{-1} (a) and 231 m s^{-1} (b) and by a 2.4 mm diameter tungsten carbide sphere at 231 m s^{-1} (c).

Shockey, et al., 1990

<u>Conceptualized Temporal Events*</u>

- **"shatter bullet" –disperse energy**
- **Shock Induced Damage**
- **"Dwell" Projectile at Interface**
- **Instantaneous Plate Bending**
- **Dynamic Hertzian Damage**
- **Comminuted Zone Formation and Penetration**

***<u>Environment/Design (package) independent</u>**

- Can mitigate shock
- Can mitigate bend
- Can extend "dwell"
- Change Hertzian damage
- Change fragmentation

Key Issue in Armor Ceramics

What combination of static/dynamic mechanical properties (figure of merit) control armor performance and how are these properties controlled/influenced by intrinsic and extrinsic material characteristics?

<u>Intrinsic</u>:

- **Anisotropic crystallographic elasticity**
- **Phase transitions**

<u>Extrinsic</u>: (microstructure)

- **Grain size**
- **Grain boundary regions**
- **Defects: pores, inclusions, residual stress, etc.**

<u>Intrinsic and extrinsic control of dynamic mechanical properties</u>:

- **"Effective Plasticity"**
- **Deformation and damage mechanisms**
- **Static/dynamic Compressive strength**
- **Confinement**
- **etc.**

Armor Ceramics Development

- Much anecdotal and hard evidence that intrinsic and extrinsic material characteristics significantly influence armor ceramic performance – they certainly influence static and dynamic mechanical properties
- Further development of armor ceramics would significantly benefit from valid Figures of Merit (FoM). Would allow for a systematic approach to processing and microstructure control.

$$FoM_{threat} = fct\ (property\ 1,\ property\ 2,\ property\ n,\ \ldots)$$

- Three step process: (threat dependent)
  - Quantify property - material characteristics relationships
  - **Validate mechanical property measurements**
  - Relate and validate FoM relationship to ballistic performance
- Limited past success:
  - Wrong or incomplete properties
  - **Property measurements not valid or lacked reproducibility**

Is One Figure of Merit Possible For Ceramics?

- Given different threats and nature of event – complicated, but may be possible!
  - small, medium, large calibre, projectile material, and different velocities
  - suggests a series of figures of merit, even for the different stages of the ballistic event – movement from monolithic to layered or graded materials

Ceramic Armor Figure of Merit*

- $M = EH/\rho$
- Nominal Values:

  B_4C = 480

  Al_2O_3 = 143

  TiB_2 = 418

- Does this work??

* Stiglich, 1968; Niese, Unknown date

Ballistic Energy Dissipation Figure of Merit*

$$D = 0.36(H_v cE)/K^2_{Ic}$$

D = energy dissipation

H_v = Vickers hardness

c = longitudinal sound velocity = $((K+(4/3)\ G)/\rho)^{1/2}$

K = bulk modulus; G = shear modulus

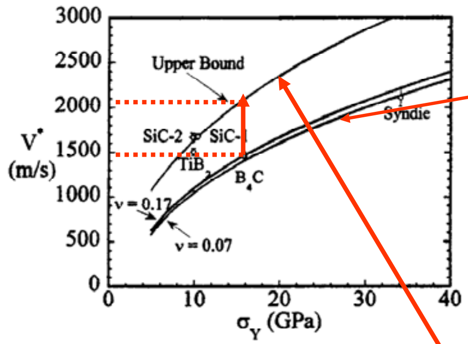
E= elastic modulus

K_{Ic} = fracture toughness

* Neshpor, Zaitsev, Dovgal et al., CIMTEC, 1995

Plasticity

Lundberg, et al. 2000 Analysis of Interface Defeat or Dwell



Reverse ballistics on confined ceramics using WHA

V* = penetration velocity; transition from interface defeat to normal penetration

σ = compressive yield strength of target

Determine the two extremes for the maximum normal surface load per unit area

- **Elastic case**:

$P_o = (2.601 + 2.056\, \upsilon)\, \tau_y$

τ_y = shear yield stress

If $\tau_y = \sigma_y/2$; then $P_o = (1.30 + 1.03\, \upsilon)\, \sigma_y$

$\upsilon = 0.1;\ P_o = 1.4\, \sigma_y$

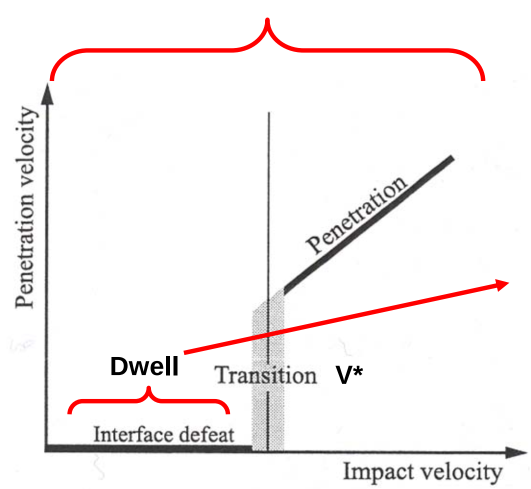
$\upsilon = 0.5;\ P_o = 1.82\, \sigma_y$

- **Plastic case – add plasticity**:

$P_o = 5.7\, \tau_y$ or $2.85\, \sigma_y$

Can maximize P_o by:

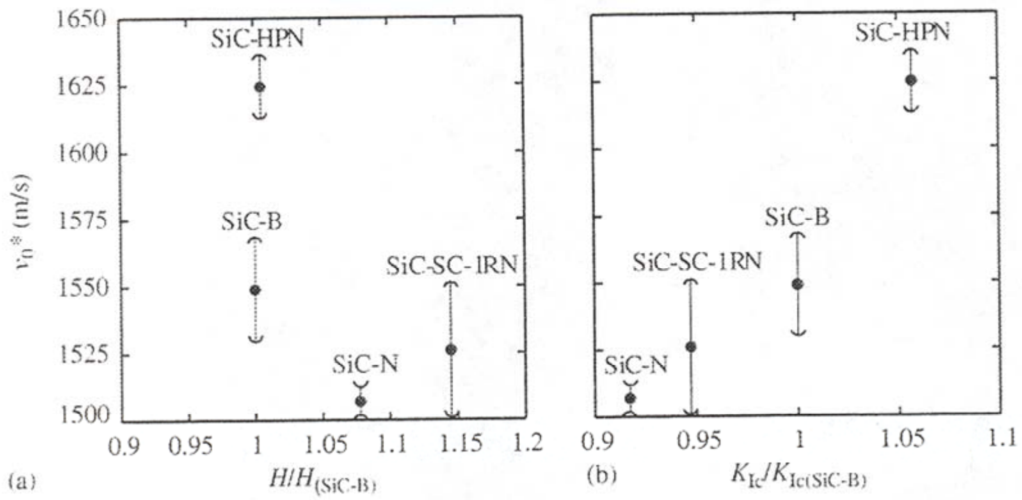
- increasing shear strength or yield strength
- increasing υ (Poisson's ratio)
- **adding effective plasticity**



Can we measure this in a simple test

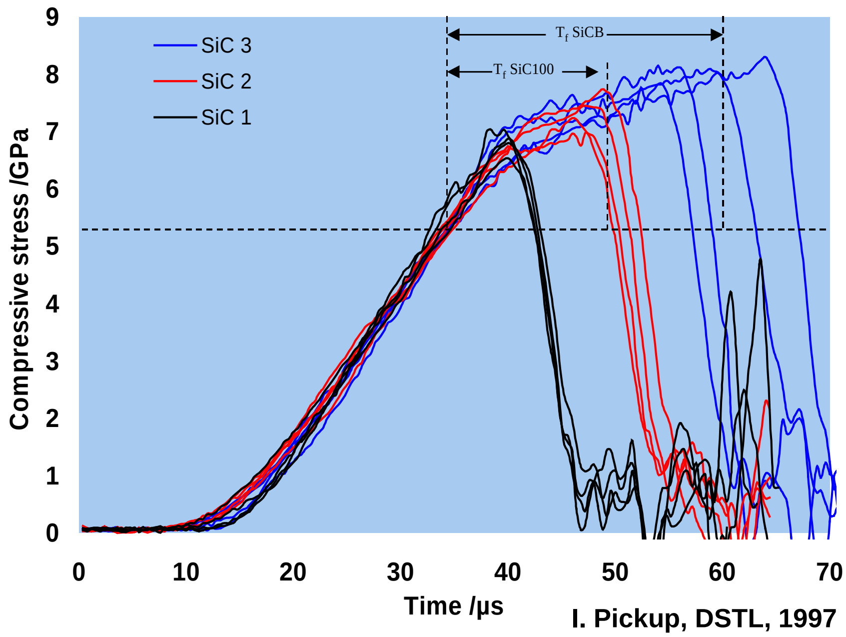
FIGURE 6: Penetration velocity versus impact velocity. Transition between interface defeat and penetration. The shaded area indicates the transition velocity interval.

Patrik Lundberg, Acta Universitatis Upsaliensis, Uppsala 2004



Transitional Velocity v_0^* vs. Vickers hardness H (a) and fracture toughness K_{Ic} (b).

Data are normalized to SiC-B. Lundberg and Lundberg, 2004, in press, Int. J. of Impact Engineering.



Tusit Weerasooriya
Impact Physics Branch

Obtaining High-Rate Behavior of Ceramics using Valid Hopkinson Bar Experiments

Some Personal Observations

Tusit Weerasooriya
ARL

Tusit Weerasooriya
Impact Physics Branch

Issues

- Challenges in using SHPB to determine material properties of brittle material:
  - Premature failure from non-equilibrated loading
  - Maintaining constant strain-rate during testing
  - Premature failure from early damage accumulation
  - Premature failure from stress concentration
  - Accurate measurement of small strains
  - Repeated experiments to get statistical behavior and the effect of flows
    - Elimination of scatter from experimental methods
  - Effective and controllable methods of dynamic confinement
    - Strain measurements

2

Conventional Split Hopkinson Pressure Bar

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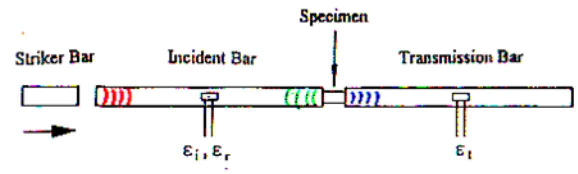
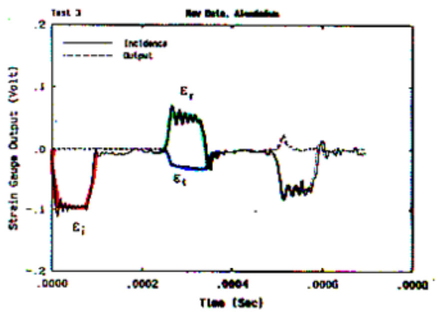
Impact Physics Branch





$$\dot{\varepsilon}(t) = -\frac{2c_0}{L}\varepsilon_r(t), \quad c_0 = \sqrt{\frac{E}{\rho}}$$

$$\varepsilon(t) = \int_0^t \dot{\varepsilon}(\tau)d\tau$$

$$\sigma(t) = \frac{A_0}{A_s}E\varepsilon_t(t)$$

3

Ref: Frew, Chen and Forrestal

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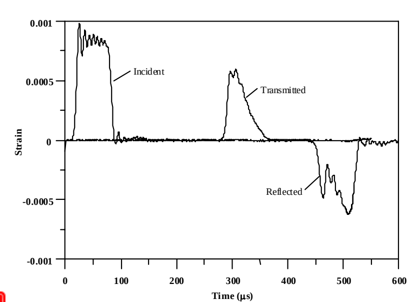
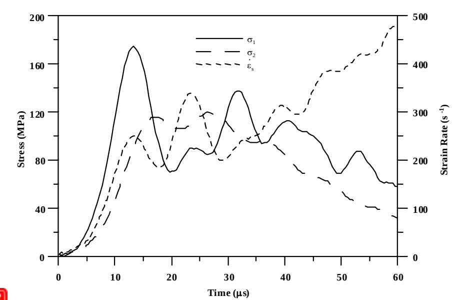
Strain-Time Signals for a Conventional SHPB Experiment with a Limestone Sample



US Army Corps of Engineers — Engineer Research and Development Center

Interface Stresses and Strain Rate from a Conventional SHPB Experiment with a Limestone Sample



US Army Corps of Engineers — Engineer Research and Development Center

- Axial stress not in dynamic equilibrium
- Strain rate not constant during the experiment

4

Conditions for a Valid SHPB Experiment

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Impact Physics Branch

- Stress in the specimen is in dynamic equilibrium.
- Specimen deforms homogeneously.
- Specimen deforms at a constant strain rate.
- Stress concentrations are minimum in both the specimen and the bars.
- Bar end faces remain flat and parallel.
- Bars remain elastic.

5

Dynamic Equilibrium

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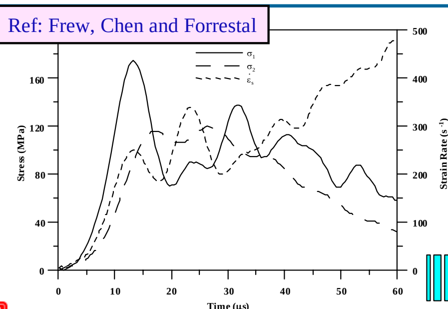
Interface Stresses and Strain Rate from a Conventional SHPB Experiment with a Limestone Sample

Ref: Frew, Chen and Forrestal



US Army Corps of Engineers
Engineer Research and Development Center

Disadvantages:

- Lower maximum strain-rates
- Greater efforts - experiments are not easy
- Wave-shaping is a Science-Art

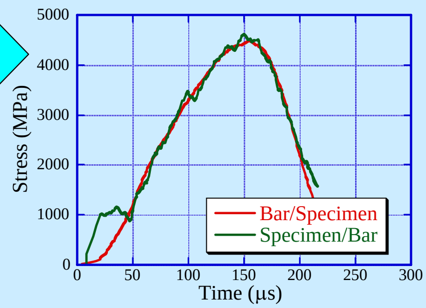
Effect:

- Early damage
- Wrong failure strength
- Loading history unknown

Remedy:

Sophisticated Wave-shaping

Stresses at the Specimen/Bar Interfaces



Constant Strain-Rate

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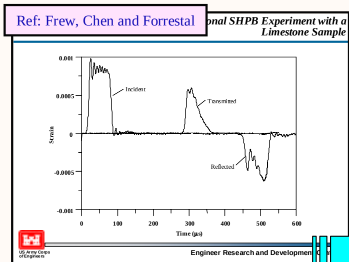
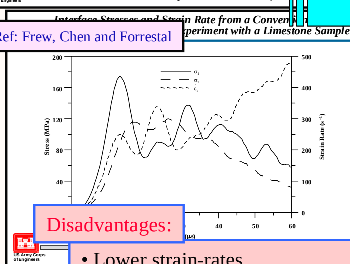
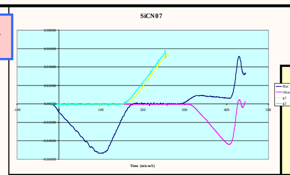
Effect:
• Unknown strain-rate history

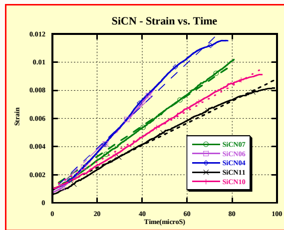
Ref: Frew, Chen and Forrestal

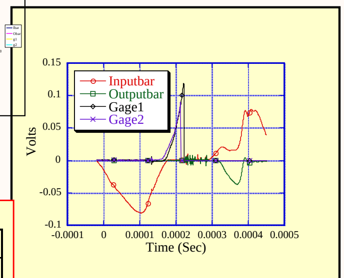


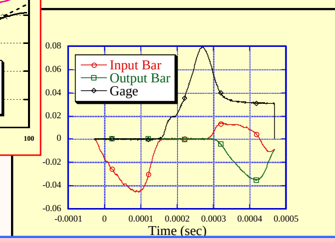
Ref: Frew, Chen and Forrestal











Disadvantages:
• Lower strain-rates
• Greater efforts - experiments are not easy
• Wave-shaping is a Science-Art

Remedy:
• Sophisticated wave-shaping to obtain constant strain-rate
• Ramp loading for linear elastic behavior
• Change from ramp for any non-linear behavior

Annealed Copper Pulse Shaping Models for Linear Stress-Strain Behavior

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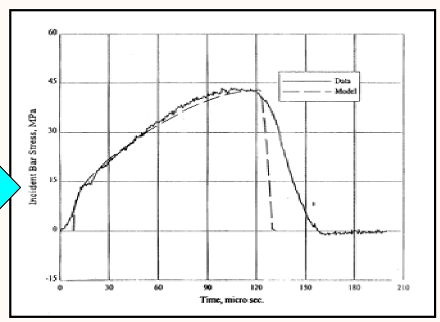
Impact Physics Branch

$$\sigma_c = \sigma_o \frac{\varepsilon_c^n}{(1-\varepsilon_c^m)}$$

$$\sigma_i = \frac{\sigma_o a_o}{A} \frac{\varepsilon_c^n}{(1-\varepsilon_c^m)(1-\varepsilon_c)}$$

$$t = \frac{h_o}{V_o} \int_0^{\varepsilon_c} \left[1 - K \frac{x^n}{(1-x^m)(1-x)} \right]^{-1} dx$$

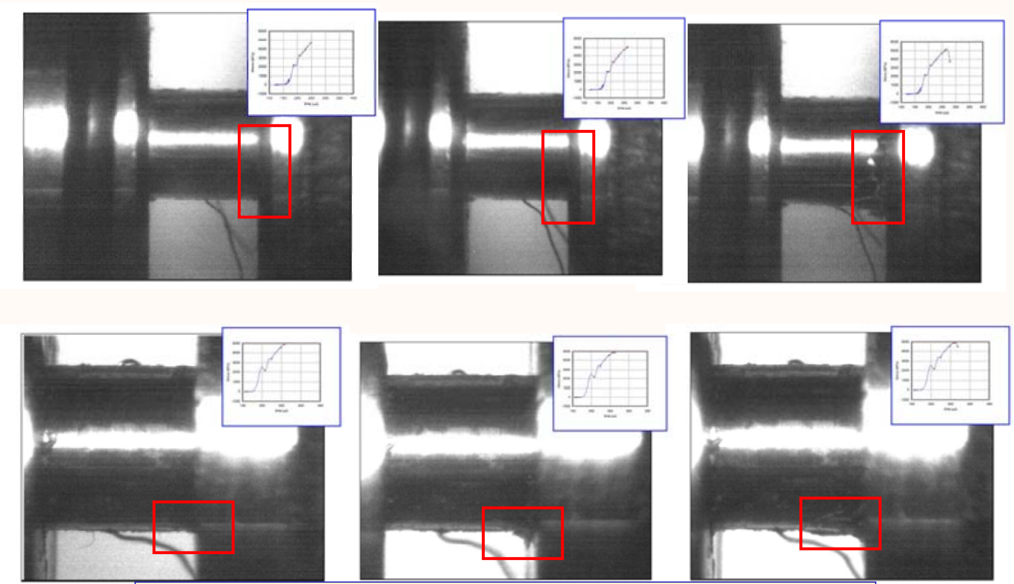


Nemat-Nasser et al
Frew, Chen and Forrestal

8

Homogeneous Deformation
Stress Concentration

Tusit Weerasooriya
Impact Physics Branch



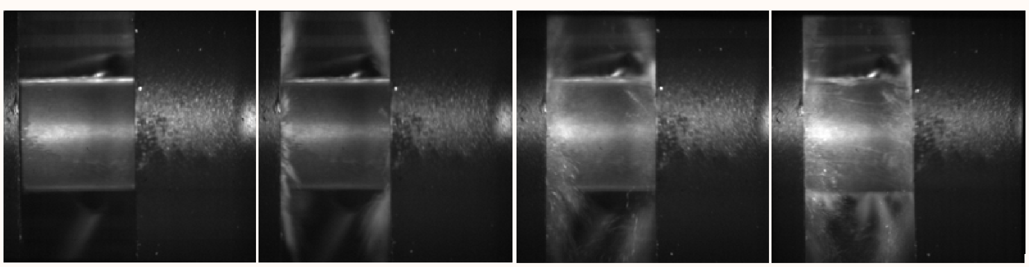
Failure initiation is at the input-bar/specimen interface - at corners ?

9

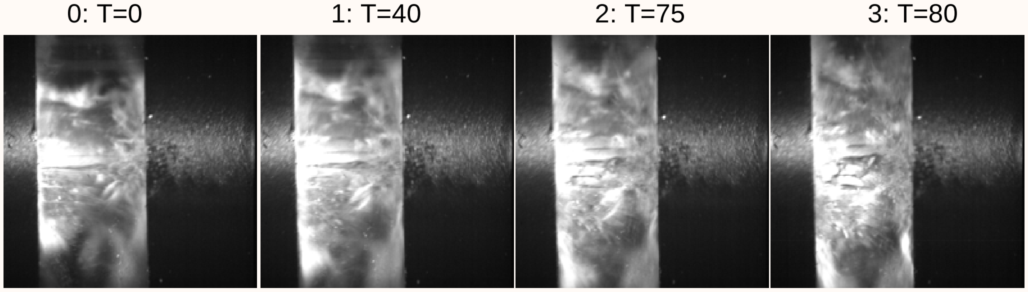
Dynamic Failure of SiC-N
(from Wayne Chen at Purdue)

Tusit Weerasooriya
Impact Physics Branch

Unit: microsecond



0: T=0 1: T=40 2: T=75 3: T=80



4: T=85 5: T=90 6: T=95 7: T=100

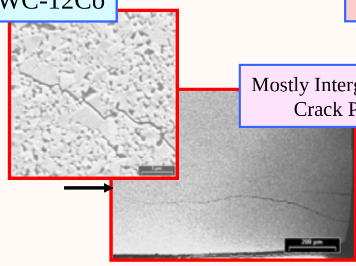
10

Homogeneous Deformation
Stress Concentration

Tusit Weerasooriya
Impact Physics Branch

Effect:
- Failure not dependent on defect distribution
- Lower failure strengths

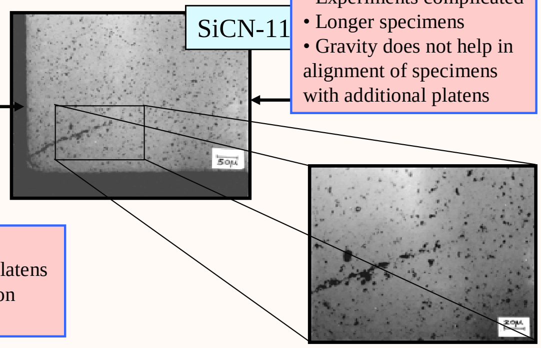
WC-12Co



Mostly Intergranular Crack Path

Disadvantages:
- Expensive specimens
- Experiments complicated
- Longer specimens
- Gravity does not help in alignment of specimens with additional platens

SiCN-11



Remedy:
- Innovative alignment devices
- High machining tolerances for specimens, bars, platens
- Specimen geometries with less stress concentration
  - cylindrical -> dumbbell

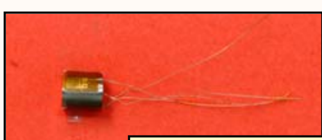
Failure initiation at the loading surface starting most probably at a corner

11

Small strain measurements
(less than 2% strains)

Tusit Weerasooriya
Impact Physics Branch

Effect:
- Large errors from strains from reflected pulse
  - loading train
  - specimen indenting into bars or platens
  - specimen misalignment



Strain Gauged Specimen

Remedy:
- Strain gauging specimens
- Innovative alignment devices
- High tolerance specimens
- Can observe the presence of bending

Disadvantages:
- Hard to gauge on smaller specimens
- Unreliable bonding of adhesives at high-rates

12

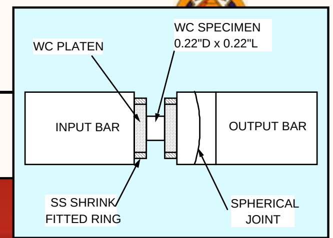
Bar/Specimen Interface

Effect:

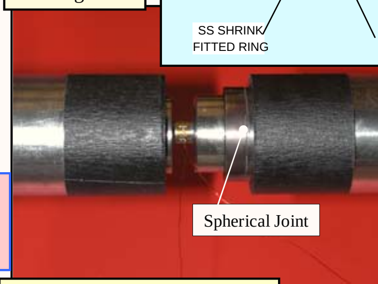
- Imperfection in loading train
- Specimens indenting into bar or loading-platens
- Loading faces not perfectly flat and parallel

Remedy:

- Impedance matched WC platens
  fitted with heat shrunk steel ring
- Dumbbell specimens - impedance matched flange



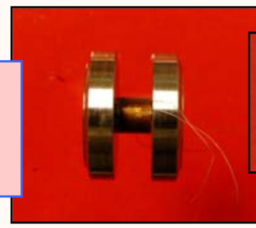
Loading Train



Platens/Specimen/Alignment device

Disadvantages:

- Expensive
- Experiments complicated
- Gravity does not help in alignment
- Longer specimens (in dumbbell)
- More parts to align (in WC platens + specimen)



Platens

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Lateral Confinement

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Impact Physics Branch

- Challenges in experiment design
  - Methods of confinement
    - Sleeve
      - Initial clearance
      - Material to use
      - Inability to control the confining pressure
    - Hydraulic confinement
      - Effect of fluids
  - Much higher strengths: may not be achievable with SHPB technique
  - Direct strain measurement not possible

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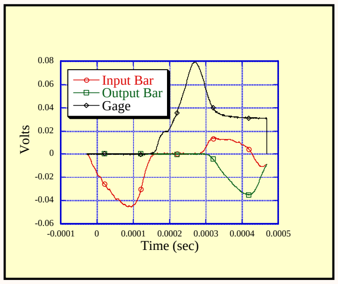
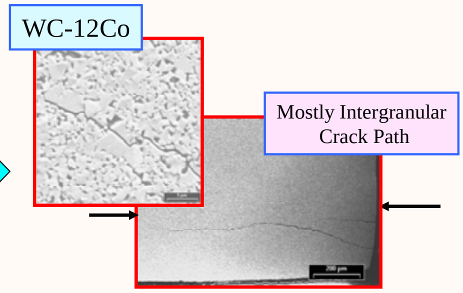
Specimen Recovery

Tusit Weerasooriya
Impact Physics Branch

- Specimen recovery with a know loading history
  - Observation of damage from recovered specimens can be related to the loading history
  - Short input pulse or loading stopper sleeve
  - Shorter output bar to avoid reloading



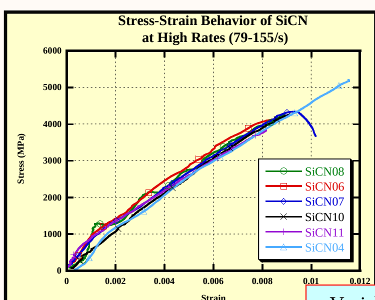


15

Measure of Success Concerns to be Resolved

Tusit Weerasooriya
Impact Physics Branch

- Repeatability
  - Need more tests at the same condition to capture the ceramic behavior
- Scatter should be due to
  - material defects distribution
  - not due to inability to do good experiments
- May be able to identify differences in material behavior due to the material microstructural differences
  - Example: WC-6Co vs. WC-12Co
- May be able to identify rate sensitivity
- Ability to relate the observed microstructural damage to loading history
- May be good enough to use in material models for simulations
- Data may not be good enough to develop micro-mechanistic based material models



- Variability in failure behavior (failure stress)
- Repeatability in deformation behavior

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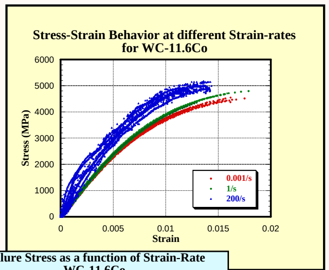
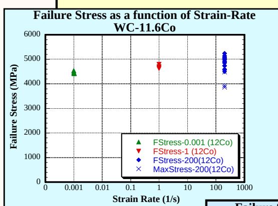
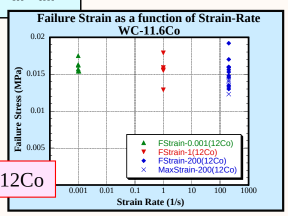
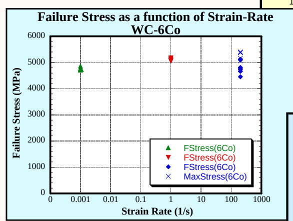
Measure of Success
Concerns to be Resolved

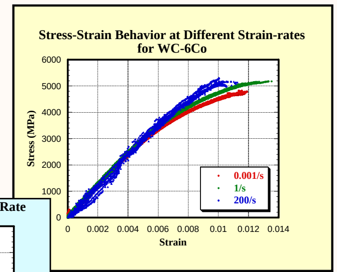
Tusit Weerasooriya
Impact Physics Branch

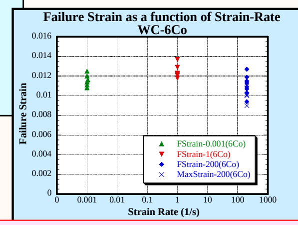












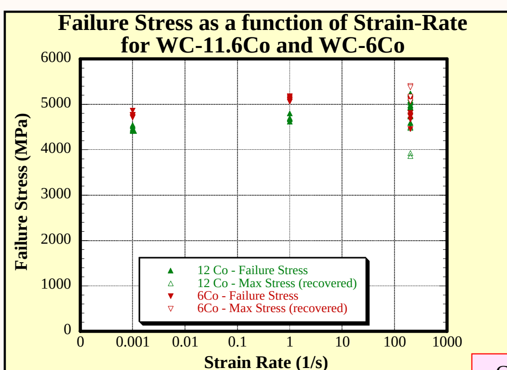
- Reasonable for WC-12Co

- Contradictory for WC-6Co
  - Failure stress/strain increases and then decreases with strain-rate - is it real or due to experimental inabilities

Measure of Success
Concerns to be Resolved

Tusit Weerasooriya
Impact Physics Branch

- Slow and intermediate rate data is good (SD ≈ 50MPa)
- High rate data could be improved (SD ≈ 650MPa)
  - With better experimental methods
    - Better specimen geometry ?
    - Better alignment methods ?



- Can I make conclusions from this high rate data?
- Preliminary WC-0Co data have even bigger scatter…

Measure of Success
Concerns to be Resolved

Tusit Weerasooriya
Impact Physics Branch

- To correlate the compressive failure strength as a measure of ballistic performance and also to compare it with a failure strength from another material
  - Strength obtained should be from many tests
  - Scatter due to experimental methods should be minimized or eliminated
  - Scatter should only be from material microstructural variations

• So far I cannot differentiate Compressive Strengths of WC-12Co, WC-6Co and WC-0Co at high rates, but I can differentiate them at low rates ………

I have a long way to go in improving experimental methods

19

High-Rate Measurements on Ceramics by *George Quinn and Richard Fields*

From NIST's Microsecond Thermophysics Lab:

High Rate Measurements on Ceramics

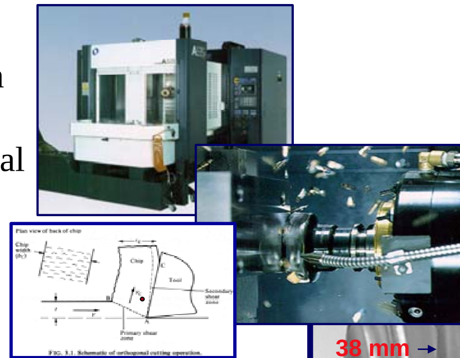
George Quinn and Richard Fields
Materials Science and Engineering
NIST

NIST-ARL Ceramic Kolskey Meeting
Cocoa Beach - January 27, 2005

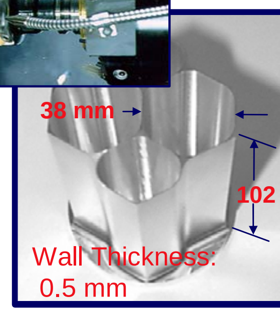
- NIST participants:
  - Richard Rhorer, Eric Whitendon, Mike Kennedy – Manuf. Eng. Lab
  - Tim Burns – Info. Tech. Lab
  - Howard Yoon – Physics
  - Lyle Levine – Metallurgy
- External Collaborators
  - Tusit Weerasooriya, Jim McCauley – ARL
  - Wayne Chen – ASU
  - Achter Khan – John Hopkins
  - Matt Davies – UNC State

Motivation for developing NIST Facility

- Successful NIST High Speed Spindle program with industry
- Need for Metal Removal process models in high speed machining operations
- Data and const. Eqns. needed for high rate deformation at high temperatures and high heating rates



$$\sigma = \sigma_r \left[1 - \left(\frac{T - T_r}{T_M - T_r} \right)^m \right]$$



Machining in the 21st Century

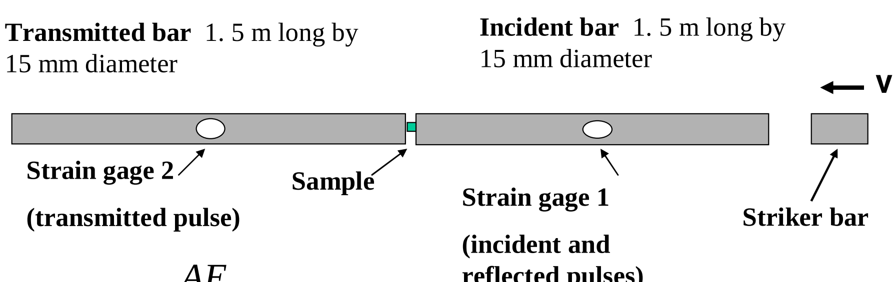
- Machining objectives:
  - Material removal rates are rapidly increasing: >3000 cm^3 /min
  - Precision, or the allowable uncertainty, of processes has to improve at the same time the removal rates are increasing: Goal < 1μm tolerances.
- Determine machining parameters using computer-based models
  - Tool geometry
  - Cutting speed
  - Feed rate

- Need models that represent materials behavior under the following conditions:
  - Very high strain rate: up to 10^6 s^{-1}
  - High strains: 100% to 2000%
  - Temperatures: 100 to 1000 C
  - High heating rates: ~ 10^6 C/s
  - Heating times: 1 ms to 1 s

Pulse Heated Kolsky Bar

- Strain rates between 10^3 and 10^4 s^{-1}
- Max Strain: 20-40%
- Heating rates up to 10^6 °C/s^{-1}
- Max Temp: >1000 °C
- Imaging
  - Visible: >10^5 frames/s
  - I.R.: >10^4 frames/s

Traditional Split Hopkinson Pressure Bar, or Kolsky Bar



$$\sigma(t) = \frac{AE}{A_s}\varepsilon_T$$

where, A = area of the bar
A_s = area of the sample
E = modulus of the bar

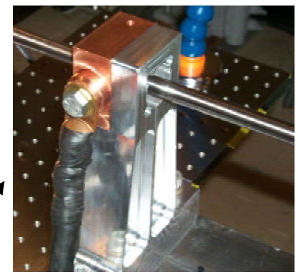
$$\varepsilon(t) = \int \frac{2c_0}{l_s}\varepsilon_R(t)dt$$

Where c_0 = wave speed of bar
l_s = length of the sample

Pulse heating applied to the NIST Kolsky bar apparatus

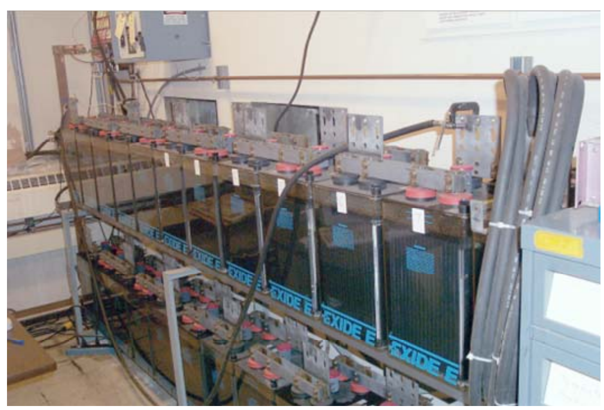
Photo by Robert Rathe

Note: thermal camera and micro pyrometer

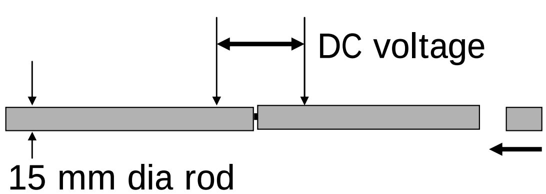


Electric current carried to the bar and sample through graphite bearings

Pulse heating



- Large bank of batteries to provide a DC voltage
- FET switches provide millisecond programmable control of current



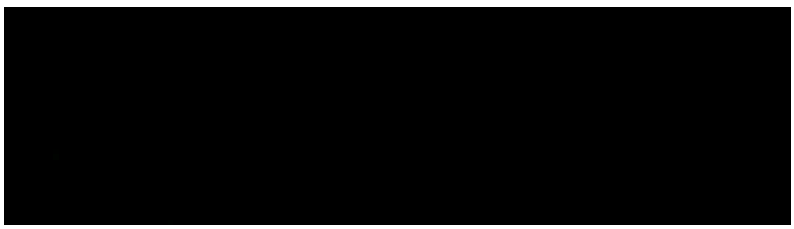
Smaller sample size than used in the traditional Kolsky bar

Sample: 4 mm diameter with 2 mm length for a 15 mm diameter bar

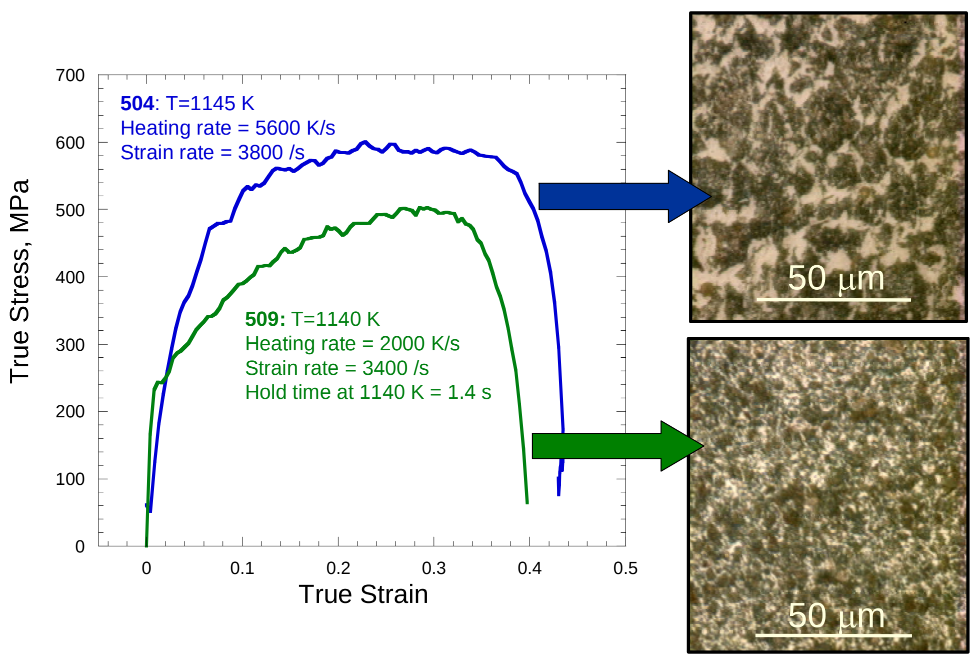
Thermal imaging of impacts

(320 x 256 InSb array, 3000 frames/s)

End of bar reflecting the emissions of the sample. There may also be some emissions from the bar as well.



Effect of Heating Rate on C Steel



Other Applications

- Machining Steels, Al alloys, Ti alloys, cast irons
- Frangible bullets
- WTC columns
- UHPM
- Nitrogen SS (some like ceramics)
- High Rate compaction of amorphous powders
- CERAMICS…

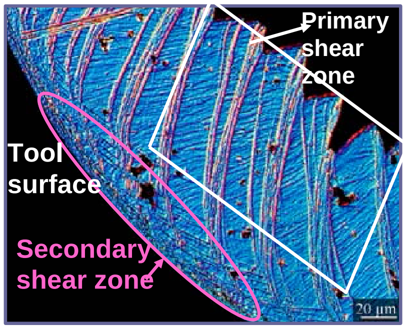
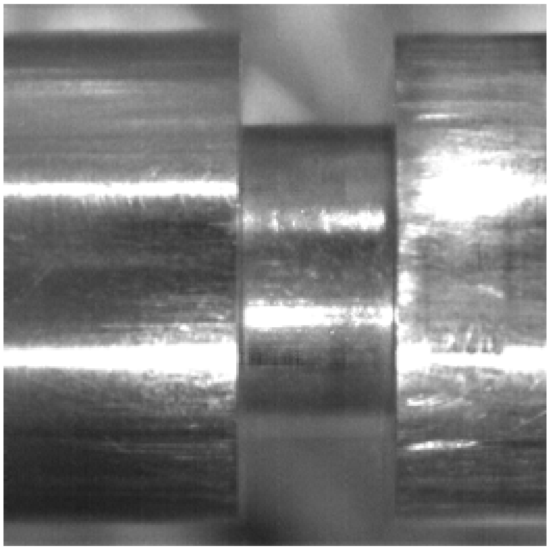
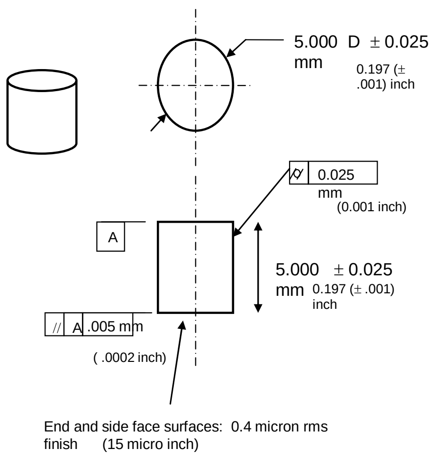


Photo: Remington "Disintegrator"

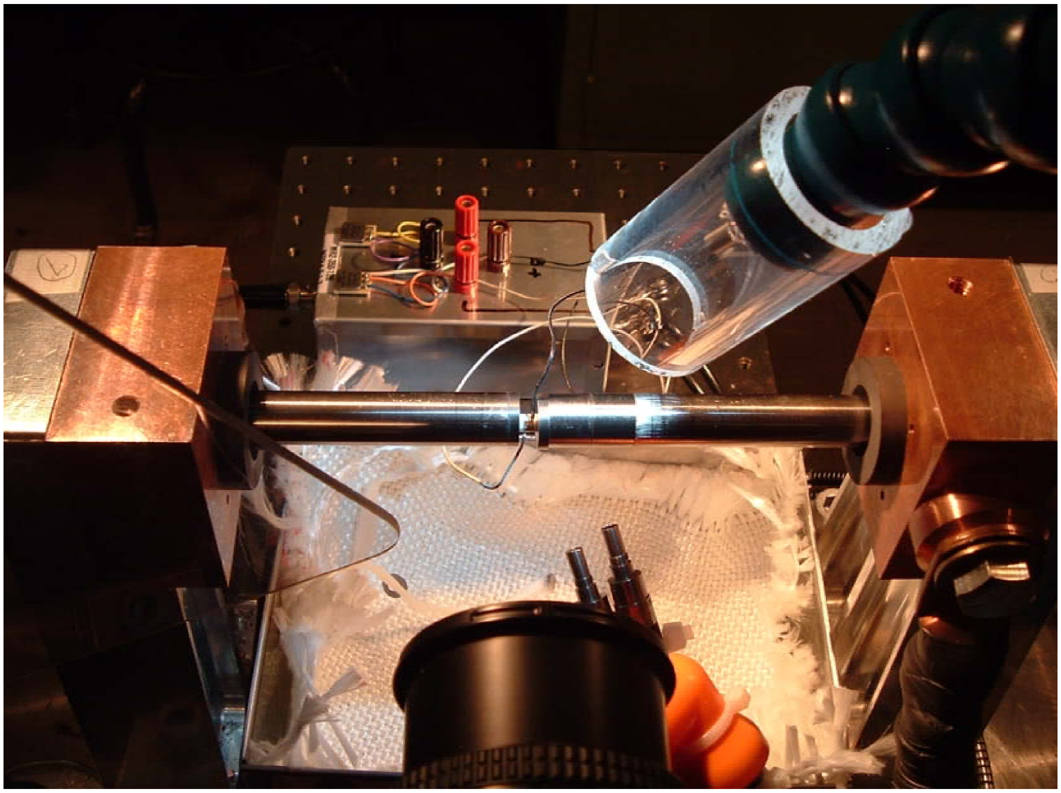
Frangible Bullets



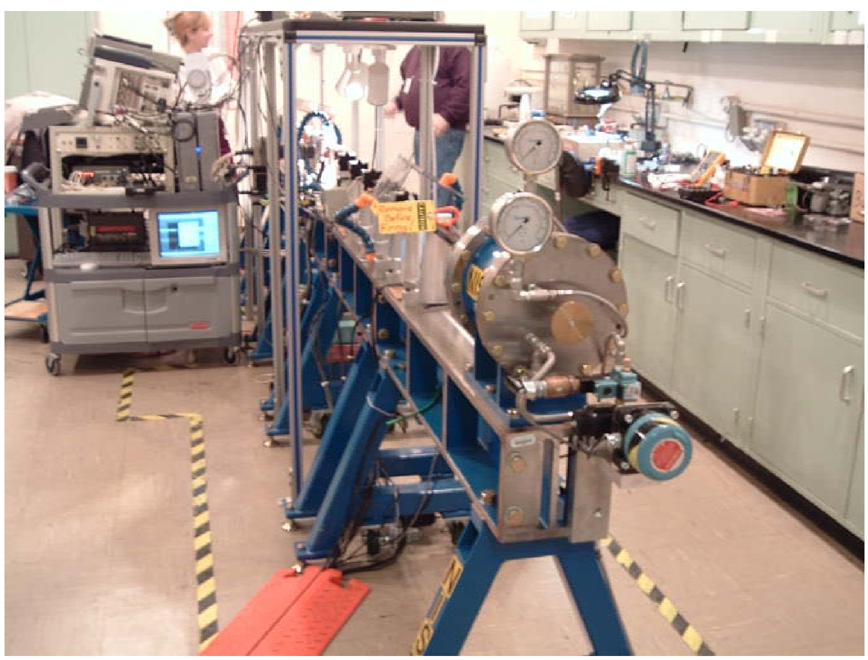
High Rate Testing of Ceramics



- Cylinder vs Dumbell shaped samples
- Alignment Critical
- Need to achieve high stresses
- Method to detect dissipation (plastic strain and/or heat)

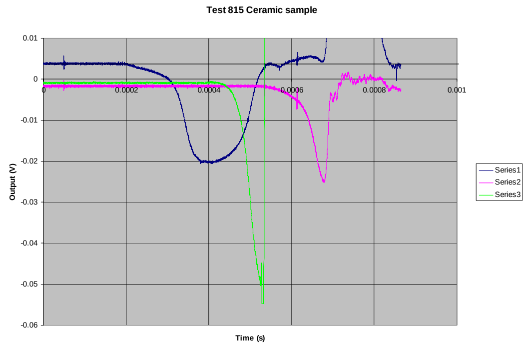


High Speed Imaging

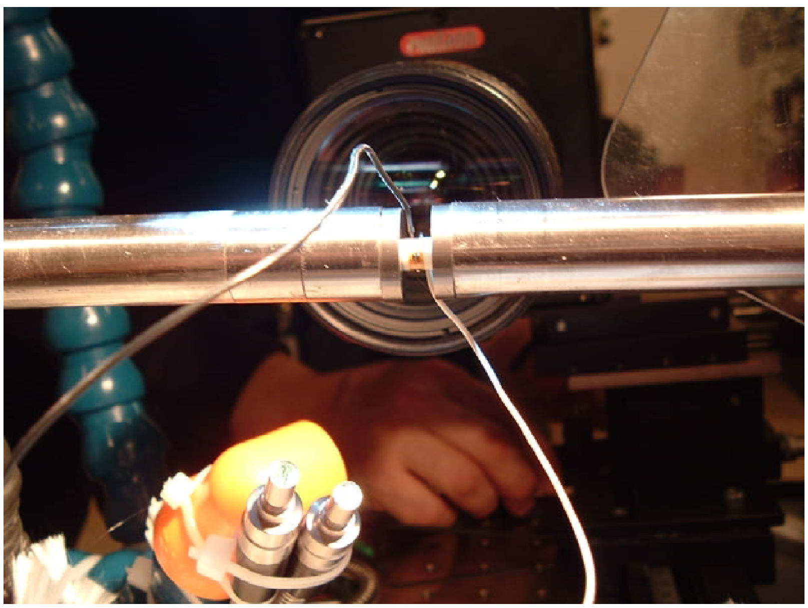


Shaping the incident wave

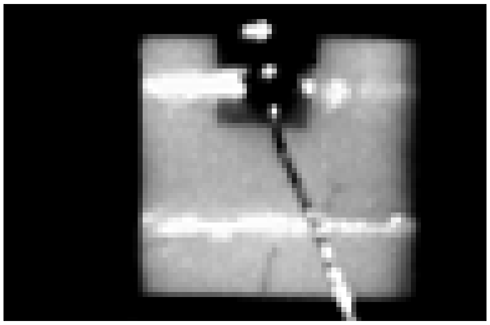
- Copper disks added between striker bar and incident bar
- Gives ramp loading so that point of fracture can be more easily detected
- Needs to be optimized

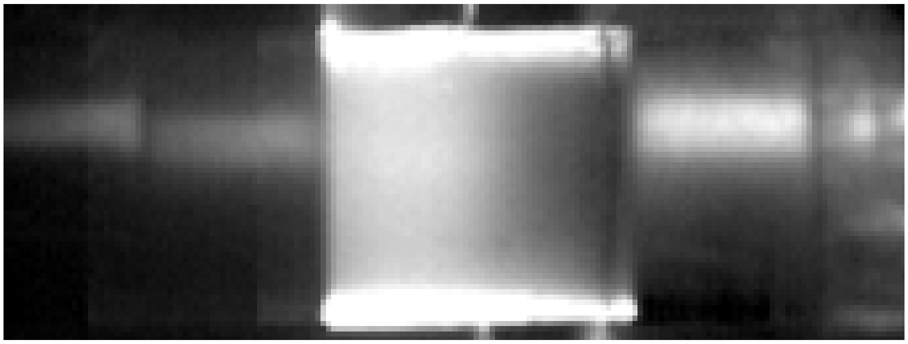


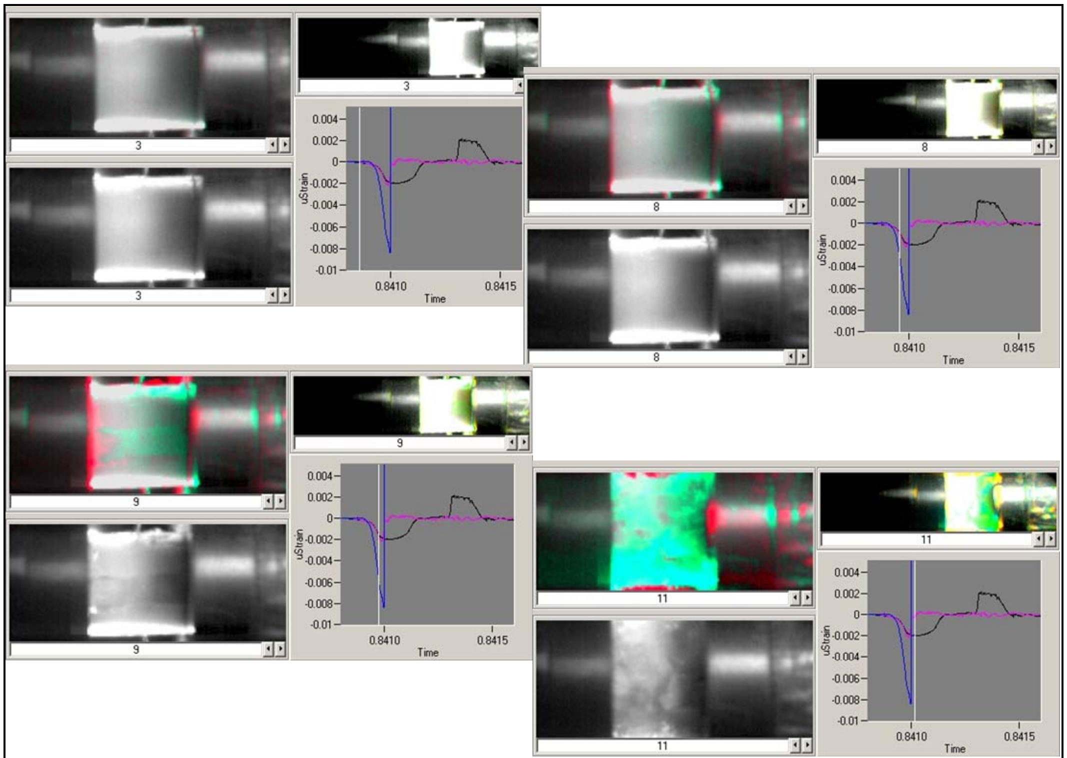
Sample in Kolsky Bar



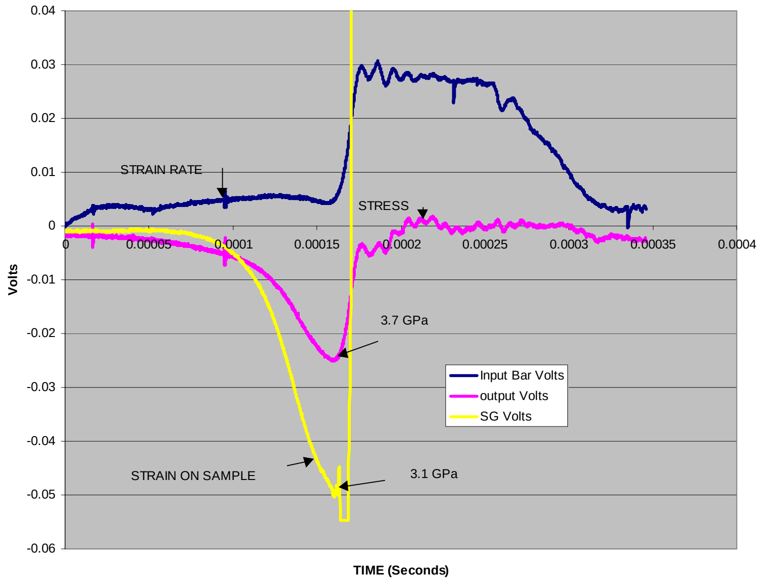
Alignment is Critical



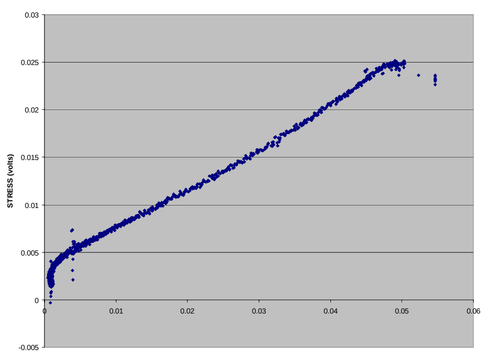


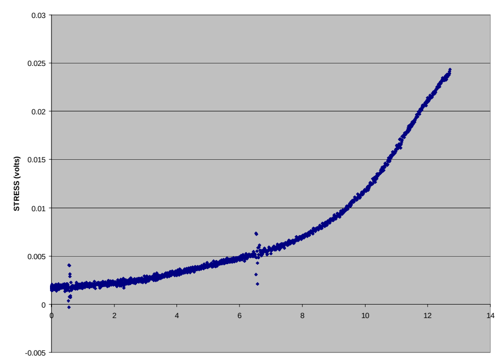


SG Records quantify behavior



Energy Dissipation Process at High Stresses?





Thermal Imaging may help.

Uncertainty Analysis of Kolsky Bar Strain Gage Output

Dick Rhorer
National Institute of Standards and Technology
Gaithersburg, Maryland

Presented to the ASPE Summer Meeting 2004
Penn State—July 1, 2004

Some Issues to Address

- Consistency and uncertainty in Kolsky Bar Testing
- Ways to routinely achieve high stress loadings
  - sample geometry
  - alignment
- Detection of dissipation processes
  - strain gages
    - wave shaping important
  - thermal imaging
- High speed video important to understanding what's happening

Quinn's Rules of Thumb for Round Robins by *George Quinn*

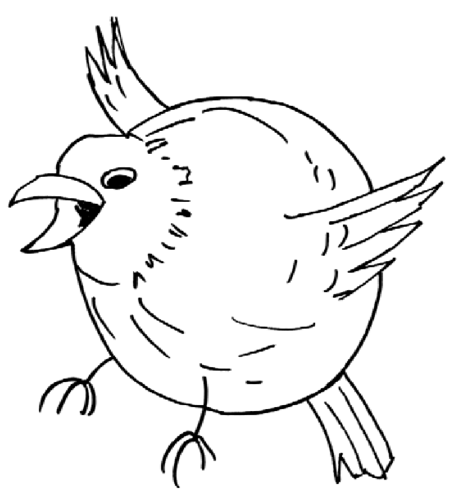
Quinn-kolsky round robin subtalk.ppt

Quinn's Rules of Thumb for Round Robins

1. **Have a specific, focused objective. Do not undertake one "just for the fun of it!"**
2. **Run a 2-3 laboratory mini round robin first.**
3. **Keep it to less than one man week of work per participant.**
4. **Ensure that the material is consistent and uniform.**
5. **Give the participants extra specimens or material.**
6. **Keep some extra material as a reserve.**
7. **Write the instructions very, very carefully.**
8. **Don't add too many "interesting" side issues.**
9. **Start with no fewer than 6-8 labs.**
10. **Expect the unexpected. Murphy's laws are very active**
11. **Consult a statistician, if there is any doubt about the test plan or the interpretation of the results.**

G. Quinn, "VAMAS at 12," Bulletin of the American Ceramic Society, Vol. 78, No. 7, July 1999, pp 78-83.

Round robins



Experience with Round robins

Quinn:

Set up and ran 6

Participated in 9 more

Observed 26 others

LIST OF CERAMICS ROUND ROBINS (September 2004)

(Quinn participated in or led the ones that are color coded

The Technical Cooperation Program (TTCP)	
Flexure Strength	**(1983-1985)**
Tension Strength of Ceramic Matrix Composites	(1986-1991)
International Commission on Glass, TC#6	
Strength and Dynamic Fatigue of Flexure Bars	(- 1985)
Instrumented Hardness	(1992-)
Versailles Advanced Materials and Standards (VAMAS) TWA #3	
Dynamic Fatigue, Flexure Strength	(1987-1990)
Hardness I, Vickers, Knoop, Rockwell C	(1988-1989)
Fracture Toughness I, Room Temp. (SEPB, IS, IF)	**(1989-1992)**
Fracture Toughness II, High Temp. (SEPB, CN, SEVNB)	(1990-1993)
Quantitative Microscopy I (V_f, GS)	(1992)
Fracture Toughness III, Room Temp. (SCF)	**(1992-1993)**
Fractography	**(1993-1994)**
Fracture Toughness IV, Ceramic Composites (SEPB, SEVNB)	(1994-1997)
Quantitative Microscopy II (V_f and AIA)	(1996-1997)
Hardness II, Ceramic Composites, Knoop and Vickers	(1996-1997)
Hardness III, Recording Hardness	**(1996-1997)**
Fracture Toughness V, Room Temp. (SEVNB)	(1997-2000)
Elevated Temperature Flexural Strength	(1999-2000)
Percent Cyrstallinity in Calcium Hydroxyapatite	(2000-)
Inert Flexural Strength of Alumina	(2001 -)
Versailles Advanced Materials and Standards (VAMAS) TWA #22	
Mechanical Properties of Thin Films and Coatings	(1990's)
Versailles Advanced Materials and Standards (VAMAS) TWA #1	
Wear 1, Pin on disk	(1987)
Wear 2, Pin on disk	(1987-1989)
International Energy Agency (IEA)	
Powder Characterization, subtask 2	(- 1989)
Powder Characterization, subtask 6	(1990-1992)
Flexure Strength, subtask 4	(1985-1989)
Flexure Strength, subtask 5(Room and High Temp.), Tension (R.T.) Fractography	(1990-1993)
Machining, Flexure strength, Fractography-origins, subtask 7	(1994-1996)
Thermal Shock, subtask 9	(1996-1998)
Other	
Dynamic Fatigue in Flexure and Biaxial Disk Strength (UK)	(1987-1990)
Fracture Toughness by Double Torsion (ASTM E24.07)	(1982-1983)
Fractography (ASTM E24.07)	(1982)
Flexure and Biaxial Ring-on-Ring Strength (Germany DKG)	(1987-1989)
Fracture Toughness (CSF, IS, IF, SEPB, CN, SENB) (Japan)	(1984-1987)
ESIS Fracture Toughness (CVN, IS, IF, SENB, SEPB)	(1992-1995)
ESIS Characterization of Silicon Nitride, Ceramtec SL 200	(2001-)
NIST SRM Hardness prototypes, HK, HV	**(1993-1994)**
MPA German Hardness, HK, HV	(1994-1995)
NIST Creep of Silicon Nitride	(1996-1999)
DKG (German Ceramic Society) Fracture Toughness and R-curve, SCF	(1996)
CIRP-CSIRO Australian Ultra Micro Hardness (glass, steel, silicon, polymer, ceramic coatings)	(1993-1997)
Ceranorm, German hardness, HK, HV, Rc	(1998-2000)

Why do a Round Robin?

1. Try a new method. Does it work?

2. Expose people to a new procedure.

3. Sell a procedure.

4. Answer a challenge!

5. Determine the repeatability and reproducibility of a procedure.

E.g. ASTM Precision and Bias statement

6. Determine whether the procedure can be done by other labs.

Practicality, equipment, instructions ...

7. Uncover problems, weak points, over sights in the procedure.

8. Determine the robustness of a procedure.

9. Foster good communications between <u>labs</u> and between <u>researchers</u>.

10. Serve a political need.

e.g. "international cooperation"

11. Generate new knowledge.

12. Identify needs for future research.

13. Identify needs for Reference Materials.

Round robins

Key Preliminaries

- Precursor experiments
- Mini round robin

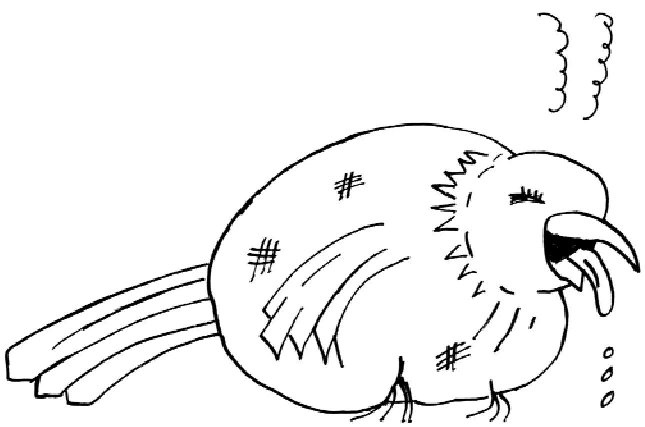
Critical Factors for Success

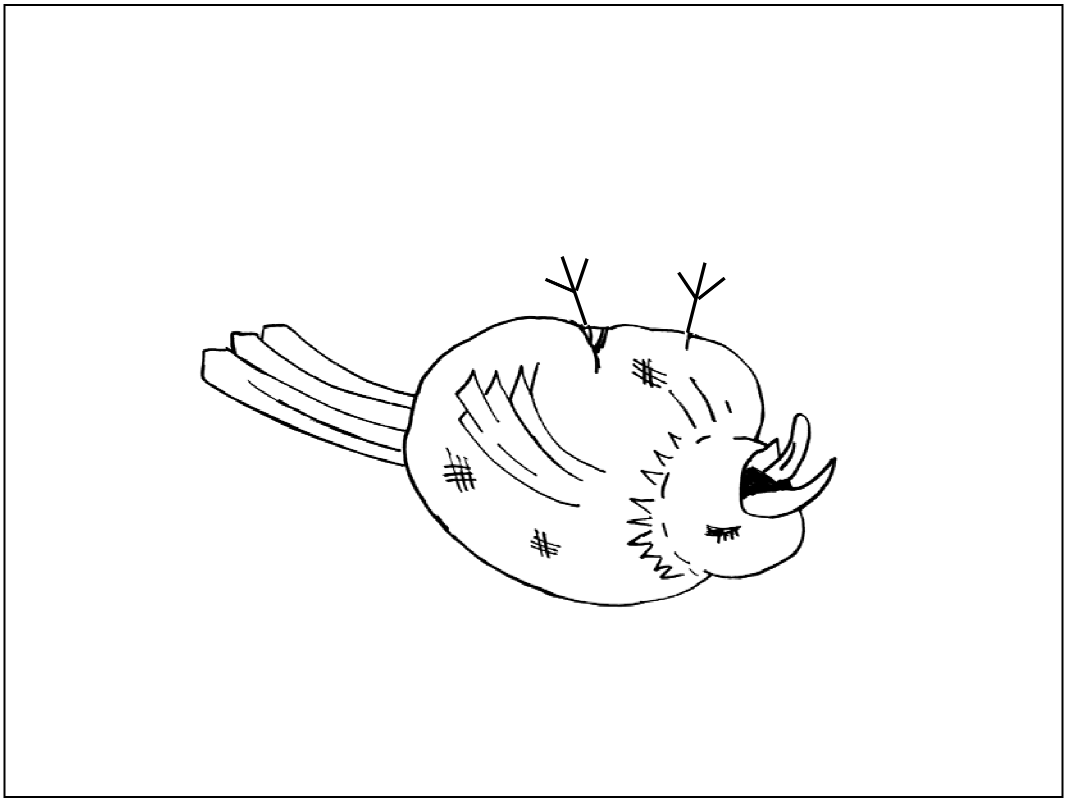
- Organizational Skills
- Persistence
- Uniform, Consistent Material
- Spare Material
- Recognition that Murphy's Laws are active

Conclusions

- Round robins can be very valuable, but should not be undertaken lightly!
- They are a lot of work.
- They can raise more questions than they answer.
- They can backfire!

Round robins - the finish





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