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14. ABSTRACT

Development and failure characterization of an Interpenetrating Phase Composite (IPC) foam system involving open-cell metallic scaffold infiltrated by lightweight polymeric syntactic foam for energy dissipation under high-strain rate conditions is the primary objective of this research. Unlike conventional composites, here the constituent phases are interconnected three-dimensionally and topologically throughout the microstructure. That is, both the matrix and reinforcement phases interpenetrate in all the three spatial dimensions. Consequently, the

15. SUBJECT TERMS

lightweight materials, structural foams, interpenetration phase composites, experimental mechanics, loading rate effects, mechanical failure, energy absorption

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a. REPORT	b. ABSTRACT	c. THIS PAGE			Hareesh Tippur
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Report Title

Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

ABSTRACT

Development and failure characterization of an Interpenetrating Phase Composite (IPC) foam system involving open-cell metallic scaffold infiltrated by lightweight polymeric syntactic foam for energy dissipation under high-strain rate conditions is the primary objective of this research. Unlike conventional composites, here the constituent phases are interconnected three-dimensionally and topologically throughout the microstructure. That is, both the matrix and reinforcement phases interpenetrate in all the three spatial dimensions. Consequently, the architecture of an IPC helps each phase to contribute its property to the overall macro scale characteristics synergistically. IPC architecture also enables tailoring residual stresses in the constituents of the composite to produce an advantageous macro scale response. Mechanical characterization and modeling of these IPC foams in general and compressive failure behavior in particular is emphasized in this research. This research offers alternative heterogeneous materials to create lightweight energy dissipation systems for military enclosures, vehicles, and personnel gear.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received	Paper
2012/08/27 1' 15	C. Periasamy, H.V. Tippur. Experimental measurements and numerical modeling of dynamic compression response of an interpenetrating phase composite foam, Mechanics Research Communications, (7 2012): 0. doi: 10.1016/j.mechrescom.2012.03.002
2012/08/27 1(13	R. Jhaver, H. Tippur. Characterization and modeling of compression behavior of syntactic foam-filled honeycombs, Journal of Reinforced Plastics and Composites, (06 2010): 0. doi: 10.1177/0731684410369023
2012/08/27 1(12	Hareesh Tippur, Rahul Jhaver. Processing, compression response and finite element modeling of syntactic foam based interpenetrating phase composite (IPC), Materials Science and Engineering: A, (1 2009): 0. doi: 10.1016/j.msea.2008.09.042
2011/08/29 1(5	C. -E. Rousseau, V. B. Chalivendra, H. V. Tippur, A. Shukla. Experimental Fracture Mechanics of Functionally Graded Materials: An Overview of Optical Investigations, Experimental Mechanics, (7 2010): 0. doi: 10.1007/s11340-010-9381-z
2011/08/29 1(4	H. V. TIPPUR. Coherent gradient sensing (CGS) method for fracture mechanics: a review, Fatigue & Fracture of Engineering Materials & Structures, (12 2010): 0. doi: 10.1111/j.1460-2695.2010.01492.x
2010/02/16 1: 2	C. Periasamy, R. Jhaver, H. tippur. Quasi-static and dynamic compression response of a lightweight interpenetrating phase composite foam, Materials Science and Engineering, (01 2010): . doi:

TOTAL: 6

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

1. 'Static and dynamic characterization of a lightweight interpenetrating phase composite in compression', R. Jhaver*, C. Periasamy* and H. V. Tippur, Proceedings of ASME-IMECE, Boston, MA, 2008.

Number of Presentations: 1.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper
2011/08/29 1{ 11	Chandru Periasamy, Hareesh Tippur. Dynamic Response of Homogeneous and Functionally Graded Foams When Subjected to Transient Loading by a Square Punch, 2011 SEM Annual Conference. , . : ,
2011/08/29 1{ 10	Chandru Periasamy, Rahul Jahver, Hareesh Tippur. Static and Dynamic Compression Response of a LightweightInterpenetrating Phase Composite (IPC) Foam, SEM Annual Conference. 2009/06/04 01:00:00, . : ,
2011/08/29 1{ 9	Chandru Periasamy, Hareesh Tippur. Dynamic Compression of an Interpenetrating Phase Composite (IPC) Foam:Measurements and Finite Element Modeling, International Conference on Experimental Mechanics. 2010/06/12 01:00:00, . : ,

TOTAL: **3**

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper
2010/06/23 1' 3	R. Jhaver, H. Tippur. Characterization and modeling of compression behavior of syntactic foam-filled honeycombs, (01 2010)
2009/05/14 0! 1	R. Jhaver, H. Tippur. Processing, Compression Response and Finite Element Modeling of Syntactic Foam Based Interpenetrating Phase Composite (IPC), ( )

TOTAL: **2**

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

'Lightweight Interpenetrating Phase Composite Foam for High Energy Absorption Applications', R. Jhaver and H. Tippur, U.S. Provisional Patent Application No. 61/217,548

Patents Awarded

Awards

- Allen Craven, an MS student involved in this research, received DoD's NSSEFF-SMART Program fellowship for his MS degree (2009-2011) research. He is currently employed at a DoD installation (Robins AFB, GA).
- Chandru Periasamy, an MS student involved in this research, received 2010 outstanding graduate student award (MS students category) from the Graduate School at Auburn University.
- The PI received Flyde Electronic Prize from the British Society for Strain Measurement (BSSM). The award recognizes the best paper published in the journal STRAIN during 2009.
- The PI was selected to hold McWane Endowed Chair Professorship (2010-2015) at Auburn University.
- The PI was appointed as the Editor-in-Chief of Experimental Mechanics, flagship journal of the Society for Experimental Mechanics (SEM).
- The PI was elected as the Fellow of the Society for Experimental Mechanics (SEM).
- The PI received W. F. Walker teaching award for excellence from Auburn University (College of Engineering), 2012.

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Rahul Jhaver	0.50	
Chandru Periasamy	0.50	
Allen Craven	0.00	
FTE Equivalent:	**1.00**	
Total Number:	**3**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Hareesh Tippur	0.13	No
FTE Equivalent:	**0.13**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:	0.00

Names of Personnel receiving masters degrees

NAME
Rahul Jhaver
Chandru Periasamy
Allen Craven

Total Number: **3**

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

5 **'Lightweight Interpenetrating Phase Composite Foam for High Energy Absorption Applications', R. Jhaver and H. Tippur,**

Patent Filed in US? (5d-1) Y

Patent Filed in Foreign Countries? (5d-2) Y

Was the assignment forwarded to the contracting officer? (5e) N

Foreign Countries of application (5g-2):

5a: Hareesh Tippur and Rahul Jhaver

5f-1a: Auburn University - Mechanical Engineering

5f-c: 1418 Wiggins Hall, Auburn 36849

Auburn AL 36849

Scientific Progress

See attachment

Technology Transfer

Project Summary - Grant # 54361-EG
(Reporting Period: August 1, 2008 – July 31, 2012; includes no-cost extension period)

Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

Hareesh V. Tippur
Department of Mechanical Engineering
Auburn University, Auburn, AL 36849-5341

Objective

Development and failure characterization of an Interpenetrating Phase Composite (IPC) foam system involving open-cell metallic scaffold infiltrated by lightweight polymeric syntactic foam for energy dissipation under high-strain rate conditions is the primary objective of this research. Unlike conventional composites, here the constituent phases are interconnected three-dimensionally and topologically throughout the microstructure. That is, both the matrix and reinforcement phases interpenetrate in all the three spatial dimensions. Consequently, the architecture of an IPC helps each phase to contribute its property to the overall macro scale characteristics synergistically. IPC architecture also enables tailoring residual stresses in the constituents of the composite to produce an advantageous macro scale response. Mechanical characterization and modeling of these IPC foams in general and failure behavior under compression in particular is emphasized in this research. This research has the potential to offer alternative materials to create lightweight energy dissipation systems for stationary as well as mobile military enclosures, vehicles, and personnel gear.

Approach

Lightweight IPC foams have been developed by infiltrating polymer (epoxy) syntactic foams into metallic (aluminum) open-cell scaffolds. A combination of global and local mechanical measurements are being made using full-field optical methods for understanding the failure behavior of the constituent phases as well as the composite foam. Complementary finite element modeling is being used to augment experimentation. Currently material responses from low and high strain rate conditions are being compared in order to identify loading rate effects. Preliminary flat punch tests on foam sheets under dynamic loading conditions are carried out to study failure responses under more general loading conditions. The synergistic interaction between different phases (such as constraint of ligaments of one phase by the other) in these IPC foam composites produces complex but generally favorable mechanical responses.

Relevance to Army

Lightweight structural foams play a significant role in many applications of relevance to the Army – head-gear, rapidly deployable structures, and armored vehicles – to name a few involving impact and shock energy dissipation. This research is aimed towards demonstrating the feasibility of a novel structural foam made of polymer syntactic foam infused into a lightweight metallic open-cell preform resulting in a co-continuous, three dimensionally interpenetrating composite foam. The resulting Interpenetrating Phase Composite (IPC) foam is investigated for higher amounts of mechanical energy dissipation relative to the traditional syntactic variety due to synergistic mechanical constraint effects between the constituent phases.

Accomplishments

- Using epoxy based Syntactic Foam (SF) and open-cell aluminum scaffolds Interpenetrating Phase Composite (IPC) foams have been prepared. Hollow glass microballoons are dispersed in epoxy to produce syntactic foam. By infusing uncured syntactic foam into open-cell aluminum scaffolds, IPC foams have been prepared. By varying the volume fraction (in the range of 10-40%) of microballoons in the syntactic foam, IPC foams of different density have been realized. Syntactic foams without metal scaffolds are also prepared for comparative study.
- Quasi-static compression tests have been performed on cylindrical SF and IPC samples. The stress-strain responses under quasi-static conditions of SF and IPC foams show elastic, softening, plateau, and densification regimes. The volume fraction (V_f) of microballoons plays a dominant role in the overall response of the SFs and IPCs. A monotonic increase in elastic modulus, yield stress, and plateau stress are evident as V_f of microballoons decrease. The IPC foams consistently have higher value of each of these characteristics relative to the corresponding SF. The densification strain decreases with increasing V_f of microballoons in SF. The IPC foams have a slightly lower densification strain relative to the corresponding SF.
- The plateau stresses for IPC foams are greater than the sum of the plateau stresses of the corresponding SF and unfilled aluminum preform/scaffold. This is attributed to the prevalence of synergistic constraint between the scaffold and SF phases of the 3D interpenetrating microstructure. The energy absorbed up to 22% true strain for SF and IPC samples show that IPC absorbs ~35% higher energy per unit volume than the corresponding SF under quasi-static conditions. IPC also outperforms SF samples by 10-15% when energy dissipated per unit mass is a consideration.
- A unit-cell based finite element model has been developed using a filled Kelvin-cell subjected to compression. Elasto-plastic, large deformation analysis (up to 40% strain) using measured properties of the SF and Aluminum produce a high accuracy reproduction of measured IPC response.

- A split Hopkinson pressure bar apparatus has been developed and calibrated for testing low-impedance materials at strain rates of ~1500/sec. Cylindrical SF and IPC foam samples have been prepared and dynamic compression testing has been carried out. The results show that under dynamic loading conditions, SF and IPC samples show a stress-strain response that has only two dominant regimes – a linear zone up to a maximum stress, and a monotonically softening zone following that. The foams with lower V_f of microballoons tend to soften more rapidly than the ones with higher V_f. The maximum stress increase with decreasing V_f of microballoons under high-strain rate conditions. The values for IPC foams are again higher than those for SF under dynamic conditions by 10-15%. The dynamic maximum stress values are also higher for both SF and IPC relative to the quasi-static ones.

- The failure modes and mechanisms have been studied using high-speed photography by printing a linear grating pattern on the specimen surface for observation during compression failure in a split-Hopkinson pressure bar. Unlike quasi-static failure, high-speed optical recordings reveal significant spring-back in syntactic foam whereas it is negligible in IPC foams. Further, the failure process is uniform (not progressive) in both syntactic and IPC foams.

- Optical micrographs reveal that failure of syntactic and IPC foams under dynamic conditions are dominated by the formation of extensive network of shear band in the syntactic foam phase. Further, unlike in the static case, the microballoons are not uniformly crushed under dynamic conditions. Interfacial debonding between the scaffold and the syntactic foam phase in an additional failure mechanism in the IPC foams. If this aspect can be addressed satisfactorily, the dynamic energy absorption in IPC can be further enhanced.

- Mechanical response of IPC foams under a square punch loading was initiated. A long-bar apparatus to deliver a controlled, measurable stress pulse of different durations to the edge of a foam sheet was developed. To calibrate the apparatus, experiments were first carried out on standard polymer and syntactic foam sheets. Optical measurement of punch-tip deformations is performed using 2D digital image correlation method used in conjunction with high-speed photography (250,000 frames/sec). Finite element computations of the geometry based on measured stress pulse have been used to complement the measurements. Good agreement is observed between measurements and simulations. A crack analog model is invoked to assess punch-tip deformation and damage in terms of an equivalent stress intensity factor. Experiments on a punch-loaded polymer sheet and the corresponding analytical model are in good agreement.

- Flexural response of IPC foam core sandwich structures was also studied statically and under low velocity impact. The face sheets were made of thin aluminum sheets and the core was syntactic foam-filled aluminum IPC foam. The flexural response showed pronounced nonlinearity beyond the initial linear response. This is unlike the premature face-sheet debonding and catastrophic failure of sandwich structures when only syntactic foam core without the interpenetrating architecture was used in the core. The IPC foam core improves failure strain although the peak load values essentially remain the same but with a high degree of experimental consistency. Under impact loading conditions, the sandwich with an IPC core continued to bear load and absorb energy well beyond the evolution of debond and defect initiation sites in the core resulting in higher energy absorption.

Collaborations and Technology Transfer

- ‘Lightweight Interpenetrating Phase Composite Foam for High Energy Absorption Applications’, R. Jhaver and H. Tippur, Auburn University Technology Disclosure #08-067, 2008. (U.S. Provisional Patent Application No. 61/190,238)
- The above technology transfer was selected (3^{rd} place finish) during the ‘Alabama Launchpad Competition’, a university based industry incubator in the state of Alabama for seed funds to be matched by venture investors.

Resulting Journal Publications for the period (*: Graduate student)

1. ‘Processing, compression response and finite element modeling of syntactic foam based interpenetrating phase composite (IPC),’ R. Jhaver* and H. V. Tippur, *Materials Science and Engineering – A*, Vol. 499, (2009), pp 507-517.
2. ‘Quasi-static and dynamic compression response of a lightweight interpenetrating phase composite foam’, C. Periasamy*, R. Jhaver* and H. V. Tippur*, *Materials Science and Engineering A*, 527, 2845–2856, 2010.
3. ‘Mechanical characterization and modeling of compression behavior of syntactic foam-filled cellular solids,’ R. Jhaver* and H. V. Tippur, *Journal of Reinforced Plastics and Composites*, Vol. 29, No. 21, pp 3185-3197, 2010.
4. ‘Experimental Fracture Mechanics of Functionally Graded Materials: An Overview of Optical Investigations’, C. E. Rousseau, V. Chalivendra, A. Shukla and H. V. Tippur, *Experimental Mechanics*, (50^{th} Anniversary Special Issue, Guest Editor: Eric Brown), Vol. 50, No. 7, pp 845-865, 2010.
5. ‘Coherent Gradient Sensing (CGS) method for fracture mechanics: A Review’, H. V. Tippur, *Fatigue and Fracture of Engineering Materials*, Vol. 33, No. 12, pp 832-858, 2010.
6. Experimental Measurements and Numerical Modeling of Dynamic Compression Response of an Interpenetrating Phase Composite Foam,’ C. Periasamy* and H. V. Tippur, *Mechanics Research Communications*, Vol. 43, pp 57-65, 2012.
7. ‘Flexural Response of Syntactic Foam Core Sandwich Structures: Effects of Graded Face Sheets and Interpenetrating Phase Composite Foam Core,’ A. Craven* and H. V. Tippur, *in preparation*, 2012.

Resulting Theses and Dissertations for the period

a. M.S. Thesis: ‘Experimental Investigation of Syntactic Foam Core Sandwiches: Effect of Graded Face Sheet and Interpenetrating Phase Composite Foam Core,’ A. Craven, 2011.
b. M.S. Thesis: ‘A split Hopkinson pressure bar apparatus for high-strain rate testing of interpenetrating phase composites (IPC): Measurements and modeling’, C. Periasamy, 2010.

c. M.S. Thesis: ‘Compression response and modeling of interpenetrating phase composites and foam-filled honeycombs’, R. Jhaver, 2009.

Graduate Students Involved During the Project Period

- C. Periasamy (Ph.D. – Summer 2012)
- A. Craven (M.S. – Spring 2011)
- C. Periasamy (M.S. – Summer, 2010)
- R. Jhaver (M.S. – Summer, 2009)

Awards, Honors and Appointments

- Allen Craven received NSSEFF-SMART Program fellowship for his MS degree (2009-2011). Currently employed at a DoD installation (Robins AFB, GA).
- Chandru Periasamy received 2010 outstanding graduate student award (MS students category) from the Graduate School at Auburn University.
- The PI received Flyde Electronic Prize from the British Society for Strain Measurement (BSSM). The award recognizes the best paper published in the journal STRAIN during 2009.
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- The PI was appointed as the Editor-in-Chief of Experimental Mechanics, flagship journal of the Society for Experimental Mechanics (SEM).
- The PI was elected as the Fellow of the Society for Experimental Mechanics (SEM).
- The PI received W. F. Walker teaching award for excellence from Auburn University (College of Engineering), 2012.

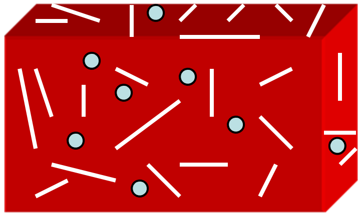
Other Personnel Involved

None

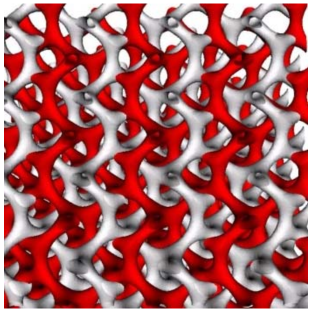
54361-EG: Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

Hareesh Tippur, Auburn U.

- Motivation
  - In interpenetrating phase composites (IPC), individual phases are interconnected three-dimensionally and topologically
  - Such a complete interpenetration does not occur in traditional composites with discrete filler or fiber phases
  - Synergistic interaction (mechanical constraint) between phases potentially improve mechanical characteristics
- Scientific challenges
  - How to create three dimensional interconnectivity between phases
  - Produce a lightweight composite with good compression characteristics



Traditional composite

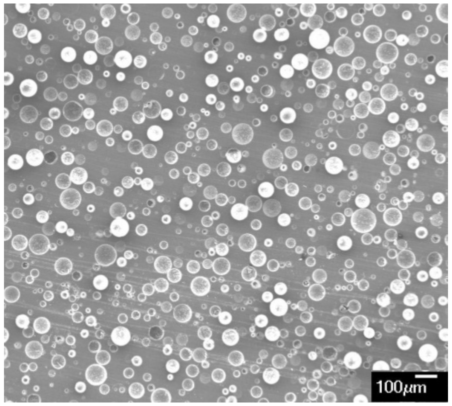


Interpenetrating phase composite

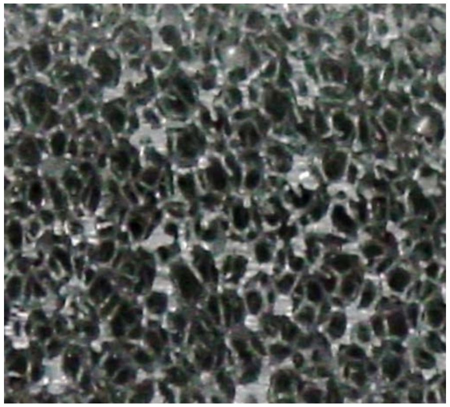
Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

Hareesh Tippur, Auburn U.

- Objectives
  - Process novel lightweight syntactic foam based interpenetrating phase composite (IPC) foams using open-cell aluminum preform
  - Study compression response of IPC foams relative to conventional syntactic foams under quasi-static and dynamic loading conditions
  - Investigate the role of adhesion strength between syntactic foam and aluminum network in IPC



Polymer syntactic foam



Open-cell scaffold

Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

Hareesh Tippur, Auburn U.

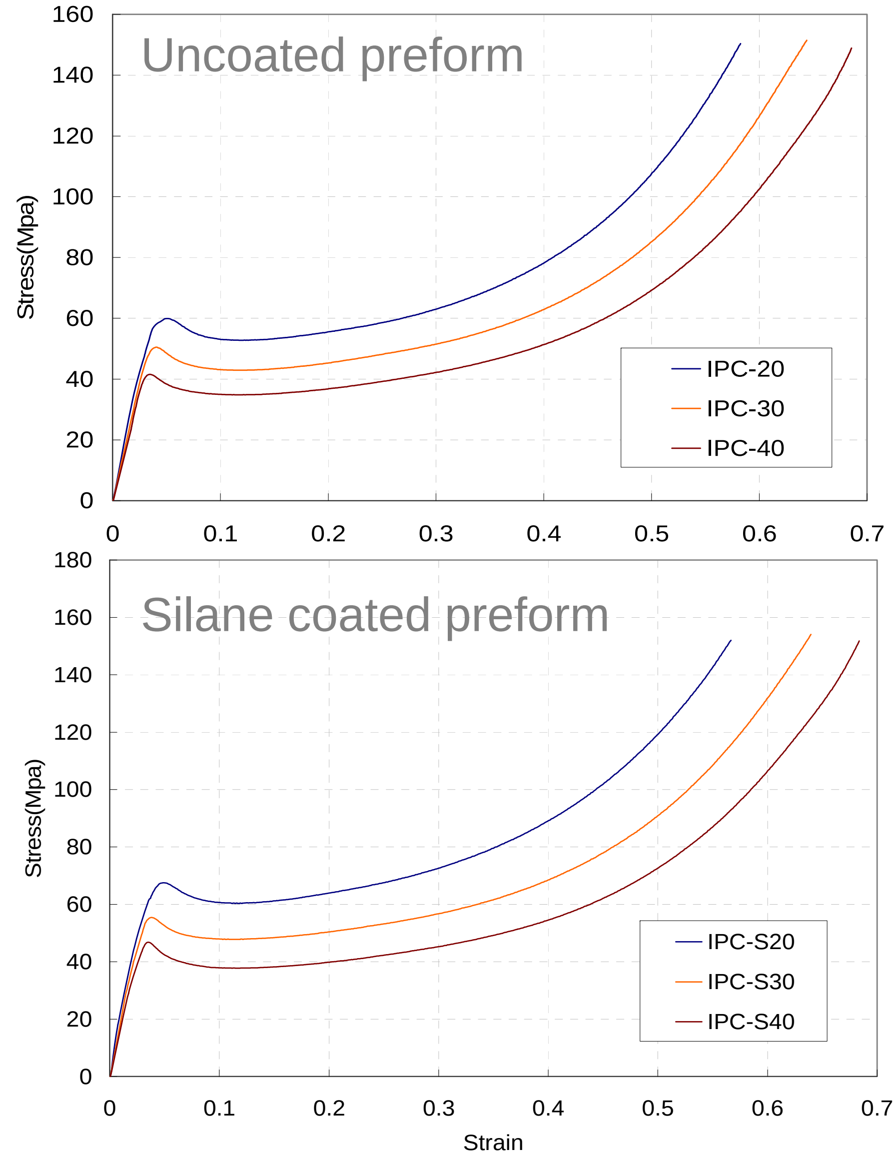
- Approach
  - Mix microballoons into epoxy resin (V_f = 10% - 40%)
  - Introduce hardener and degas
  - Transfer to silicone mold and cure at room temp to get syntactic foam
  - Infuse uncured syntactic foam into an aluminum scaffold to get IPC foam
- Uniqueness of approach
  - Simplicity of the process
  - Uses existing materials
  - Room temperature curing

IPC Foam

Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

Hareesh Tippur, Auburn U.

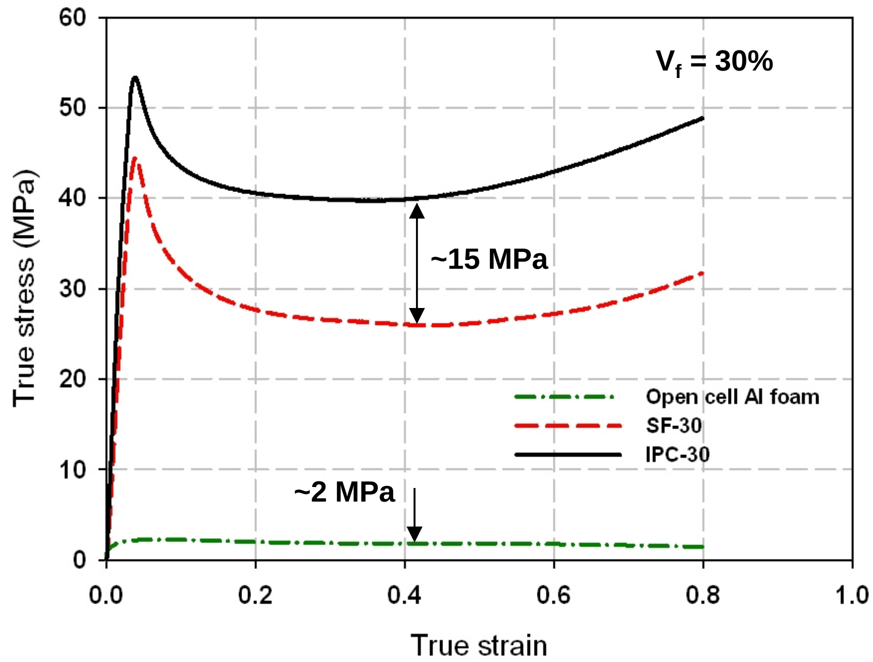
- Scientific Accomplishments
  - Quasi-static compression tests performed on IPC foams and syntactic foams
  - Silane coating results in higher elastic modulus, yield stress and plateau stress
  - Modest reduction in densification strain relative to syntactic foam responses (not shown) but densification is not as rapid



Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

Hareesh Tippur, Auburn U.

- Scientific Accomplishments (cont.)
  - Static compression responses of syntactic foam and IPC foams are shown
  - Increase in quasi-static plateau stress (~40% compared to syntactic foam) for IPC foam with silane treatment is significantly higher than the sum of the plateau stresses of syntactic foam and the unfilled scaffold

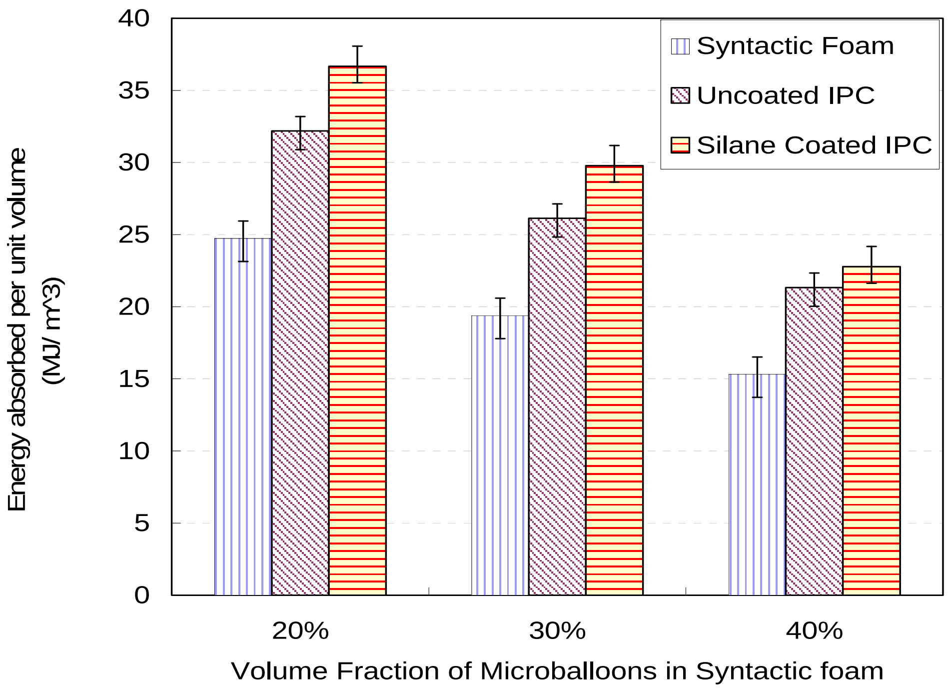


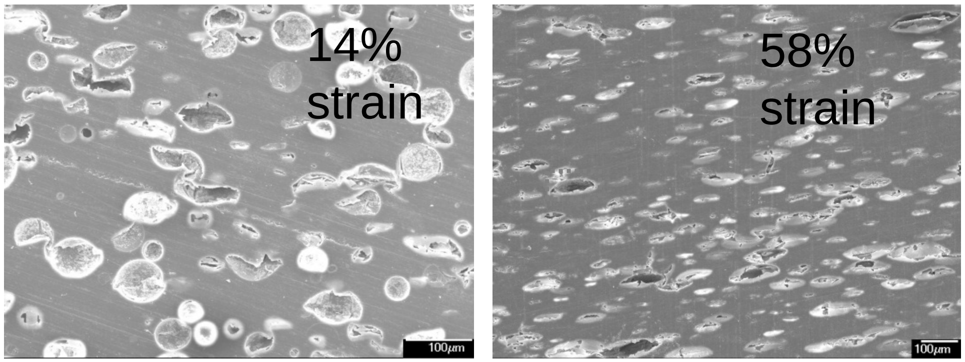
Comparison of measured stress-strain responses of syntactic and IPC foams with 30% V_f hollow microballoons

Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

Hareesh Tippur, Auburn U.

- Scientific Accomplishments (cont.)
- Energy absorption is calculated up to a strain of 50%
- Improved energy absorption by IPC foams under static conditions
- Crushing of microballoons dissipate energy
- Silane coated IPC samples show ~50% higher energy absorption per unit volume; ~33% higher energy absorption per unit mass

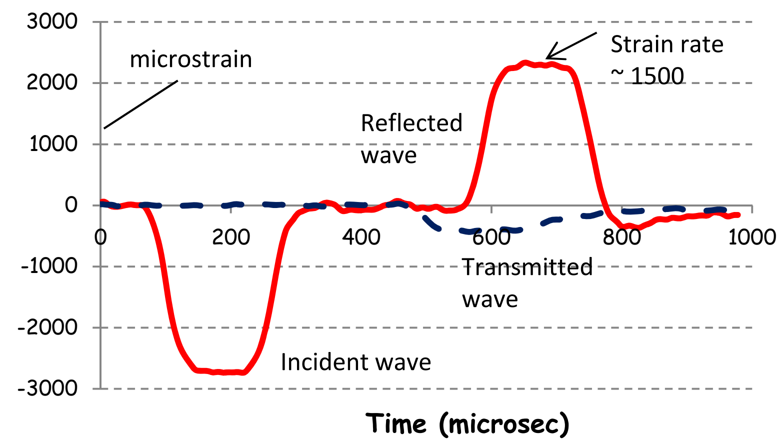


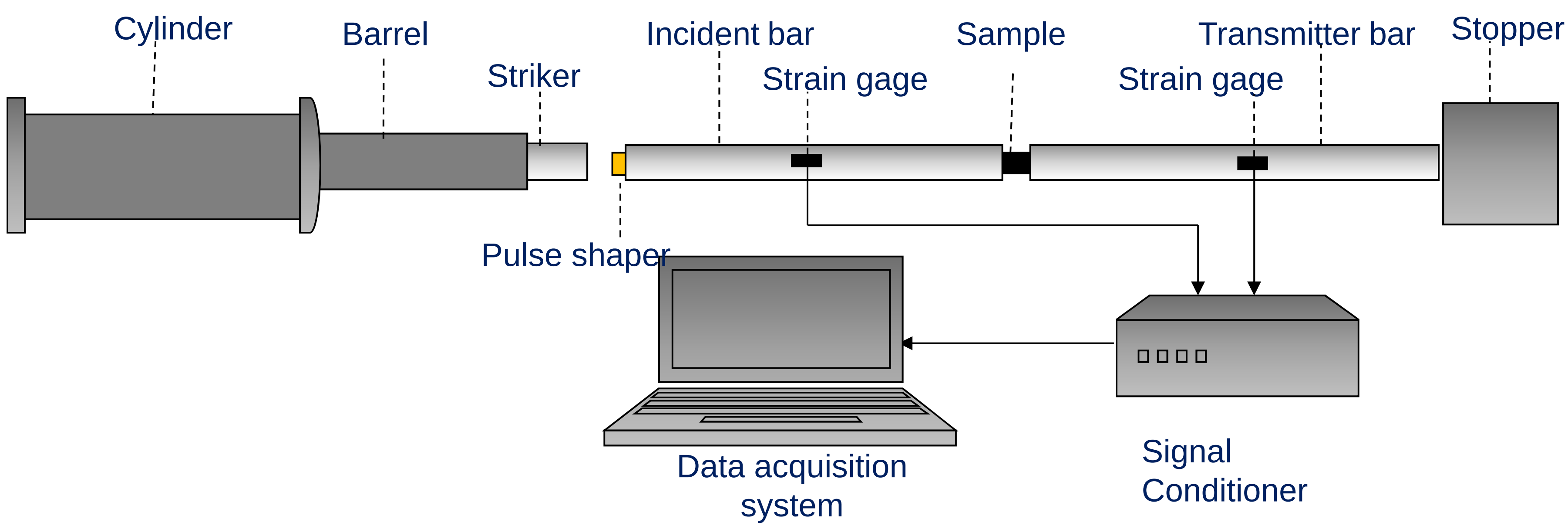


Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

Hareesh Tippur, Auburn U.

- Scientific Accomplishments (cont.)
- Developed a compression SHPB apparatus to characterize SF and IPC foams under dynamic conditions

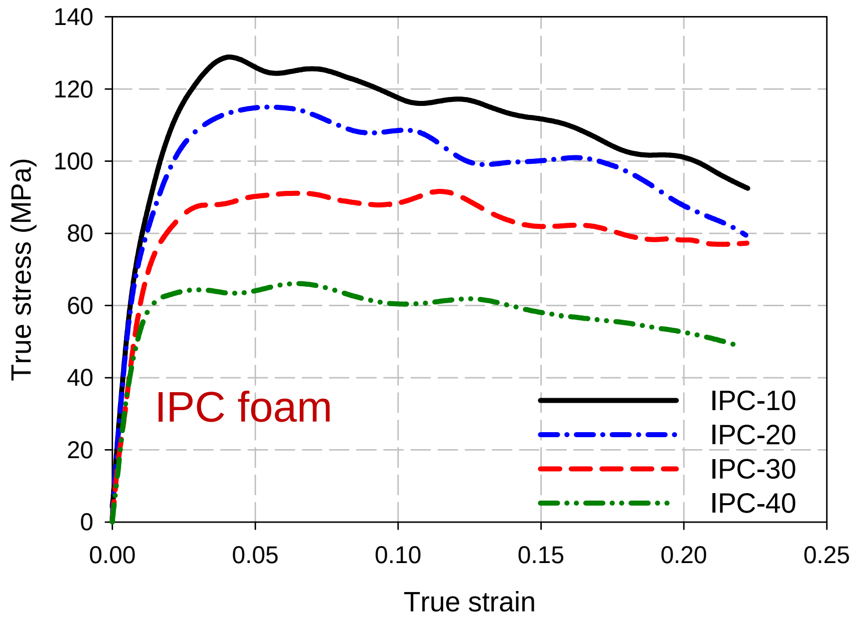


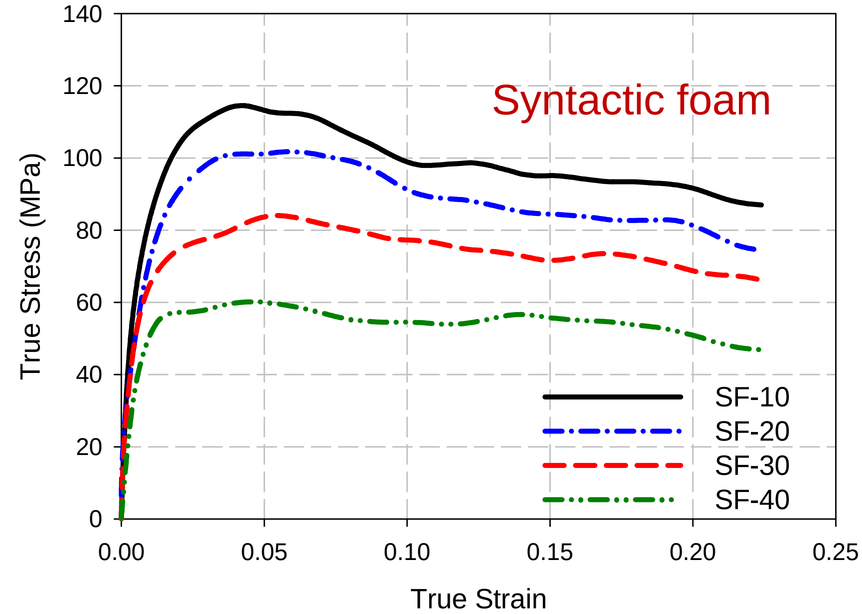


Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

Hareesh Tippur, Auburn U.

- Scientific Accomplishments (cont.)
- Dynamic compression response using SHPB apparatus (~1500/sec)





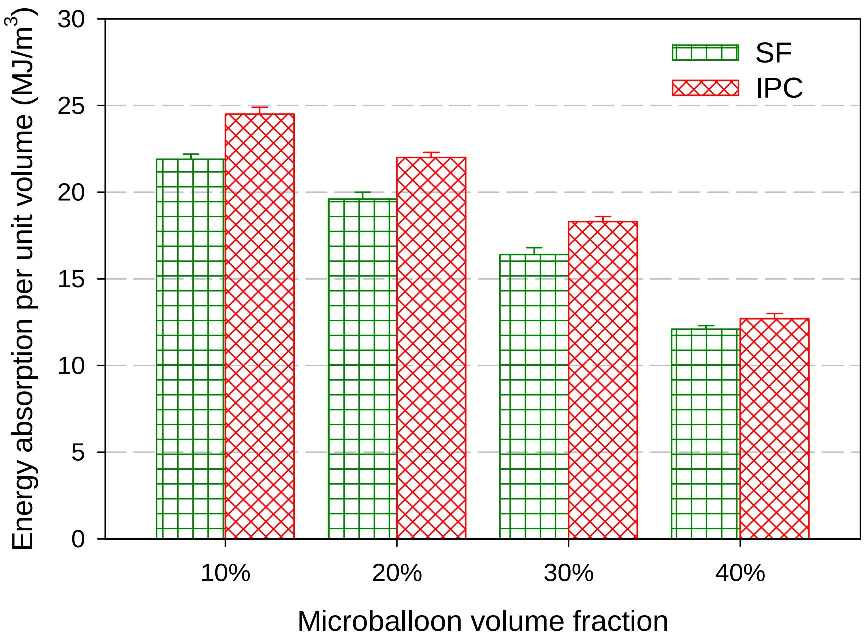
- IPC foam strength > SF strength
- Lower microballoon V_f results in higher yield stress

Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

Hareesh Tippur, Auburn U.

- Scientific Accomplishments (cont.)

- IPC absorbs more energy per unit volume than SF under dynamic loading conditions
- IPC performance is modestly better (15-20%) under dynamic conditions when compared to ~50% improvement under static conditions
- Attributed to strain rate effects which alter failure mechanisms

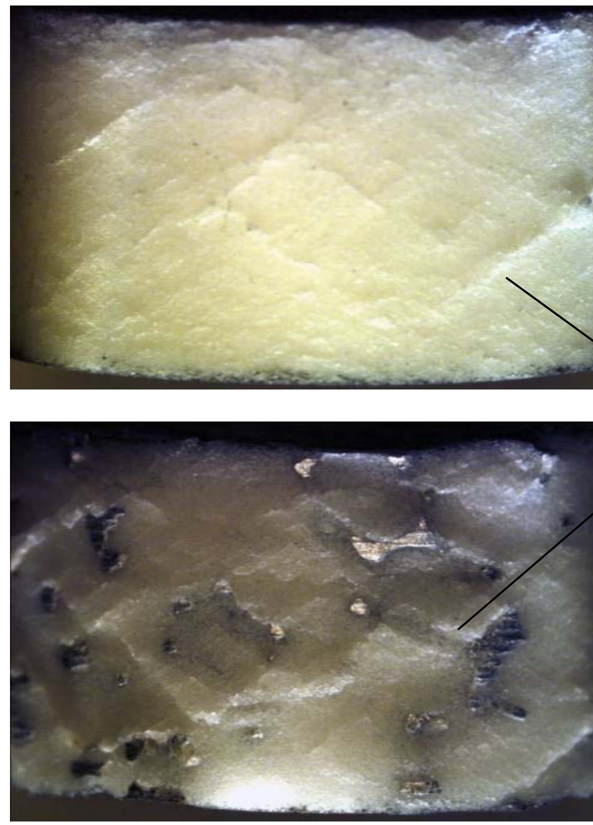


Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

Hareesh Tippur, Auburn U.

- Scientific Accomplishments (cont.)

- High-speed photography of samples during deformation shows shear band formation in both syntactic foam and IPC.
- Spring-back effect seen in syntactic foam is absent in IPC foam under dynamic loading.



Syntactic foam (V_f = 30%)

Shear bands

IPC (V_f=30%)

Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

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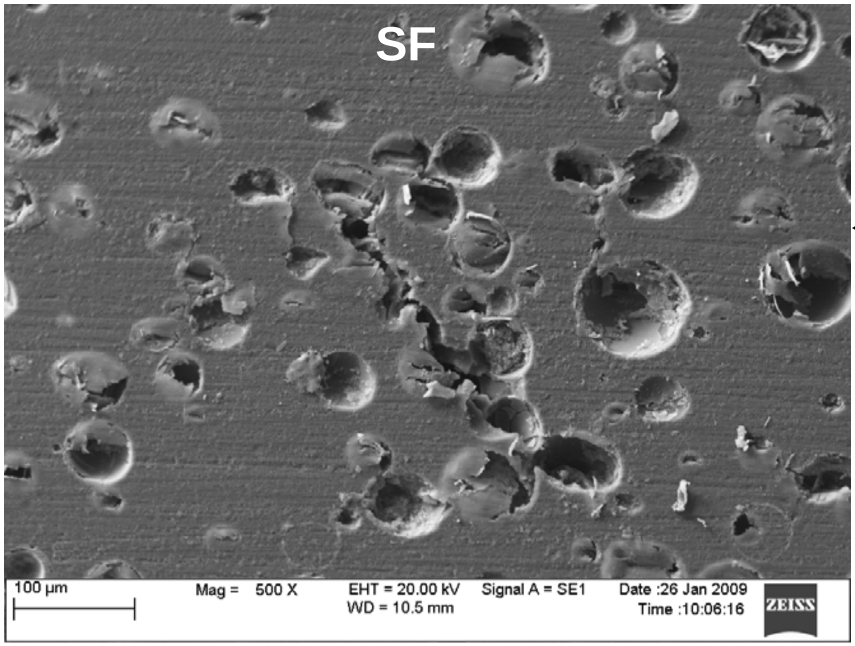
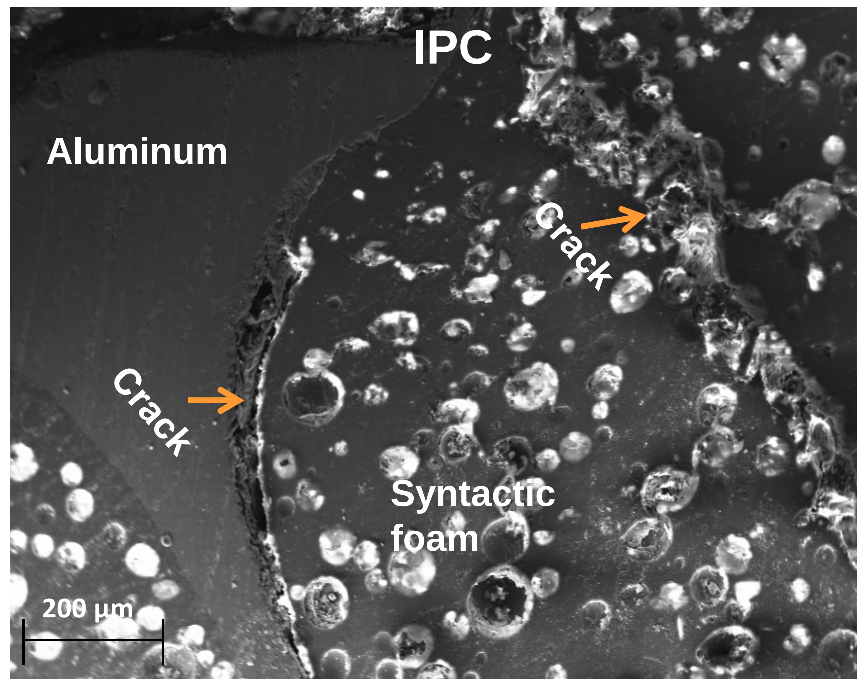


Skewed cracks suggest failure due to shear localization; microballons are relatively intact

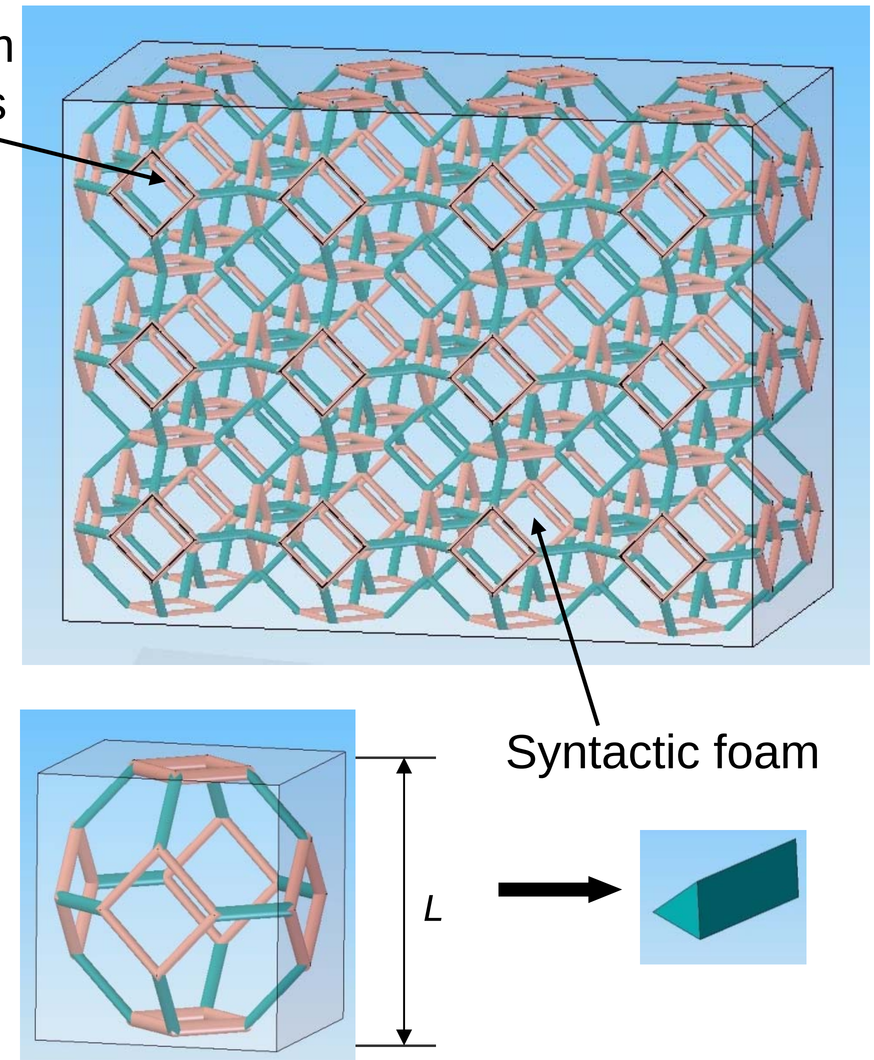
- Skewed cracks in the syntactic foam
- Cracks at the Al–SF interface



Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

Hareesh Tippur, Auburn U.

- Scientific Accomplishments (cont.)
  - Finite element modeling of IPC foam is undertaken
  - Unit cell approach is adopted using syntactic foam filled aluminum Kelvin cells
  - Kelvin cell ligaments are assumed to have equilateral triangular c.s.



Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

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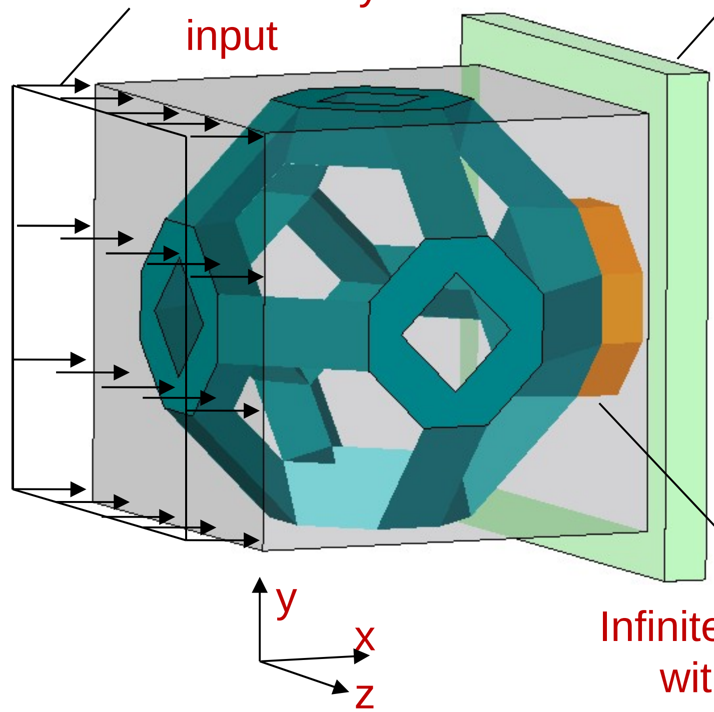
- Scientific Accomplishments (cont.)

- Infinite elements are used (on five-faces of the unit-cell) for dynamic compression simulations of IPC foam
- Aluminum and SF properties assigned to infinite element regions adjacent to aluminum and SF, respectively, in the IPC



Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

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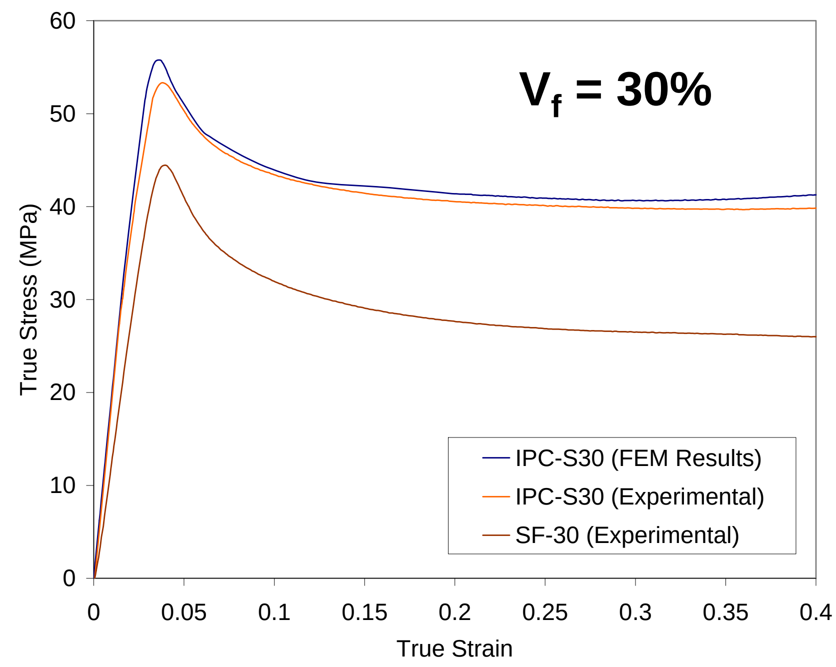
- Scientific Accomplishments (cont.)

  - Computed quasi-static stress-stress response for IPC foam is in good agreement with measurements



Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

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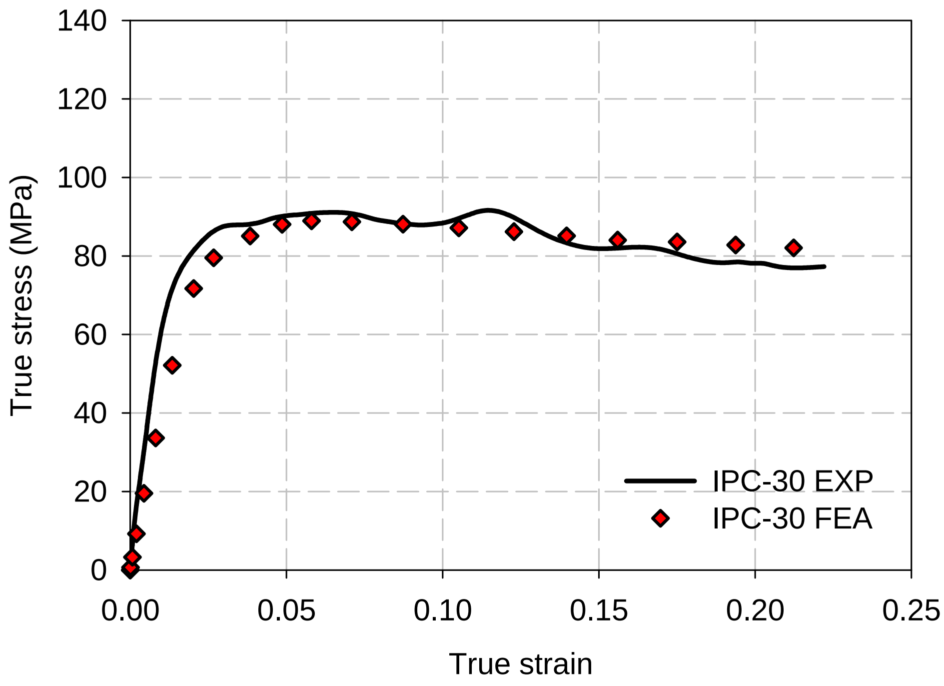
- Scientific Accomplishments (cont.)

  - Computed dynamic stress-stress response for IPC foam is in good agreement with the measurements
  - This model can be used to develop other IPC foams with other constituent phases, volume fractions and morphology



Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

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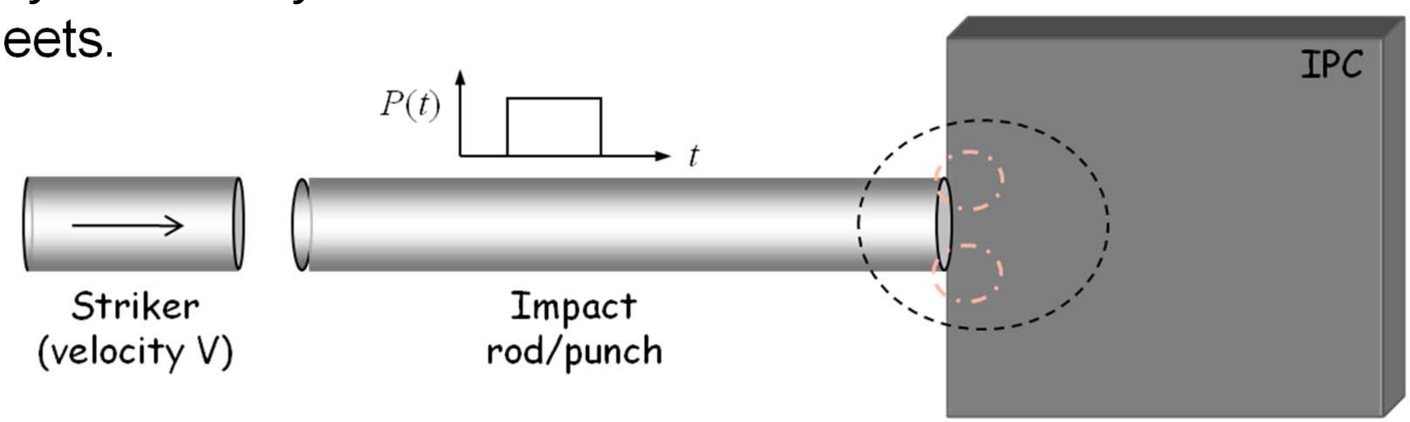
- Scientific Accomplishments (cont.)

  - Developed an apparatus to conduct square punch impact tests on SF and IPC foam sheets using a long-bar setup.
  - The devise has been calibrated using polymer and syntactic foam sheets.



Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

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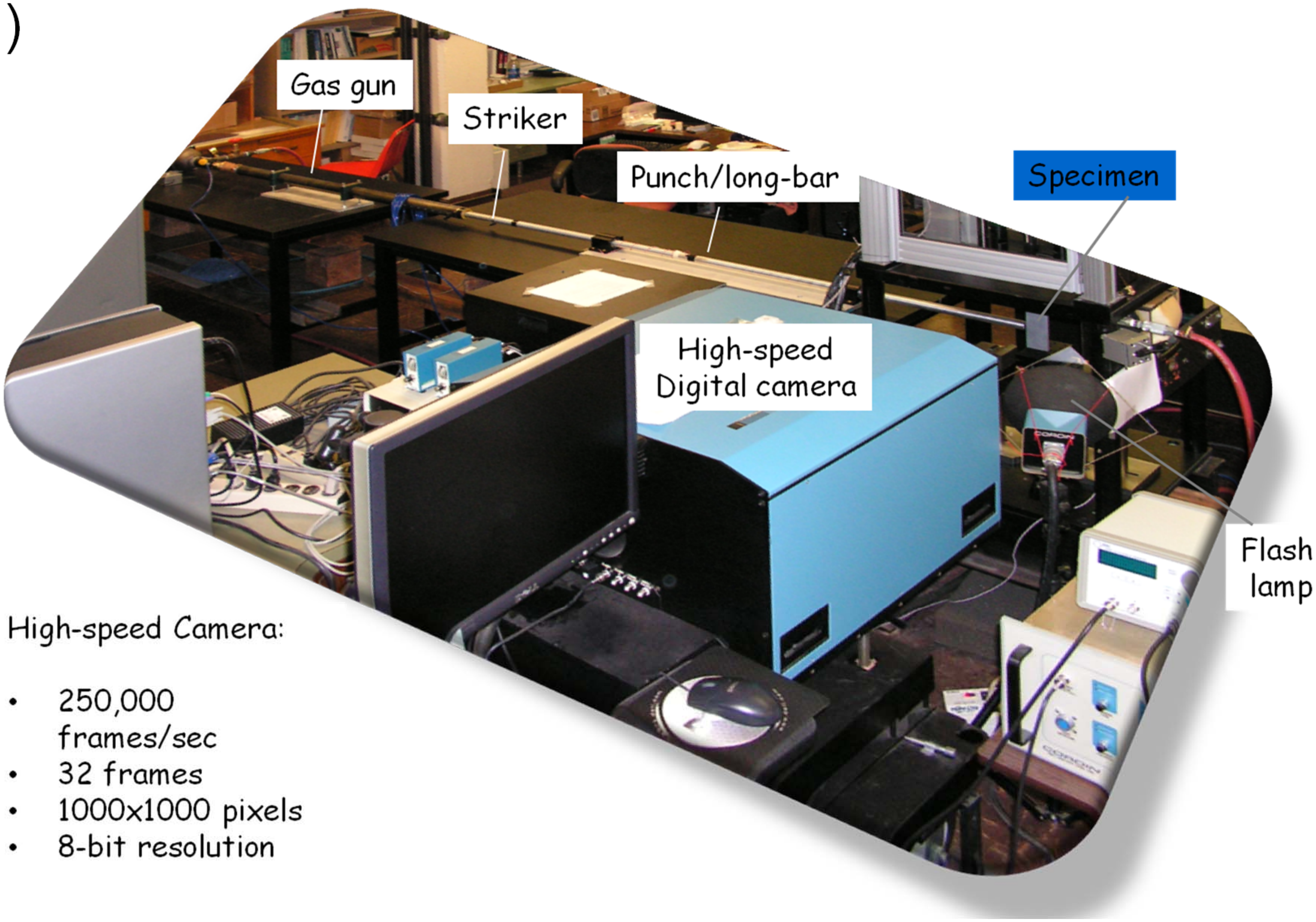
- Scientific Accomplishments (cont.)



High-speed Camera:

- 250,000 frames/sec
- 32 frames
- 1000x1000 pixels
- 8-bit resolution

Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

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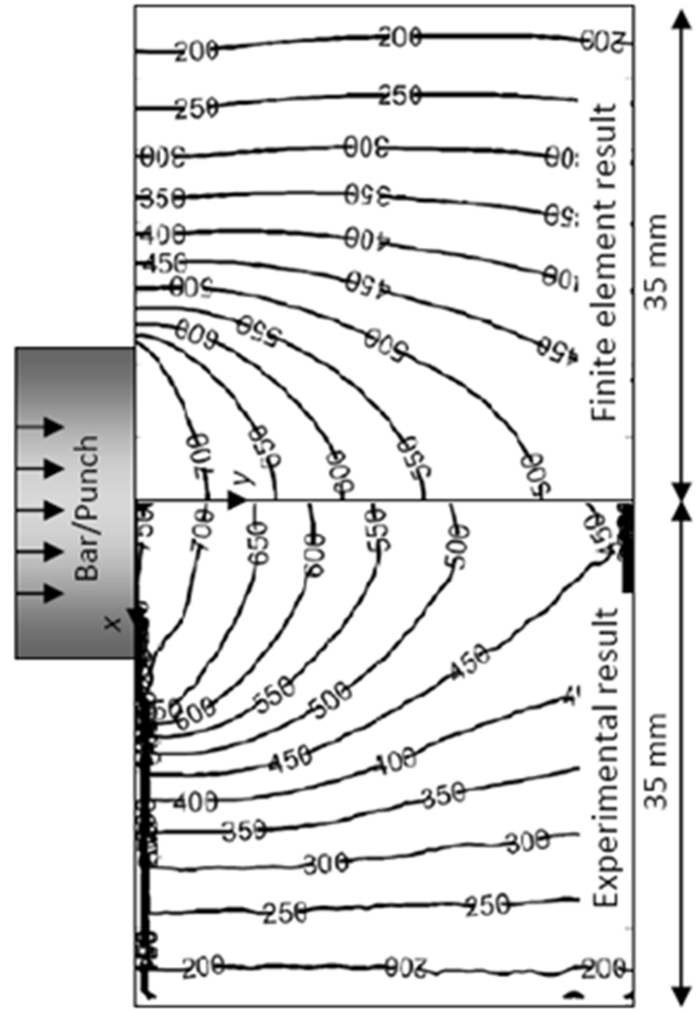
- Scientific Accomplishments (cont.)

  - Measured displacements using DIC are in good agreement with FE simulations on PMMA carried out using measured stress pulse on the long-bar.



Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

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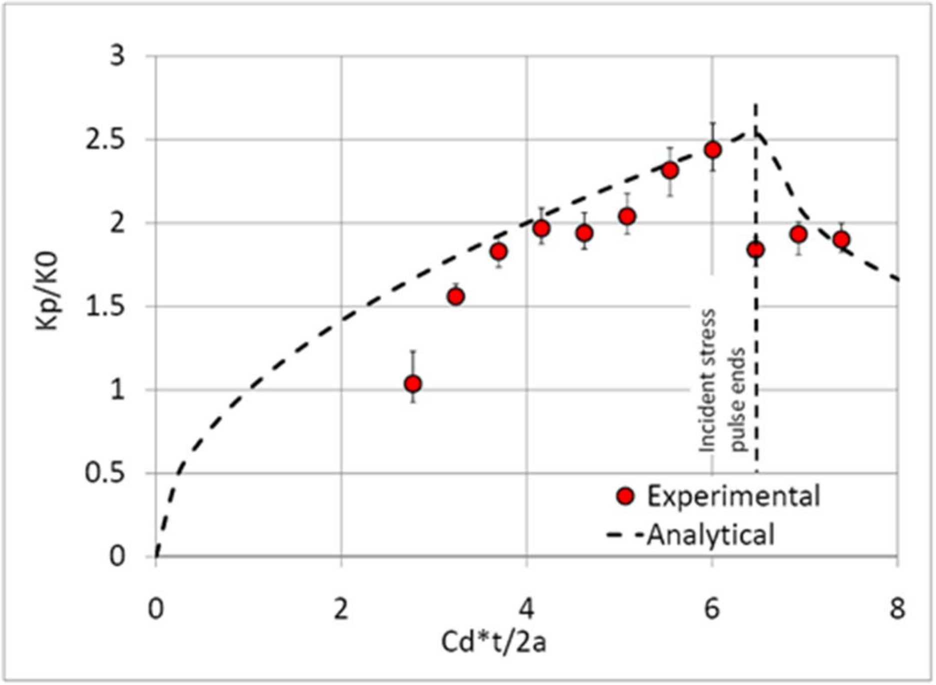
- Scientific Accomplishments (cont.)

  - Measured dynamic punch-tip stress intensity factors from DIC and based on a crack analog model are in good agreement with the analytical model for PMMA.



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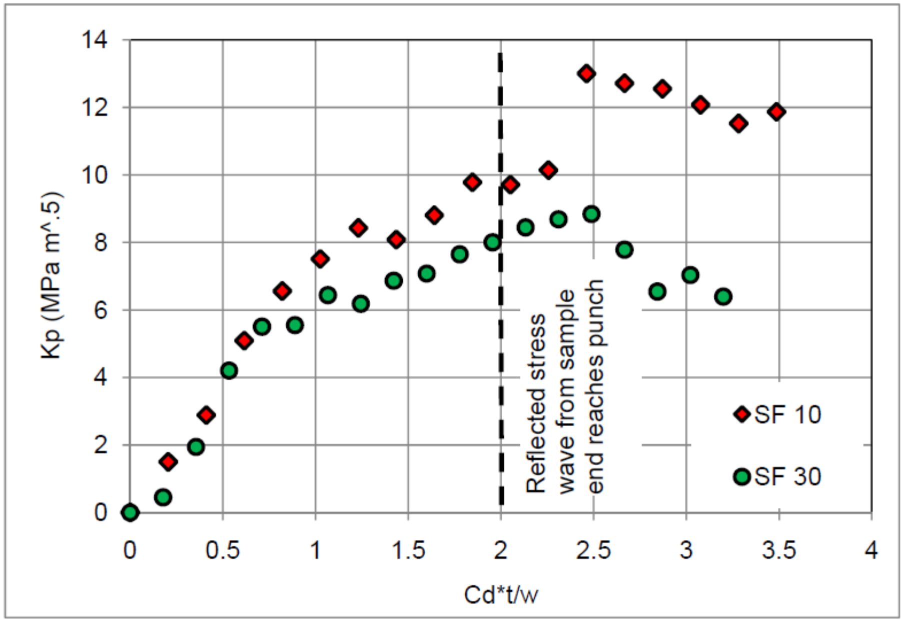
- Scientific Accomplishments (cont.)

  - Measured dynamic punch-tip stress intensity factors from DIC and based on a crack analog model for two different syntactic foams SF-10 and SF-30 are shown.

  - The onset of nonlinearity in punch tip SIF (K_p) history is attributed to plastic deformation of SF at the punch tip.



Stress pulse duration ~ 200 μsec

Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

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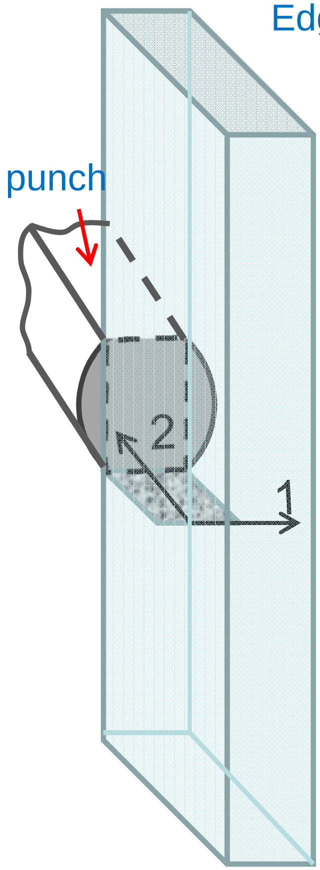
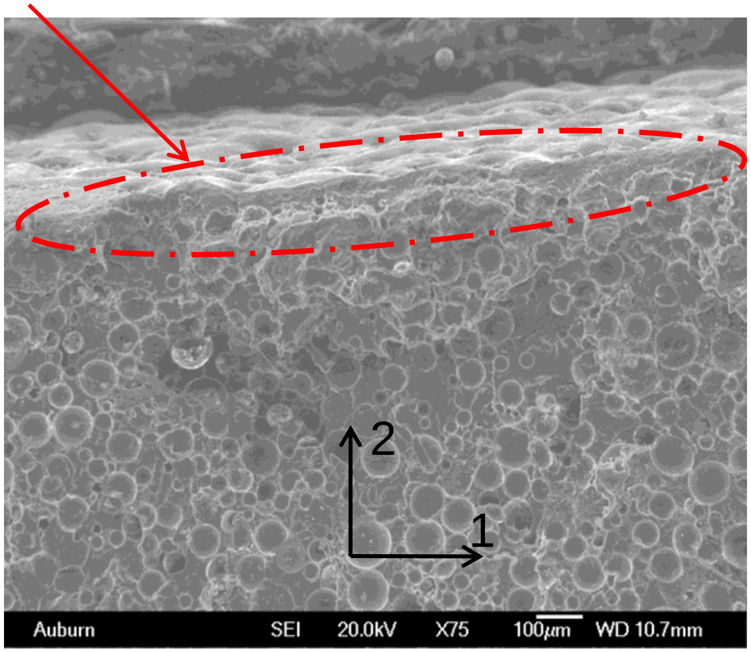
- Scientific Accomplishments (cont.)

  - SEM images at the punch tip show shear localization near the punch corner due to impact. This results in a mode I crack when the reflected tensile stress pulse returns from the far-edge.





Hint of initial shear deformation at punch corner.

Subsequent mode I type crack opening indicated by circular cross sections of microballoons.

Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

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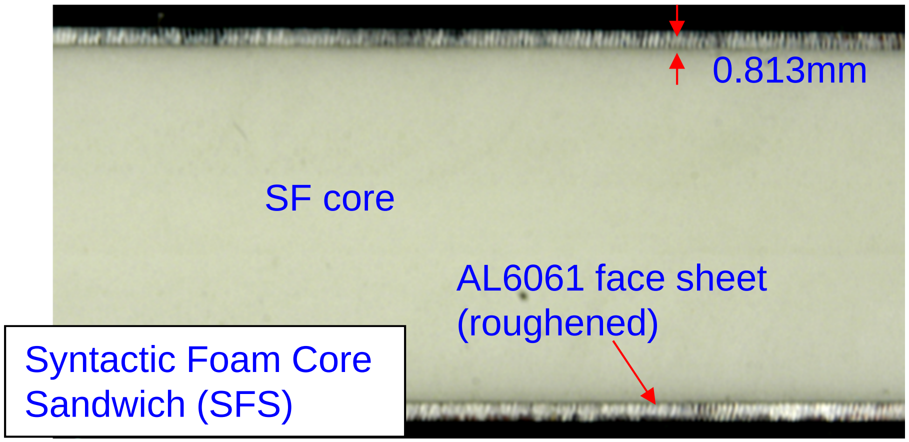
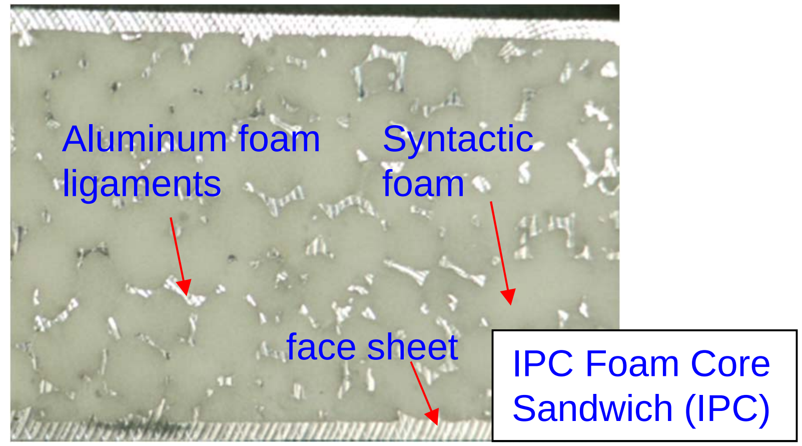
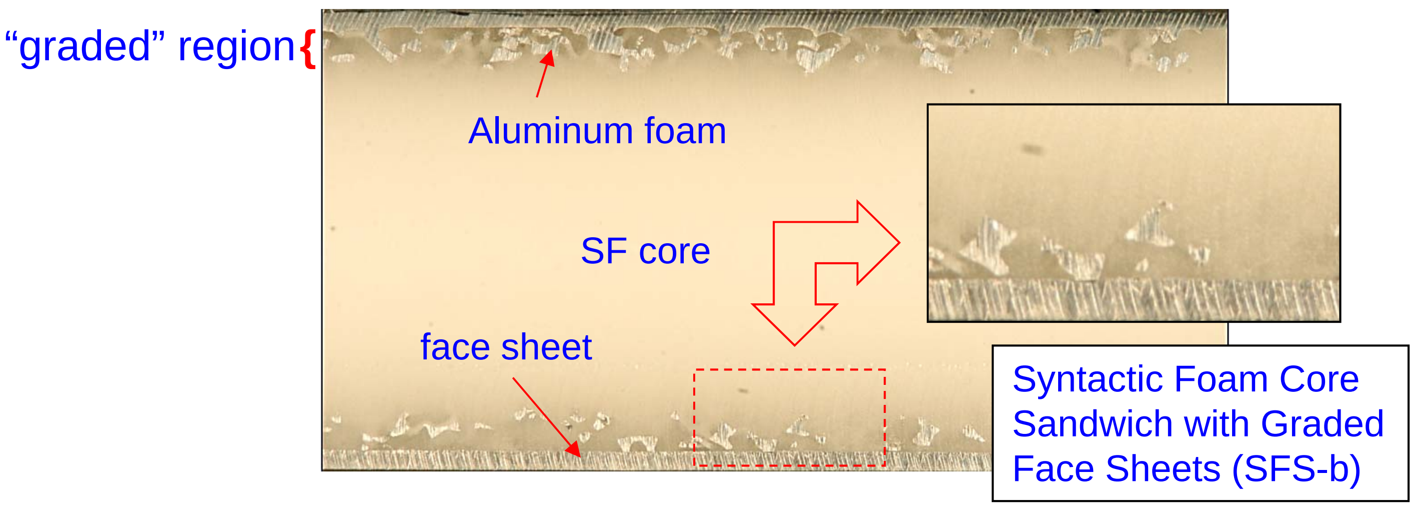
Flexural response of IPC core sandwich structures







**Nominal specimen size: 127mm x 25mm x 20mm

Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

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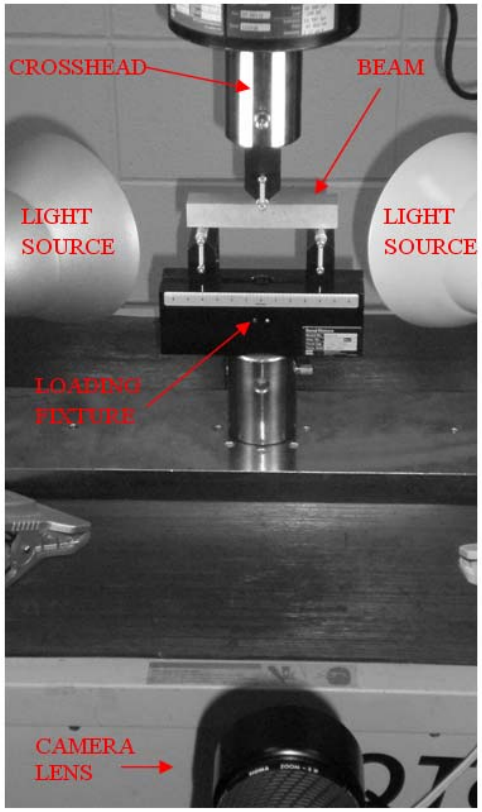
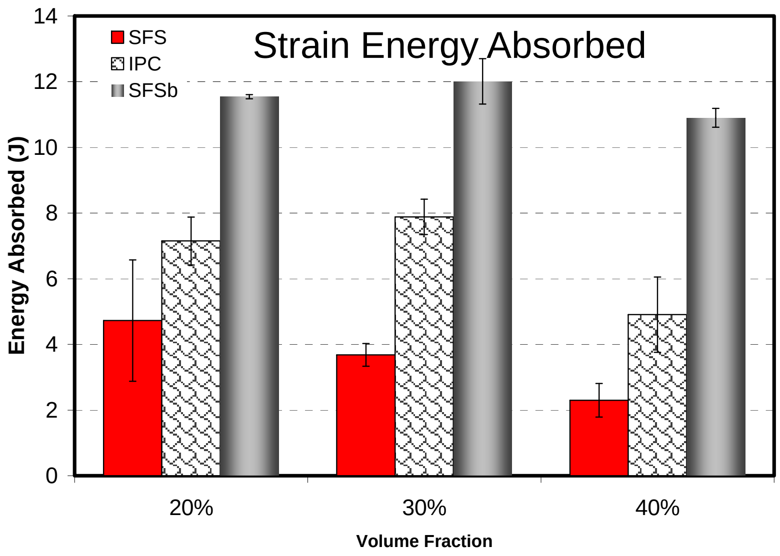
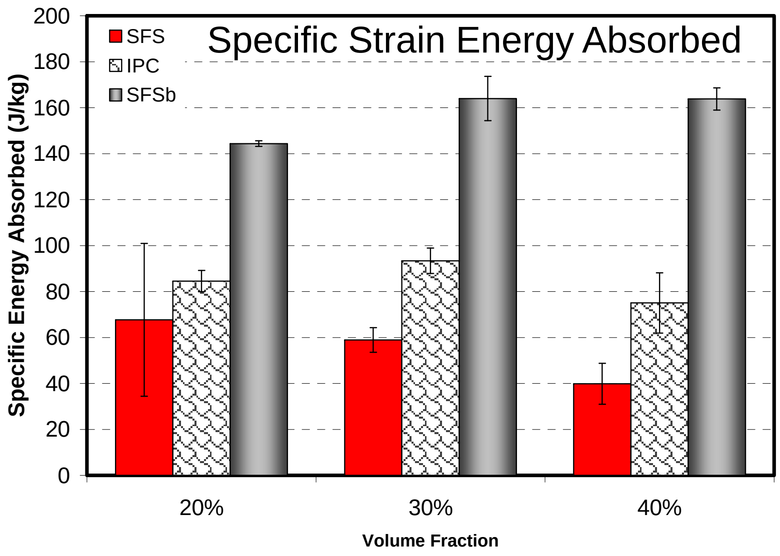
Flexural Performance of SF, IPC foam core and "graded"(SFS-b) sandwich structures







Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

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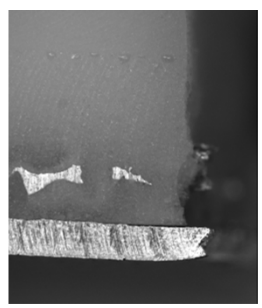
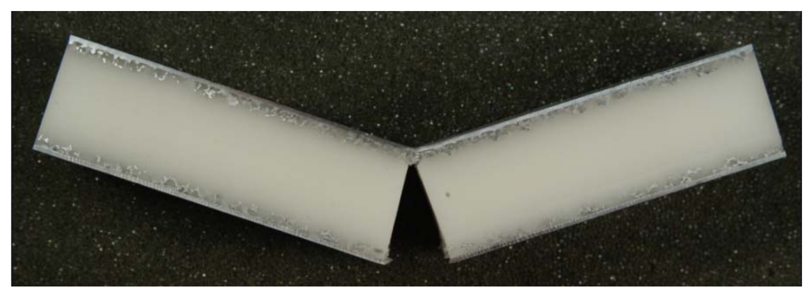
- SFS sandwiches failed due to face-core debonding. They also showed very limited nonlinearity in their load-deflection response.
- In IPC sandwiches, cracks formed in the tensile region, and bottom face sheet yielded. These beams did not fail abruptly. The aluminum foam ligaments acted as bridges holding the SF pockets and hence the sandwich together.
- In SFS-b ("graded" face sheet) samples, observed failures typically manifested as tensile failure of the SF core, leading to a tensile failure of the lower face sheet.





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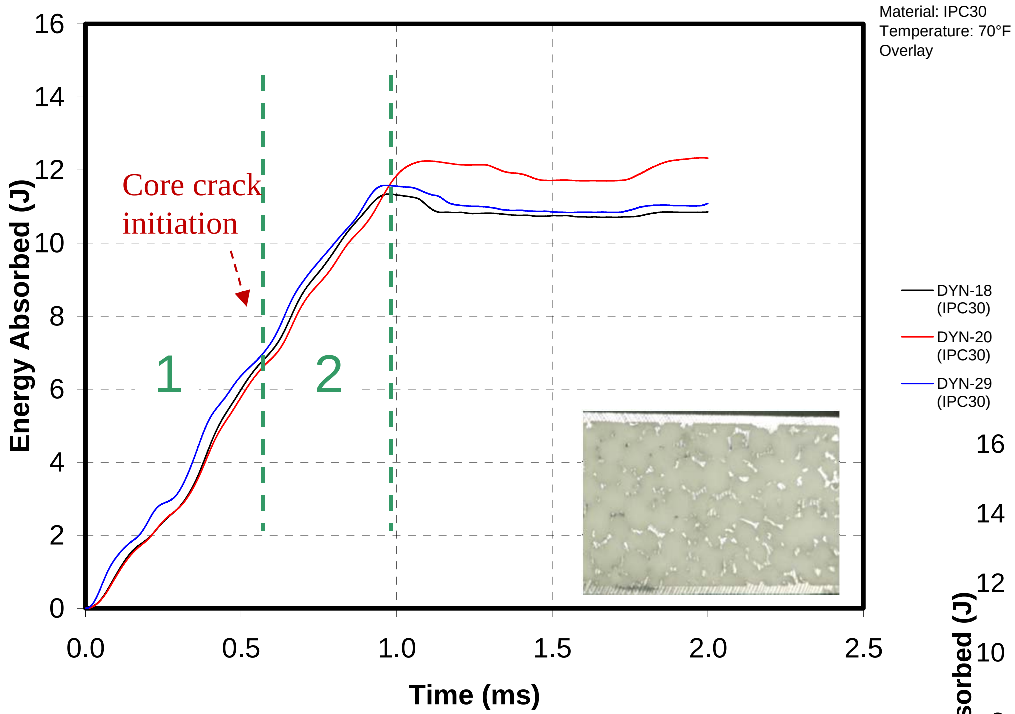
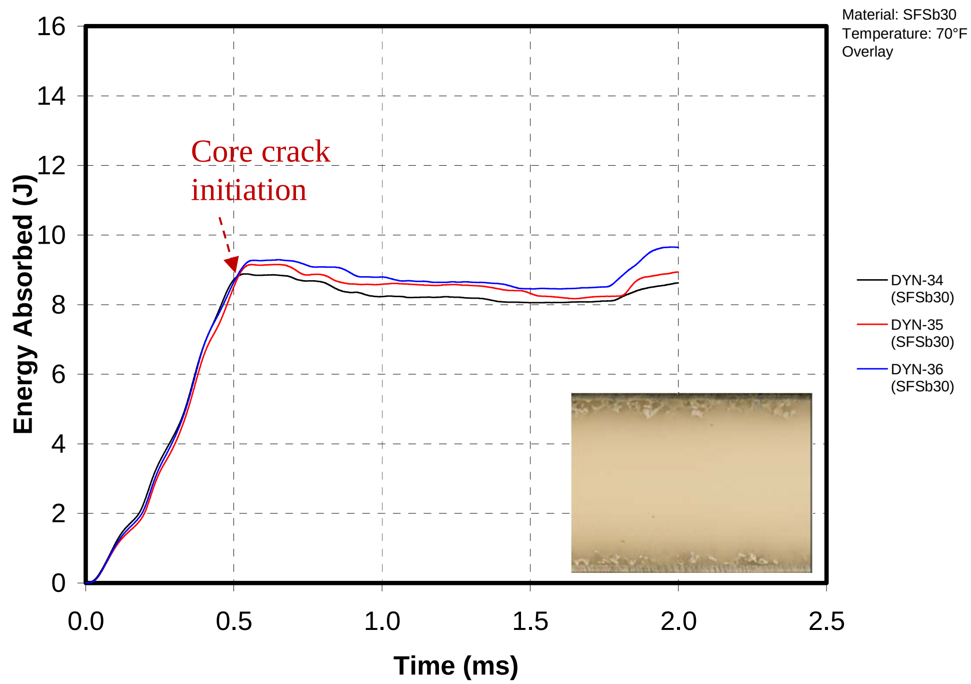


IPC (30%)

- Core is intact in Region 1
- Core is cracked, specimen continues to absorb energy in Region 2

SFS-b (30%)

- Energy absorption only up until crack initiation



Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

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Quasi-static Response

- IPC foam core sandwiches show specific strain energy improvements of 25%-88% over SFS sandwiches.
- With specific strain energy improvements of 71%-118% over IPC foam core sandwiches, SFS-b ("graded face sheet") sandwiches prove to perform better in bending. This is attributed to the weaker tensile response of IPC foam core in the tensile region.
- Failure in SFS-b was abrupt, whereas with IPC was more gradual.

Dynamic Response

- Failure initiates in tensile region of the core as in static cases; Diffuse cracking pattern in IPC
- SFS-b sandwiches show 14% lower specific energy absorbed compared to IPC foam core sandwiches.
- Contrary to quasi-static case, IPC architecture seems to have a positive influence under impact loading → Loading rate effects!

Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

Hareesh Tippur, Auburn U.

- Journal Publications
  - ‘Flexural Response of Syntactic Foam Core Sandwich Structures: Effects of Graded Face Sheets and Interpenetrating Phase Composite Foam Core,’ A. Craven* and H. V. Tippur, *in preparation*, 2012.
  - ‘Experimental Measurements and Numerical Modeling of Dynamic Compression Response of an Interpenetrating Phase Composite Foam,’ C. Periasamy* and H. V. Tippur, *Mechanics Research Communications*, accepted, 2012.
  - ‘Quasi-static and dynamic compression response of a lightweight interpenetrating phase composite foam,’ C. Periasamy*, R. Jhaver* and H. V. Tippur*, *Materials Science and Engineering A*, 527, 2845–2856, 2011.
  - ‘Mechanical characterization and modeling of compression behavior of syntactic foam-filled cellular solids,’ R. Jhaver* and H. V. Tippur, *Journal of Reinforced Plastics and Composites*, Vol. 29, No. 21, pp 3185-3197, 2010.
  - ‘Processing, compression response and finite element modeling of syntactic foam based interpenetrating phase composite,’ R. Jhaver* and H. V. Tippur, *Materials Science and Engineering – A,* 499, pp 507–517, 2009.
- Conference Publications / Presentations
  - ‘Dynamic response of homogeneous and functionally graded foams when subjected to transient loading by a square punch,’ C. Periasamy and H. V. Tippur, paper #335, 2011 SEM annual conference, Uncasville, CT, June 2011.
  - ‘Dynamic Compression of an Interpenetrating Phase Composite (IPC) Foam: Measurements and Finite Element Modeling’, C. Periasamy and H. V. Tippur, paper #407, 2010 SEM annual conference, Indianapolis, IN, June 2010.
  - ‘Dynamic compressive response of a syntactic foam based interpenetrating phase composite’, C. Periasamy* and H. V. Tippur, Proceedings of 2009 SEM annual conference, Albuquerque, NM.
  - ‘Static and dynamic characterization of a lightweight interpenetrating phase composite in compression’, R. Jhaver*, C. Periasamy* and H. V. Tippur, Proceedings of ASME-IMECE, Boston, MA, 2008.

Processing, Failure Characterization and Modeling of Lightweight Interpenetrating Network Composites

Hareesh Tippur, Auburn U.

- Theses / Dissertations
  - M.S. Thesis: 'Experimental Investigation of Syntactic Foam Core Sandwiches: Effect of Graded Face Sheet and Interpenetrating Phase Composite Foam Core,' A. Craven, 2011.
  - M.S. Thesis: 'A split Hopkinson pressure bar apparatus for high-strain rate testing of interpenetrating phase composites (IPC): Measurements and modeling', C. Periasamy, 2010.
  - M.S. Thesis: 'Compression response and modeling of interpenetrating phase composites and foam-filled honeycombs', R. Jhaver, 2009.
- Transitions
  - 'Lightweight Interpenetrating Phase Composite Foam for High Energy Absorption Applications', R. Jhaver and H. Tippur, U.S. Provisional Patent Application No. 61/190,238 No. 61/217,548
  - An entry of a commercialization plan based on IPC technology into 2011 "Alabama Launchpad" competition won 3rd place and $50K in seed funds for possible commercialization of the technology
- PI Awards/Honors
  - Fylde Electronics Prize from the British Society for Strain Measurement (2010)
  - Appointed Editor-in-Chief of Experimental Mechanics (2010)
  - Elected Fellow of the Society for Experimental Mechanics (2011)
  - W. F. Walker teaching award for excellence, Auburn University (2012)