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Investigating the Structural and Mechanical Properties of Boron Nitride Nanotubes and Their Polymer Nanocomposites

Changhong Ke
Research Foundation For The State University Of New York, The

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14. ABSTRACT
This research project has focused on investigating the structural and mechanical properties of boron nitride nanotubes (BNNTs) in high temperature environments, and the mechanical properties of boron nitride nanotubes (BNNTs) reinforced polymer nanocomposites. Systematic and quantitative material characterization of BNNTs in high temperature environments demonstrated that BNNTs are capable of surviving up to 900 °C in air and over 1300°C in inert gas and vacuum environments. The mechanical integrity of individual BNNTs is shown to remain intact at up to 900 °C in air. The strengths of the interfaces formed by individual BNNTs with Poly(methyl methacrylate) (PMMA) and epoxy were characterized by using in situ electron microscopy single-nanotube pull-out techniques. BNNTs were found to form strong binding interfaces with polymers, which is in part attributed to the partially ionic nature of B-N bonds. This project also conducted exploratory studies on the reinforcing mechanisms of BNNTs in metal and ceramic nanocomposites. Particularly, substantial fracture toughness improvement for silica was demonstrated even with low concentrations of BNNTs. The research findings demonstrate that BNNTs are structurally and mechanically stable in high temperature environment

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Summary of Accomplishments/New Findings

1. Structural and Mechanical Properties of BNNTs in High Temperature Environments

The thermal-stability of boron nitride nanotubes (BNNTs) that were produced using the HTP (high-temperature pressure) method was characterized on both bulk and individual tubes basis by using a variety of materials characterization tools, including AFM, TEM, TGA, XRD, optical and Raman microscopy, and Hypersonic Materials Experiment Test System (HYMETS). The *in situ* optical, Raman and XRD measurement results consistently show that bulk HTP-BNNTs were capable of maintaining their structural integrity at up to 1000 ºC in air (Fig. 1a). The AFM and HRTEM measurements show that the tubular structure of individual dispersed BNNTs could survive up to 900 ºC in air (Fig. 1b). The mechanical integrity of thermally annealed HTP-BNNTs was characterized by using AFM-based nanomechanical compression testing techniques. The effective transverse elastic modulus of individual BNNTs is found to remain intact when the tubes were thermally annealed at up to 850 ºC in air (Fig. 1c). HYMETS test and analysis reveal that an oxidation reaction occurred during the HYMETS tests (at Mach 5), but the sample kept its mechanical integrity even after one minute hypersonic thermal test at 1300 ºC. In summary, our studies demonstrate that HTP-BNNTs possess superior thermal stability in both structural and mechanical properties, and are promising for high-performance multifunctional material applications in high temperature environments, such as hypersonic applications.

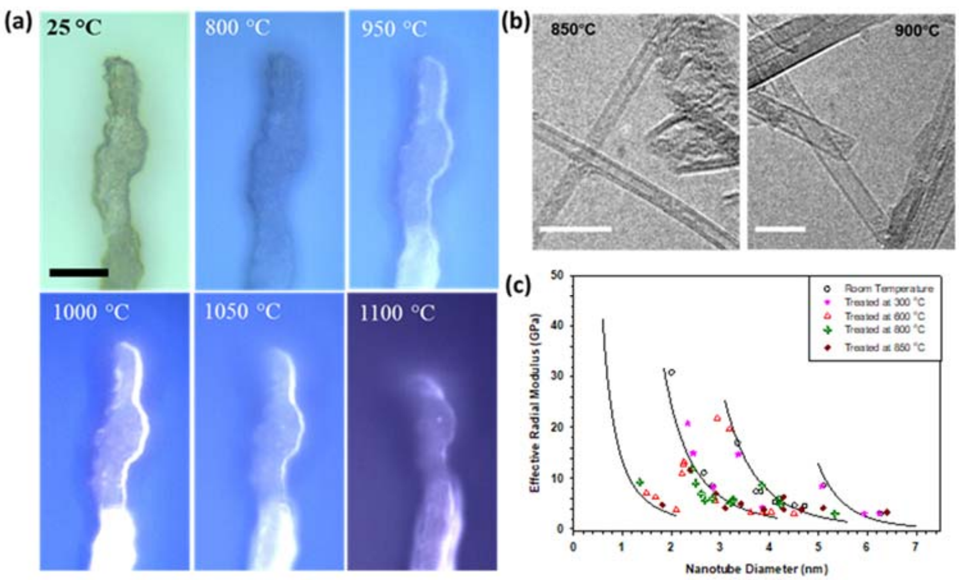

Figure 1: (a) Selected *in situ* optical images showing the morphology evolutions of one tested BNNT microfibril being heated at different temperatures (the scale bar represents 20 μm); (b) HRTEM images of individual BNNTs deposited on Ni grid after being heated at 850 °C and 900 °C in air for 10 mins. (c) The dependence of the measured effective radial modulus of BNNTs on the tube's outer diameter at room temperature and after being annealed at 300, 600, 800 and 850 °C, respectively. The solid curves represent the power-function fitting curves of the effective radial elastic moduli data of single- to quadruple-walled BNNTs at room temperature.

Publication:

1. Xiaoming Chen, Christopher M Dmuchowski, Cheol Park, Catharine C. Fay and Changhong Ke, "Quantitative Characterization of Structural and Mechanical Properties of Boron Nitride Nanotubes in High Temperature Environments," *Scientific Reports*, Vol. 6, pp.11388, 2017.

2. Mechanical Strength of Boron Nitride Nanotube Polymer Interfaces

The strengths of the nanotube-polymer interfaces formed by individual BNNTs with epoxy and poly(methyl methacrylate) (PMMA) were characterized by using *in-situ* electron microscopy nanomechanical single-tube pull-out testing techniques (Fig. 2a). The nanomechanical measurements show that the shear strengths of BNNT-epoxy and BNNT-PMMA interfaces reach 323 and 219 MPa, respectively (Fig. 2b&2c). It was discovered that BNNTs can form substantially stronger binding interfaces with polymers than comparable carbon nanotubes (CNTs) (Fig. 2d). Molecular dynamics simulations show that the higher BNNT-polymer binding strength is partially attributed to the strong electrostatic interaction on BNNT-polymer interfaces, which is originated from the polarized electronic structure in BNNTs. The research findings on the mechanical properties of BNNTs and BNNT-polymer interfaces demonstrate that BNNTs hold great potential (and are even better than CNTs) for innovative light-weight and high-strength multifunctional aerospace materials.

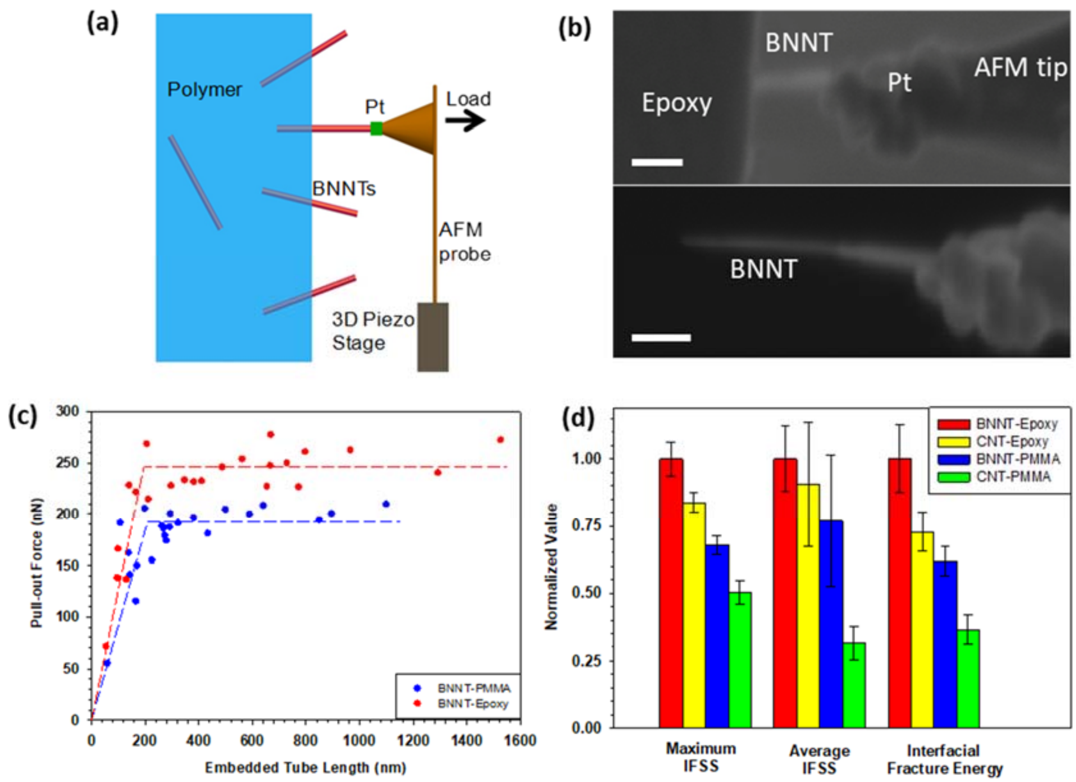

Figure 2: *In situ* SEM nanomechanical single-tube pull-out measurement. (a) 2D testing schematic; (b) Selected snapshots of one representative single-tube pull-out measurement (*scale bars* 200 nm). (c) The measured dependences of the pull-out load on the embedded length for both BNNT-PMMA and BNNT-epoxy interfaces. The dashed lines represent the respective linear fitting curves to the data sets whose embedded tube lengths are below or above the critical embedded length. (d) Comparison of the diameter-weighted IFSS and IFE for four types of nanotube-polymer interfaces.

<u>Publication</u>:

1 Xiaoming Chen, Liuyang Zhang, Cheol Park, Catharine C. Fay, Xianqiao Wang and Changhong Ke, "Mechanical Strength of Boron Nitride Nanotube-Polymer Interfaces," *Applied Physics Letters*, Vol. 107, 253105, 2015. (***Editor's pick, on the most read list***).

3. Mechanical Strength of Carbon and Boron Nitride Nanotube Metal Interfaces

We performed exploratory studies on the reinforcing mechanism of nanotube-reinforced metal nanocomposites. Specifically, we quantitatively characterized the mechanical strengths of the nanotube-metal interfaces formed by individual carbon nanotubes (CNTs) and BNNTs with aluminum (Al) and Titanium (Ti) by using *in situ* electron microscopy nanomechanical single-tube pull-out testing techniques (Fig. 3a). The nanomechanical measurements show that the shear strengths of CNT-Al and CNT-Ti interfaces reach about 28.7 MPa and 37.8 MPa, respectively. (Fig. 3b-d). Thermal annealing is found to have a prominent impact on CNT-metal interfaces (Fig. 3c). The pilot study on testing the mechanical strength of BNNT-Al/Ti interfaces is in progress. The research findings are useful to better understand the load transfer process on the nanotube-metal interface and the reinforcing mechanism of nanotubes and ultimately contribute to the optimal design and performance of nanotube-reinforced metal matrix nanocomposites.

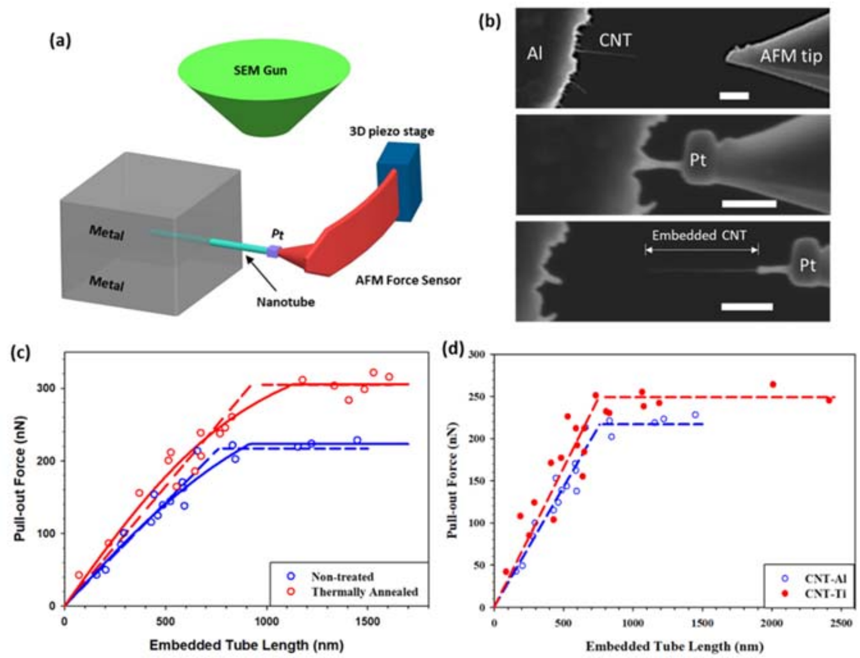

Figure 3: **(a)** Schematic of the *in situ* nanomechanical single-tube pull-out testing technique inside a high resolution scanning electron microscope. (b) Selected high-resolution SEM snapshots showing the key processes in one representative single-tube pull-out measurement. (c) The measured dependences of the pull-out force on the embedded tube length for both as-prepared/non-treated (blue dots) and thermally annealed (red dots) CNT-Al interfaces. (d) The measured dependence of the pull-out force on the embedded tube length for CNT-Ti interfaces (solid red dots), which is contrasted with the measurement data reported on CNT-Al interfaces (blue empty dots).

<u>Publications</u>:

1. Chenglin Yi, Xiaoming Chen, Feilin Gou, Christopher M Dmuchowski, Anju Sharma, Cheol Park, and Changhong Ke, "Direct Measurements of the Mechanical Strength of Carbon Nanotube - Aluminum Interfaces," Carbon, Vol. 125, pp. 93-102, 2017.
2. Chenglin Yi, Soumendu Bagchi, Christopher M Dmuchowski, Feilin Gou, Xiaoming Chen, Cheol Park, Huck Beng Chew, and Changhong Ke, "Direct Nanomechanical Characterization of Carbon Nanotube - Titanium Interfaces," Carbon, Vol. 132, pp. 548-555, 2018.
3. Soumendu Bagchi, Changhong Ke, and Huck Beng Chew, "Oxidation effects on the shear strength of graphene on aluminum and titanium surfaces," Physical Review B, Vol. 98, pp. 174106, 2018.

4. Mechanical Strength of Boron Nitride Nanotube Ceramic Interfaces

We performed exploratory studies on the reinforcing mechanism of BNNT-reinforced ceramic matrix nanocomposites. Specifically, we performed the first direct measurement of the interfacial strength by pulling out individual BNNTs from silica (silicon dioxide) matrices using in situ electron microscopy techniques (Fig. 4a). Our nanomechanical measurements show that the average interfacial shear stress reaches about 34.7 MPa (Fig. 4b-d). The fracture toughness of BNNT-silica ceramic matrix nanocomposite is evaluated based on the measured interfacial strength property, and substantial fracture toughness enhancements are demonstrated at even small filler concentrations (Fig. 4e). This study demonstrates that BNNTs are excellent reinforcing filler materials for light, strong and durable ceramic matrix nanocomposites that may find usage in many demanding applications, such as those that are involved with harsh thermal, chemical, and/or radiation environments.

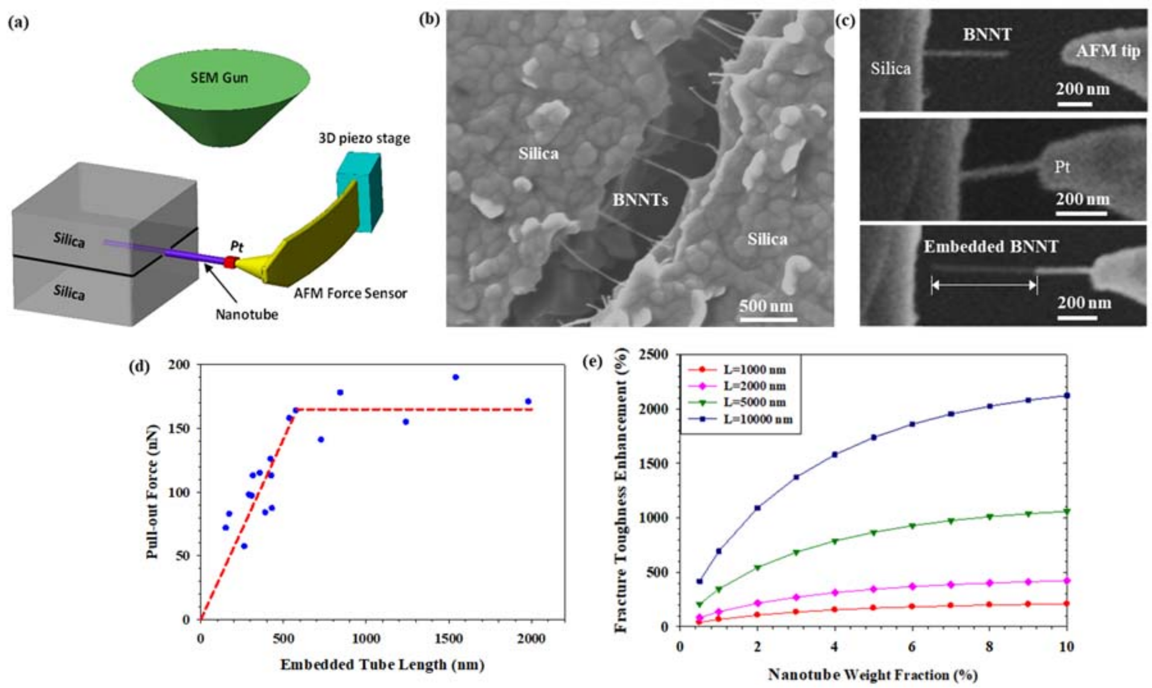

Figure 4: (a) *In situ* SEM nanomechanical single-tube pull-out testing scheme; (b) SEM image of one fractured silica/BNNT/silica thin-film composite with bridging, pulled-out and fractured BNNTs. (c) Selected SEM snapshots showing a typical single-nanotube pull-out experiment conducted on a BNNT-silica composite sample. (d) The measured pull-out force versus the embedded tube length for BNNT-silica interfaces (solid circle) with the bi-linear fitting curves (dashed lines). (e) Theoretically predicted fracture toughness improvement based on HTP-BNNTs that were employed in the present pull-out test.

Publication:

1. Chenglin Yi, Soumendu Bagchi, Feilin Gou, Christopher M Dmuchowski, Cheol Park, Catharine C. Fay, Huck Beng Chew, and Changhong Ke, "Direct Nanomechanical Measurements of Boron Nitride Nanotube - Ceramic Interfaces," *Nanotechnology*, Vol. 30, pp. 025706, 2019.

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Post-docs: Dr. Xiaoming Chen (September 2015 to February 2017)

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Archival Publications (partially or fully supported by this project, 09/2015-09/2018)

1. Xiaoming Chen, Liuyang Zhang, Cheol Park, Catharine C. Fay, Xianqiao Wang and Changhong Ke, "Mechanical Strength of Boron Nitride Nanotube-Polymer Interfaces," *Applied Physics Letters*, Vol. 107, 253105, 2015. (***Editor's pick, on the most read list***).
2. Xiaoming Chen, Meng Zheng, Qing Wei, Stefano Signetti, Nicola M. Pugno and Changhong Ke, "Mechanical Deformation of Nanotubes in Peeling Contact with Flat Substrate: an *in situ* Electron Microscopy Nanomechanical Study," *Journal of Applied Physics*, Vol. 119, 154305, 2016.
3. Xiaoming Chen and Changhong Ke, "Structural and physical properties of boron nitride nanotubes and their applications in nanocomposites," chapter in book "*Boron Nitride Nanotubes in Nanomedicine*," Editors Dr. Gianni Ciofani and Dr. Virgilio Mattoli, Elsevier, 2016.
4. Keun Su Kim, Myung Jong Kim, Cheol Park, Catharine Fay, Sang-Hyon Chu, Christopher Kingston, and Benoit Simard, "Scalable Manufacturing of Boron Nitride Nanotubes and Their Assemblies: A Review," Semiconductor Science and Technology, 32(1), December 1 (2016).
5. Chenglin Yi, Xiaoming Chen, Feilin Gou, Christopher M Dmuchowski, Anju Sharma, Cheol Park, and Changhong Ke, "Direct Measurements of the Mechanical Strength of Carbon Nanotube - Aluminum Interfaces," *Carbon*, Vol. 125, pp. 93-102, 2017.
6. Xiaoming Chen, Christopher M Dmuchowski, Cheol Park, Catharine C. Fay and Changhong Ke, "Quantitative Characterization of Structural and Mechanical Properties of Boron Nitride Nanotubes in High Temperature Environments," *Scientific Reports*, Vol. 6, pp.11388, 2017.
7. Xiaoming Chen, and Changhong Ke, "Load Transfer and Energy Absorption in Transversely Compressed Multi-walled Carbon Nanotubes." *Coupled Mechanics Systems*, Vol. 6, pp. 273-286, 2017.
8. Vesselin Yamakov, Cheol Park, Jin Ho Kang, Xiaoming Chen, Changhong Ke, Catharine Fay, "Piezoelectric and Elastic Properties of Multiwall Boron Nitride Nanotubes and Their Fibers: a Molecular Dynamics Study," *Computational Materials Science*, Vol. 135, pp. 29-42, 2017.
9. Wenyang Qu, Xiaoming Chen, Changhong Ke, "Temperature-dependent Frictional Properties of

Ultra-thin Boron Nitride Nanosheets," *Applied Physics Letters*, Vol. 110, pp.143110, 2017.

10. Mohammed Adnan, Daniel M. Marincel, Olga Kleinerman, Sang-Hyon Chu, Cheol Park, Samuel Hocker, Catharine Fay, Sivaram Arepalli, Yeshayahu Talmon, and Matteo Pasquali, "Extraction of boron nitride nanotubes and fabrication of macroscopic articles using chlorosulfonic acid," *Nano Letters*, Vol. 18, No. 3, pp 1615–1619 (2018).
11. Olga Kleinerman, Mohammed Adnan, Daniel M. Marincel, Anson W. K. Ma, E. Amram Bengio, Cheol Park, Sang-Hyon Chu, Matteo Pasquali, and Yeshayahu Talmon, "Dissolution and Characterization of Boron Nitride Nanotubes in Superacid," *Langmuir*, Vol. 33, No. 50, pp 14340–14346 (2017).
12. Chenglin Yi, Soumendu Bagchi, Christopher M Dmuchowski, Feilin Gou, Xiaoming Chen, Cheol Park, Huck Beng Chew, and Changhong Ke, "Direct Nanomechanical Characterization of Carbon Nanotube - Titanium Interfaces," *Carbon*, Vol. 132, pp. 548-555, 2018.
13. Stefano Signetti, Xiaoming Chen, Changhong Ke, and Nicola M. Pugno, "Quantifying the tribological behavior of a defective carbon nanotubes bundle under peeling configurations by finite element simulations," accepted & in press, *Journal of Physics D: Applied Physics*, 2018
14. Soumendu Bagchi, Changhong Ke, and Huck Beng Chew, "Oxidation effects on the shear strength of graphene on aluminum and titanium surfaces," *Physical Review B*, Vol. 98, pp. 174106, 2018.
15. Chenglin Yi, Soumendu Bagchi, Feilin Gou, Christopher M Dmuchowski, Cheol Park, Catharine C. Fay, Huck Beng Chew, and Changhong Ke, "Direct Nanomechanical Measurements of Boron Nitride Nanotube - Ceramic Interfaces," *Nanotechnology*, Vol. 30, pp. 025706, 2019.

Patent and invention disclosure (partially or fully supported by this project, 09/2015-09/2018)

1. NASA Langley Invention Disclosure, "In-situ Passivation and Insulation Layer for a Flexible Thermal Protection System (FTPS)," LAR-18792-1, Nov 19 (2015).

Interactions/Transitions (partially or fully supported by this project, 09/2015-09/2018)

Graduate Thesis and Dissertations

1. Chenglin Yi, PhD dissertation, "Nanomechanical Z-shape Folding and Unfolding of Graphene and Direct Measurements of the Mechanical Strength of Carbon Nanotube-Metal interface," May 2018.
2. Wenyang Qu, MS thesis, "Frictional Characteristics of Boron Nitride Nanosheets," May 2016.
3. Christopher M Dmuchowski, MS thesis, "DNA Assisted Dispersion of Boron Nitride and Carbon Nanotubes," May 2016.
4. Feilin Gou, MS thesis, "Mechanical Characterization of Carbon Nanotube Based Polymer Nanocomposites," December 2016.
5. Ohood Q Alsmairat, MS thesis, "Mechanical Characterization of Electrospun Composite Nanofibers," May 2017.
6. Wuxiang Feng, MS thesis, "Mechanical Reinforcement of Polyacrylamide Hydrogels Using Pristine Single-walled Carbon Nanotubes" May 2018.

Other interactions include the following technical presentations:

1. Xiaoming Chen and Changhong Ke, "Load Transfer in Transversely Compressed Multi-walled Nanotubes," *2015 ASME International Mechanical Engineering Congress and Exposition (IMECE15)*.
2. Xiaoming Chen, Meng Zheng, Cheol Park, and Changhong Ke, "Nanomechanical Characterization of the Interfacial Load Transfer between Carbon Nanotubes and Polymers," *2015 ASME International Mechanical Engineering Congress and Exposition (IMECE15)*.
3. S. Hocker, S.-H. Chu, C. Park, M. Adnan, M. Pasquali, S. Scotti, C. Fay, "Boron Nitride Nanotubes as a Lightweight Thermal Protection Material," Mater. Res. Soc., Boston, MA, Dec 4 (2015).

4. C. Park, C. Fay, S. Hocker, and S. Chu, "Multifunctional Nanocomposites for Aerospace Applications: Overview," Invited Talk, KIST, Seoul, South Korea, Oct 19-23 (2015).
5. C. Park, C. Fay, S. Hocker, and S. Chu, "Multifunctional Nanocomposites for Aerospace Applications: Overview," Invited Talk, Seoul National University, Seoul, South Korea, Oct 23 (2015).
6. Xiaoming Chen and Changhong Ke, "Mechanical Strength of Nanotube-polymer Interfaces," *2016 SEM Annual meeting,* 2016.
7. Changhong Ke, "Experimental Nanomechanics of Low Dimensional Nanostructures," Department of Engineering Mechanics, China University of Petroleum, 2016. (Invited seminar)
8. Changhong Ke, "Experimental Nanomechanics of Low Dimensional Nanostructures," Department of Materials Science and Engineering, Shandong University of Technology, 2016. (Invited seminar)
9. Xiaoming Chen and Changhong Ke, "Nanomechanical characterization of boron nitride and carbon nanotubes polymer interfaces," *Proceeding of 2016 24th International Congress of Theoretical and Applied Mechanics* (*ICTAM2016*).
10. Xiaoming Chen; Liuyang Zhang; Cheol Park; Catharine Fay; Xianqiao Wang; Changhong Ke, "Nanomechanical Strength of Boron Nitride Nanotube Polymer Interfaces," 2016 MRS Fall meeting.
11. Xiaoming Chen and Changhong Ke, "Mechanical Strengths of Boron Nitride and Carbon Nanotubes Polymer Interfaces," 2016 ASME International Mechanical Engineering Congress and Exposition (IMECE16).
12. Changhong Ke, Sang-Hyon Chu, Cheol Park, "Investigating Structural and Mechanical Properties of Boron Nitride Nanotubes and Their Polymer Nanocomposites," AFOSR LDM Research Program Review Meeting, 2016.
13. C. Park, S. Hocker, S. Chu, and C. Fay, "Boron Nitride Nanotube and BNNT Nanocomposites for Aerospace Applications," Invited Talk, IUPAC, Jeju, South Korea, October (2016).
14. S. Hocker, S. Chu, V. Yamakov, J. Newman, S. Messina, E. Judd, C. Rohmann, D. Berhardt, C. Park, and C. Fay "Titanium Alloy Metal Matrix Nanocomposite using Boron Nitride Nanotubes," PacSurf2016, Kohala Coast, Hawaii, December 11-15 (2016).
15. C. Park, R. Bryant, C. Fay, S. Hocker, and S. Chu, "Multifunctional Nanocomposites for Aerospace Applications: Overview," Invited Talk, POSTECH/KIST, South Korea, April 25-28 (2016).
16. C. Park, C. Fay, S. Hocker, and S. Chu, "Emerging Advanced Aerospace Materials," Materials Blue Sky Workshop, Hampton, VA, June 21-22 (2016).
17. S. Chu, S. Hocker, C. Park, C. Fay, "BNNT Research for Aerospace and Beyond - Synthesis and Application Development," Canada-Korea Conference on Science and Technology 2016 (CKC 2016), Ottawa, Canada, Aug 7-9 (2016).
18. Xiaoming Chen and Changhong Ke, "Nanomechanical Characterization of Interfaces in Boron Nitride and Carbon Nanotubes Polymer Nanocomposites, ICF14, Rhodes, Greece, 2017.
19. Wenyang Qu, Xiaoming Chen, and Changhong Ke, "Temperature-dependent Frictional Properties of Ultra-thin Boron Nitride Nanosheets," 2017 SEM Annual meeting, 2017.
20. Xiaoming Chen, Meng Zheng, Qing Wei, Stefano Signetti, Nicola M. Pugno and Changhong Ke, "Deformation of Nanotubes in Peeling Contact with Flat Substrate: An in Situ Electron Microscopy Nanomechanical Study" 2017 SEM Annual meeting, 2017.
21. Xiaoming Chen, Christopher Dmuchowski, Cheol Park, Catharine C. Fay, Changhong Ke, "Structural and Mechanical Properties of Boron Nitride Nanotubes in High temperature Environment," 2017 MRS Fall meeting (poster).
22. Chenglin Yi, Xiaoming Chen, Feiliin Gou, Christopher Dmuchowski, Anju Sharma, Cheol Park, Changhong Ke, "Nanomechanical Characterization of Carbon Nanotube-Metal Interfaces." 2017 MRS Fall meeting (poster).
23. Wenyang Qu, Xiaoming Chen, and Changhong Ke, "Temperature-dependent Structural and Frictional Properties of Boron Nitride Nanosheets," 2017 ASME International Mechanical Engineering Congress and Exposition (IMECE17).
24. Chenglin Yi, Xiaoming Chen, Changhong Ke "Direct Measurements of the Mechanical Strength of

Carbon Nanotube-Metal Interfaces," 2017 ASME International Mechanical Engineering Congress and Exposition (IMECE17).

25. Xiaoming Chen, Meng Zheng, Qing Wei, Stefano Signetti, Nicola M. Pugno and Changhong Ke, "In situ Electron Microscopy Nanomechanical Study of Nanotubes in Peeling Contact with Flat Substrate," 2017 ASME International Mechanical Engineering Congress and Exposition (IMECE17).
26. C. Park, S. Hocker, S. Chu, V. Yamakov, and C. Fay, "Multifunctional Boron Nitride Nanotube and BNNT Nanocomposites for Extreme Space Environment," Invited Talk, Mid-Atlantic Micro/Nano Alliance (MAMNA) Spring 2017 Symposium, Johns Hopkins APL, MD, April 17 (2017).
27. C. Park, S. Hocker, S. Chu, and C. Fay, "Boron Nitride Nanotube and BNNT Nanocomposites for Aerospace Applications," Invited Talk, 9th International Conference on Materials for Advanced Technologies (ICMAT 2017), Suntec, Singapore, June 18-23, (2017).
28. S. Chu, C. Park, S. Hocker, and C. Fay, "Boron Nitride Nanotubes Synthesis and Applications," Nano Korea 2017, Seoul, South Korea, July 12-14 (2017).
29. S. Chu, C. Park, S. Hocker, and C. Fay, "Boron Nitride Nanotubes Synthesis and Applications," Invited Talk, Korea Institute of Materials Science (KIMS), Changwon, South Korea, September 19 (2017).
30. C. Park, S. Hocker, S. Chu, V. Yamakov, and C. Fay, "Boron Nitride Nanotube and BNNT Nanocomposites for Aerospace Applications," Invited Talk, 2017 International Conference on BioNano Innovation (ICBNI), Brisbane, Australia, September 24-27 (2017).
31. Xiaoming Chen, Christopher Dmuchowski, Cheol Park, Catharine C. Fay, Changhong Ke, "Structural and Mechanical Properties of Boron Nitride Nanotubes in High temperature Environments," 2018 ASME International Mechanical Engineering Congress and Exposition (IMECE18).
32. Chenglin Yi, Christopher Dmuchowski, Feiliin Gou, Xiaoming Chen, Cheol Park, Changhong Ke, "Direct Nanomechanical Measurements of Carbon Nanotube-Metal Interfaces," 2018 ASME International Mechanical Engineering Congress and Exposition (IMECE18).
33. Wenyang Qu, Xiaoming Chen, and Changhong Ke, "Probing the Structural and Mechanical Properties of Boron Nitride Nanosheets," 2018 ASME International Mechanical Engineering Congress and Exposition (IMECE18).
34. Changhong Ke, Sang-Hyon Chu, Cheol Park, "Investigating Structural and Mechanical Properties of Boron Nitride Nanotubes and Their Polymer Nanocomposites," AFOSR LDM Research Program Review Meeting, 2018.
35. Chenglin Yi, Christopher Dmuchowski, Feiliin Gou, Xiaoming Chen, Changhong Ke, "Nanomechanical Measurements of Carbon Nanotube-Metal Interfaces," The 10th European Solid Mechanics Conference, Bologna, July 2-6, 2018.
36. Xiaoming Chen, Christopher Dmuchowski, Cheol Park, Catharine C. Fay, Changhong Ke, "Structural and Mechanical Properties of Boron Nitride Nanotubes in High temperature Environment," 2018 SEM Annual meeting, 2018.
37. Changhong Ke, "Experimental Mechanics of Boron Nitride Nanotubes and Their Nanocomposites," invited seminar at the NASA Langley Research Center, 2018.

Awards and Recognition

<u>Dr. Sang-Hyon Chu</u>

1. Group Achievement Award for establishing the infrastructure and programmatic development of the LaRC/NIA Boron Nitride Nanotube (BNNT) capability, 2015.