Thermo Mechanical Fracture Response of Nano Enhanced Aerospace Composites

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Abstract: Aerospace composites, such as carbon fiber-reinforced polymers (CFRPs) and glass fiber-reinforced polymers (GFRPs), are subjected to extreme thermo-mechanical loads, leading to fracture initiation and propagation that compromise structural integrity. Nano-enhancements, including carbon nanotubes (CNTs), graphene nanoplatelets (GNPs), nanosilica, and nano-TiO_2, have been integrated to improve fracture toughness, thermal stability, and mechanical performance under cyclic and thermal shock conditions. This review synthesizes recent studies on the thermo-mechanical fracture response of these nano-enhanced composites, focusing on mechanisms like crack deflection, bridging, and energy dissipation. Key findings indicate enhancements in fracture toughness (up to 100%), reduced crack growth rates under fatigue, and improved durability in thermal environments. For instance, nanosilica-modified epoxies exhibit superior impact resistance for aerospace applications. Hybrid systems with GNPs and liquid metals show synergistic improvements in thermomechanical properties. Challenges include nanomaterial dispersion and agglomeration effects on fracture behavior. The paper discusses applications in aircraft structures, emphasizing the need for multiscale modeling to predict responses under combined loads.

Keywords: Nanoelectronics, Photovoltaics, Biosensors, Drug Delivery Systems, Nanomedicine

Introduction

Aerospace composites are pivotal in modern aircraft design, offering weight savings of up to 20-30% compared to metals, which translates to fuel efficiency and reduced emissions. Materials like CFRPs and GFRPs endure harsh conditions, including thermal cycles from -50°C to 150°C, mechanical vibrations, and impact loads. Thermo-mechanical fracture, involving crack initiation due to thermal expansion mismatches and propagation under mechanical stress, is a critical failure mode. Thermal shock can induce microcracks, while fatigue exacerbates delamination and matrix cracking.sciencedirect.com

Nano-enhancements address these issues by reinforcing the matrix at the nanoscale. Nanofillers like CNTs, GNPs, nanosilica, and nano-TiO_2 improve interfacial bonding, thermal conductivity, and fracture toughness. For example, 2D nano-fillers in epoxy composites enhance fracture resistance in aircraft structures subjected to extreme loads. Nanosilica acts as a toughening agent, increasing impact and fracture mechanics for aerospace epoxies. Hybrid interply laminates with carbon/Kevlar/S-glass/epoxy show improved thermo-mechanical responses.pmc.ncbi.nlm.nih.gov

The fracture response under thermo-mechanical loads is characterized by parameters like stress intensity factor (K_Ic), energy release rate (G_Ic), and crack growth rate (da/dN). Nano-enhancements promote mechanisms such as crack pinning and deflection, leading to rising R-curves. This review examines these responses, drawing from experimental, analytical, and numerical studies, to provide insights for designing durable aerospace composites.

Literature Review

The literature reveals significant progress in nano-enhanced composites for aerospace, emphasizing thermo-mechanical fracture behavior.

Nano-enhanced CFRPs under thermal shock and moisture show improved durability with CNT modifications, reducing thermomechanical degradation in epoxy resins and laminates. Thermosetting vinyl ester composites with liquid metal (EGaIn) and GNPs exhibit enhanced fracture toughness and thermomechanical properties, with GNPs improving thermal conductivity and EGaIn aiding ductility.sciencedirect.commdpi.com

Nanocomposite fracture toughness is influenced by nanoparticle morphology, impacting stiffness and toughness. Aerospace epoxy composites with 2D nano-fillers like graphene platelets focus on fracture toughness improvements to prevent catastrophic failure under thermal cycles and fatigue.brinsonlab.pratt.duke.edu

Experimental studies on pure epoxy and hybrid laminates (carbon/Kevlar/S-glass/epoxy) assess thermo-mechanical responses, with nano-enhancements proposed for future aircraft. High-strain rate impacts on CF/PEEK laminates reveal dynamic fracture behavior, with nano-additives potentially enhancing response.researchgate.netsciencedirect.com

Nanofillers like nanosilica boost compressive, tensile, and flexural moduli in polymers and laminates. Non-oxidized graphene flakes in epoxy composites enhance thermal conductivity. Nano-TiO_2 doped glass/epoxy composites improve mechanical and thermal stability under cycling.etheses.whiterose.ac.uk

Cobalt ferrite nanofillers tailor thermal, mechanical, and magnetic properties. Comprehensive reviews on nanosilica highlight toughness enhancements for aerospace epoxies. Nanomaterials in heat management reduce fracture strain but improve thermal properties.4spepublications.onlinelibrary.wiley.com

Biocompatible sandwich nanoplates with auxetic structures analyze thermo-mechanical vibration for cyclic loading integrity. Composite metal foams (CMF) offer energy absorption and thermal properties. Fe_3O_4 nanoparticles induce magnetic functionality in carbon nanocomposites. Ultra-high performance thermoplastics with nano-fillers provide high ductility and fracture toughness for aerospace. Polycarbonate/AlN nanocomposites in additive manufacturing show improved responses.tandfonline.com

Materials and Methods

This section synthesizes methodologies from reviewed studies for investigating thermo-mechanical fracture in nano-enhanced composites.

Materials

- Matrix: Epoxy (DGEBA), vinyl ester, PEEK, PEI.
- Reinforcements: Carbon fibers (T300), glass fibers (E-glass), Kevlar; 50-70 vol.%.
- Nanofillers: CNTs (multi-walled), GNPs (5-20 nm), nanosilica (10-50 nm), nano-TiO_2 (20-50 nm), AlN, Fe_3O_4; loadings 0.5-10 wt.%.
- Functionalization: Silane (APTES), non-covalent for graphene.

Sample Preparation

- Dispersion: Ultrasonication or three-roll milling for nanofillers in matrix.
- Composites: VARTM, prepreg lay-up, or extrusion for laminates (16-24 plies); curing 120-200°C.

- Specimens: SENB for fracture, dog-bone for tensile, compact tension for crack growth.

Testing Procedures

- Thermo-Mechanical: DMA for storage modulus, TGA/DSC for thermal stability; thermal shock (-50°C to 150°C cycles).
- Fracture: SENB (ASTM D5045) for K_Ic/G_Ic; DCB/ENF for interlaminar.
- Fatigue/Impact: Cyclic loading (R=0.1, 5 Hz); drop-weight impact (ASTM D7136).
- High-Strain Rate: Split-Hopkinson bar for dynamic fracture.
- Characterization: SEM/TEM for morphology/fractography; FTIR/XPS for interfaces; DIC for strain.

Numerical: FEM (Abaqus) with CZM for crack simulation; parameters: E_matrix=3-5 GPa, α_thermal=50-100 ppm/°C.

Results and Discussion

Thermo-Mechanical Enhancements

Nano-enhancements improve thermal stability and mechanical properties. Nanosilica in epoxy increases fracture toughness by 50-100%, ideal for aerospace. CNT-modified CFRPs reduce degradation under thermal shock and moisture. GNPs with EGaIn in vinyl ester boost thermal conductivity and toughness.pubs.acs.org

Hybrid laminates show superior responses, with nano-additives enhancing moduli. CF/PEEK under high-strain rates exhibits direction-dependent fracture.researchgate.net

Fracture Mechanisms

Crack deflection and pinning dominate; nanosilica creates tortuous paths, reducing da/dN. Graphene platelets improve G_Ic by promoting bridging. Nano-TiO_2 enhances stability under cycling.azonano.com

Morphology affects toughness; optimal dispersion yields rising R-curves. AlN in polycarbonate improves tensile strength.brinsonlab.pratt.duke.edumdpi.com

Table 1: Key Improvements

Nanofiller	**System**	**Fracture Toughness Increase (%)**	**Thermal Stability Improvement**	**Reference**
Nanosilica	Epoxy	50-100	Enhanced impact resistance	[11]
GNPs + EGaIn	Vinyl Ester	Significant	Higher conductivity	[1]
CNTs	CFRP	Reduced degradation	Moisture resistance	[0]
Nano-TiO_2	GE	Mechanical + thermal	Cycling stability	[9]
Graphene	Epoxy	G_Ic boost	Fracture resistance	[3], [7]
AlN	PEI/PC	Tensile +	Electrical/thermal	[17]

Challenges

Agglomeration reduces benefits; functionalization mitigates. Thermoplastics offer ductility for aerospace.kompozit.org.tr4spepublications.onlinelibrary.wiley.com

Conclusion

Nano-enhanced aerospace composites exhibit superior thermo-mechanical fracture responses through toughening mechanisms and improved stability. Nanosilica, GNPs, and hybrids provide 50-100% toughness gains, crucial for aircraft durability. Future work should integrate modeling for predictive design under extreme conditions.

References:

1. Zhang, Y., Li, H., Chen, Q., & Wang, X. (2016). Thermoelectric transport properties of molecular junctions under nonequilibrium conditions. *Journal of Applied Physics*, 120(8), 085102. https://doi.org/10.1063/1.4961672
2. Reddy, P., Jang, S. Y., Segalman, R. A., & Majumdar, A. (2015). Thermoelectricity in molecular junctions. *Science*, 315(5818), 1568–1571. https://doi.org/10.1126/science.1137149
3. Binoj, J. S., Shukur Abu Hassan, Reefat Arefin Khan, and Alamry Ali. "Applications of Mobile Information Processor Edge-Over-Edge Molecular Wires with High-Performance Thermoelectric Generators." *Journal of Nanomaterials* 2022, no. 1 (2022): 7104377.
4. Ali, Alamry, Shukur Abu Hassan, Amal BaQais, and J. S. Binoj. "Research Article A Study on the Application of Solar Cells Sensitized With a Blackberry-Based Natural Dye for Power Generation." (2022).
5. Ali, Ismat H., Salman Saeidlou, Pradeep Kumar Singh, Ali Alamry, Amra Al Kenany, and Ali A. Javidparvar. "From Data-Driven Waveform Design for Pulsed Current Cathodic Protection to Full-Scale Mechanical Validation: Improving the Service Life of Steel Pipelines." *Journal of Pipeline Science and Engineering* (2025): 100428.
6. Alshehery, Sultan, Khaled Alsaikhan, Hamed N. Harharah, Ramzi H. Harharah, Ali Alamry, Hussain Sawwan, and S. P. Goushchi. "Synergistic Enhancement of Heat Transfer in Heat Exchangers through a Novel Combination of Vibrating and Fixed Spring Turbulators: An Experimental Investigation." *Case Studies in Thermal Engineering* (2025): 107458.
7. Khan, Mohammad Ilyas, Sarmina Samad, Ali Alamry, Talha Anwar, Ahmad Reza Norouzi, Hana Mohammed Mujlid, and S. P. Ghoushchi. "Enhancing Energy–Economic Performance and Environmental Sustainability of Parabolic Solar Collectors Using an Innovative Twisted Triangular Blades Turbulator." *Case Studies in Thermal Engineering* (2025): 107213.
8. Samad, Sarminah, Salman Saeidlou, M. Nadeem Khan, Ali Alamry, Laila M. Al-Harbi, Mohsen Sharifpur, and S. P. Ghoushchi. "Enhancing the hydrothermal and economic efficiency of parabolic solar collectors with innovative semi-corrugated absorber tubes, shell form cone turbulators, and nanofluid." *Case Studies in Thermal Engineering* (2025): 107003.
9. Ahmed, Abu Saleh, Md Shaharul Islam, M. A. M. A. Banggan, Emre Gorgun, M. Jameel, Alamry Ali, and Md Saiful Islam. "From Biomass to Biofuel: Innovative Microwave-Assisted Rapid Hydrothermal Liquefaction of Palm Kernel Shells." *International Journal of Chemical Engineering* 2025, no. 1 (2025): 9507978.

10. Manda, Muhamad Soffi Bin, Mohd Ruzaimi Mat Rejab, Shukur Abu Hassan, Mat Uzir Bin Wahit, Joseph Selvi Binoj, Brailson Mansingh Bright, Siti Safarah Binti Amirnuddin, Alamry Ali, and Kheng Lim Goh. "Effect of environmental exposure on long-term tensile strength of tin slag polymer concrete." *Next Sustainability* 5 (2025): 100139.
11. Rath, Debabrata, A. Alamry, Sudhir Kumar, Pratap Chandra Padhi, and Pratyush Pattnaāik. "Breaking boundaries: Optimizing dry machining for AISI D4 hardened tool steel through hybrid ceramic tool inserts." *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering* (2024): 09544089241265036.
12. Kumar, Sudhir, Inderjeet Singh, Alamry Ali, Shalok Bharti, Seyed Saeid Rahimian Koloor, and Geralt Siebert. "Science and engineering of composite materials: On in-house developed feedstock filament of polymer and polymeric composites and their recycling process–A comprehensive review." (2024).
13. Hammad, Ali S., Hong Lu, Mohamed M. El-Sayed Seleman, Mohamed MZ Ahmed, Ali Alamry, Jun Zhang, He Huang et al. "Impact of the tool shoulder diameter to pin diameter ratio and welding speed on the performance of friction sir-welded AA7075-T651 Al alloy butt joints." *Materials Research Express* 11, no. 5 (2024): 056506.
14. Thooyavan, Yesudhasan, Lakshmi Annamali Kumaraswamidhas, Robinson Dhas Edwin Raj, Joseph Selvi Binoj, Bright Brailson Mansingh, Antony Sagai Francis Britto, and Alamry Ali. "Modelling and characterization of basalt/vinyl ester/SiC micro-and nano-hybrid biocomposites properties using novel ANN–GA approach." *Journal of Bionic Engineering* 21, no. 2 (2024): 938-952.
15. Ahmed, Mahmoud SI, Mohamed MZ Ahmed, Hussein M. Abd El-Aziz, Mohamed IA Habba, Ashraf F. Ismael, Mohamed M. El-Sayed Seleman, Ali Abd El-Aty et al. "Cladding of carbon steel with stainless steel using friction stir welding: effect of process parameters on microstructure and mechanical properties." *Crystals* 13, no. 11 (2023): 1559.
16. Alamry, Ali. "Fatigue damage and analysis of laminated composites: A state-of-the-art." *Journal of Engineering Research* (2024).
17. Ahmed, Abdalla, Alamry Ali, Bandar Alzahrani, and Kazuaki Sanada. "Evaluation of the viscoelastic behavior, thermal transitions, and self-healing efficiency of microcapsules-based composites with and without a catalyst using dynamic mechanical analysis technique." *Journal of Applied Polymer Science* 140, no. 34 (2023): e54323.
18. Abd El-Aty, Ali, Sangyul Ha, Yong Xu, Yong Hou, Shi-Hong Zhang, Bandar Alzahrani, Alamry Ali, and Mohamed MZ Ahmed. "Coupling computational homogenization with crystal plasticity

modelling for predicting the warm deformation behaviour of AA2060-T8 Al-Li alloy." *Materials* 16, no. 11 (2023): 4069.

19. Ali, Alamry, Md Saiful Islam, Sinin Hamdan, and Masuk Abdullah. "Enhancing the performance of hybrid bio-composites reinforced with natural fibers by using coupling agents." *Materials Research Express* 12, no. 3 (2025): 035504.
20. Ahmed, Abdalla, Alamry Ali, Bandar Alzahrani, and Kazuaki Sanada. "Investigating the influence of self-healing microcapsule volume fraction on the dynamic mechanical properties and self-healing performance of epoxy-based composites." *Journal of Polymer Research* 31, no. 7 (2024): 201.
21. Abd El-Aty, Ali, Cheng Cheng, Yong Xu, Yong Hou, Jie Tao, Shenghan Hu, Bandar Alzahrani, Alamry Ali, Mohamed MZ Ahmed, and Xunzhong Guo. "Modeling and experimental investigation of UR relationship of AA6061-T6 tubes manufactured via free bending forming process." *Materials* 16, no. 23 (2023): 7385.
22. Ahmed, Abu Saleh, Alamry Ali, Emre Gorgun, M. Jameel, Tasmina Khandaker, Md Shaharul Islam, Md Saiful Islam, and Masuk Abdullah. "Microalgae to Biofuel: Cutting-Edge Harvesting and Extraction Methods for Sustainable Energy Solution." *Energy Science & Engineering* (2025).
23. Mansingh, Bright Brailson, Joseph Selvi Binoj, Shukur Abu Hassan, Gudaru Kumar Raja, Alamry Ali, and Kheng Lim Goh. "Bio-fillers: physicochemical nature, properties, and resources." In *Sustainable Fillers/Plasticizers for Polymer Composites*, pp. 57-75. Elsevier Science Ltd, 2025.
24. Kumar, Sudhir, Inderjeet Singh, Alamry Ali, Shalok Bharti, Seyed Saeid Rahimian Koloor, and Geralt Siebert. "On in-house developed feedstock filament of polymer and polymeric composites and their recycling process–A comprehensive review." *Science and Engineering of Composite Materials* 31, no. 1 (2024): 20220238.
25. Ali, Alamry, Seyed Saeid Rahimian Koloor, Abdullah H. Alshehri, and A. Arockiarajan. "Carbon nanotube characteristics and enhancement effects on the mechanical features of polymer-based materials and structures–A review." *Journal of Materials Research and Technology* 24 (2023): 6495-6521.
26. Ali, Alamry, and Andri Andriyana. "Properties of multifunctional composite materials based on nanomaterials: a review." *RSC advances* 10, no. 28 (2020): 16390-16403.
27. Gorgun, Emre, Alamry Ali, and Md Saiful Islam. "Biocomposites of poly (lactic acid) and microcrystalline cellulose: influence of the coupling agent on thermomechanical and absorption characteristics." *ACS omega* 9, no. 10 (2024): 11523-11533.
28. Meraz, Md Montaseer, Md Habibur Rahman Sobuz, Nusrat Jahan Mim, Alamry Ali, Md Saiful Islam, Md Abu Safayet, and Md Tanjid Mehedi. "Using rice husk ash to imitate the properties of

silica fume in high-performance fiber-reinforced concrete (HPFRC): A comprehensive durability and life-cycle evaluation." *Journal of Building Engineering* 76 (2023): 107219.

29. Essa, Ahmed RS, Ramy IA Eldersy, Mohamed MZ Ahmed, Ali Abd El-Aty, Ali Alamry, Bandar Alzahrani, Ahmed E. El-Nikhaily, and Mohamed IA Habba. "Modeling and experimental investigation of the impact of the hemispherical tool on heat generation and tensile properties of dissimilar friction stir welded AA5083 and AA7075 Al alloys." *Materials* 17, no. 2 (2024): 433.
30. Ali, Alamry, Andri Andriyana, Shukur Bin Abu Hassan, and Bee Chin Ang. "Fabrication and thermo-electro and mechanical properties evaluation of helical multiwall carbon nanotube-carbon fiber/epoxy composite laminates." *Polymers* 13, no. 9 (2021): 1437.
31. Alshehri, Abdullah H., Ali Alamry, Seyed Saeid Rahimian Koloor, Bandar Alzahrani, and A. Arockiarajan. "Investigating low velocity impact and compression after impact behaviors of carbon fiber/epoxy composites reinforced with helical multiwalled carbon nanotubes." *Journal of Engineering Research* (2024).
32. El-Aty, Ali Abd, Yong Xu, Wenlong Xie, Liang-Liang Xia, Yong Hou, Shihong Zhang, Mohamed MZ Ahmed et al. "Finite element analysis and experimental study of manufacturing thin-walled five-branched AISI 304 stainless steel tubes with different diameters using a hydroforming process." *Materials* 17, no. 1 (2023): 104.