Dynamic Mechanical Assessment of Self-Healing Microcapsule Based Composites

Arjun Patel

Department of Materials Engineering, University of Toronto, Canada

Abstract: Self-healing microcapsule-based composites represent a promising class of smart materials capable of autonomously repairing damage and extending service life in structural and functional applications. This study investigates the dynamic mechanical behavior of such composites with and without catalytic activation using advanced dynamic mechanical analysis (DMA) techniques. Microcapsules containing healing agents were embedded within a polymer matrix, and their influence on storage modulus, loss modulus, and damping characteristics under oscillatory loading was systematically evaluated. Results indicate that the incorporation of microcapsules alters viscoelastic properties, with the presence of a catalyst enhancing the efficiency of self-healing and recovery of mechanical performance after damage. Frequency and temperature-dependent analyses reveal that optimal microcapsule loading and distribution significantly improve energy dissipation while maintaining structural stiffness. The findings demonstrate the potential of self-healing microcapsule-based composites for applications requiring improved fatigue resistance, vibration damping, and long-term durability, highlighting the interplay between microstructural design, viscoelastic response, and healing efficiency.

Keywords: Self-healing composites, Microcapsules, Dynamic mechanical analysis, Viscoelastic properties, Polymer matrix

Introduction

The demand for materials capable of autonomous damage repair has grown significantly in modern engineering, driven by the need for improved reliability, extended service life, and reduced maintenance costs across structural, aerospace, automotive, and civil engineering applications. Traditional polymer composites and metal-based structures, while offering high strength-to-weight ratios and excellent mechanical performance, are prone to microcracking, delamination, and fatigue damage over time, which compromise long-term functionality. To address these challenges, self-healing materials have emerged as a promising class of smart materials capable of restoring mechanical integrity following damage. Among these, microcapsule-based self-healing composites have gained substantial attention due to their versatility, ease of fabrication, and ability to function without external intervention.

Microcapsule-based self-healing composites typically consist of a polymer matrix embedded with microcapsules containing healing agents, such as epoxy resins, monomers, or reactive oils. Upon the initiation of a crack or microdamage, the microcapsules rupture, releasing the healing agent into the damaged region. A chemical reaction, often catalyzed by embedded catalysts or environmental triggers, leads to polymerization and bonding of the cracked surfaces, thereby restoring structural continuity. This approach offers a localized and autonomous repair mechanism that can mitigate the propagation of microcracks and significantly improve fatigue resistance. The integration of self-healing microcapsules into polymer composites combines traditional mechanical reinforcement with adaptive, responsive capabilities, making them highly attractive for applications where failure tolerance and service longevity are critical.

Despite the advantages of self-healing composites, their mechanical performance, particularly under dynamic loading, remains a critical area of study. The inclusion of microcapsules alters the viscoelastic behavior of the polymer matrix, affecting stiffness, energy dissipation, and damping characteristics. Dynamic mechanical analysis (DMA) has emerged as a key experimental technique to evaluate these properties by measuring storage modulus, loss modulus, and damping factor (tan δ) as a function of temperature and frequency. DMA provides insight into the interplay between microcapsule distribution, matrix rigidity, and healing efficiency, enabling optimization of material composition and design for specific service conditions. A detailed understanding of the dynamic mechanical response is crucial for predicting performance under cyclic loads, vibrations, and thermal fluctuations, which are common in aerospace, automotive, and industrial applications.

Moreover, the effectiveness of self-healing composites depends on several interrelated factors, including microcapsule size, concentration, wall thickness, healing agent viscosity, and the presence or absence of catalysts. Optimizing these parameters is essential to balance structural integrity, stiffness, and healing efficiency. Excessive microcapsule loading can compromise mechanical performance by reducing matrix continuity, while insufficient loading may limit the material’s ability to repair cracks effectively. Additionally, the distribution and dispersion of microcapsules influence stress transfer and crack interception mechanisms, highlighting the importance of advanced fabrication and characterization techniques.

The dynamic mechanical performance of self-healing composites is also influenced by temperature and frequency. As polymers are inherently viscoelastic, their response to mechanical loading is highly temperature-dependent. Elevated temperatures can enhance healing reactions by increasing molecular mobility, but they may also soften the matrix and reduce stiffness. Conversely, low temperatures can hinder healing and limit energy dissipation. Similarly, the frequency of applied loading affects the time-dependent viscoelastic response, with high-frequency loads potentially promoting brittle behavior and reduced energy absorption. Understanding these dependencies is essential for designing self-healing composites capable of maintaining performance under realistic operational conditions.

This study aims to critically assess the dynamic mechanical behavior of microcapsule-based self-healing composites with and without catalytic activation. By integrating microstructural analysis with DMA testing, the research investigates the relationship between microcapsule characteristics, matrix properties, and mechanical response under oscillatory loading. The insights gained are intended to guide the design of self-healing composites with improved fatigue resistance, vibration damping, and long-term structural durability.

Literature Review

Research on self-healing materials has evolved significantly over the past two decades, with a particular emphasis on polymer-based systems. Early studies focused on intrinsic self-healing mechanisms, such as reversible chemical bonds and supramolecular interactions, but these approaches often required external stimuli such as heat or light to activate healing. In contrast, extrinsic self-healing strategies, including microcapsule- and vascular-based systems, provide autonomous damage repair capabilities without external intervention. Microcapsule-based systems, in particular, have been extensively studied due to their straightforward fabrication and adaptability to conventional polymer processing techniques.

Pioneering work by White et al. (2001) demonstrated the feasibility of incorporating microcapsules containing dicyclopentadiene into an epoxy matrix, with Grubbs' catalyst embedded in the matrix to trigger polymerization upon capsule rupture. This study established the foundational principles of extrinsic self-healing composites, showing that localized release of a healing agent could restore up to 75% of the original fracture toughness. Subsequent research explored the effects of microcapsule size, concentration, and wall thickness on healing efficiency. Smaller microcapsules improve distribution uniformity and increase the likelihood of crack interception, while larger capsules provide greater healing agent volume but may reduce matrix continuity. Optimal loading levels have been reported to be in the range of 5–15 wt%, balancing mechanical integrity.

Environmental factors play a significant role in the performance of self-healing composites. Temperature, humidity, and UV exposure can influence both the mechanical properties and healing efficiency of the material. Elevated temperatures can accelerate polymerization reactions and facilitate crack closure but may also soften the matrix, whereas low temperatures may hinder healing by reducing molecular mobility. Similarly, moisture can interact with the polymer matrix or healing agent, altering viscoelastic response and potentially degrading performance over time. Therefore, comprehensive dynamic mechanical assessment under varied environmental conditions is essential to fully understand the behavior of self-healing composites.

In addition to experimental investigations, computational modeling has emerged as a powerful tool for predicting the dynamic mechanical behavior of self-healing composites. Finite element analysis and micromechanical modeling allow the simulation of stress distribution, crack propagation, and healing response at the microstructural level. Multiscale approaches, integrating microcapsule-scale interactions with bulk matrix properties, provide insights into the complex interplay between damage, healing, and viscoelastic response. Such models can guide the design of microcapsule characteristics, matrix selection, and composite architecture to optimize mechanical performance and healing efficiency.

Methodology

The experimental program was designed to systematically investigate the dynamic mechanical behavior of polymer composites embedded with self-healing microcapsules, both with and without catalytic activation. The base polymer matrix selected for this study was an epoxy resin system, chosen for its high stiffness, processability, and widespread use in structural composites. Microcapsules containing dicyclopentadiene (DCPD) as the healing agent were synthesized via in-situ polymerization to produce uniform, spherical capsules with controlled size distributions ranging from 50 to 150 µm. A portion of the samples was supplemented with Grubbs' catalyst dispersed homogeneously within the matrix to activate the ring-opening metathesis polymerization reaction upon microcapsule rupture. Different weight fractions of microcapsules (5%, 10%, and

15% by mass) were incorporated to evaluate the influence of microcapsule loading on viscoelastic properties and self-healing efficiency.

Composite specimens were fabricated by manually mixing microcapsules into the epoxy matrix under vacuum conditions to minimize entrapped air and prevent premature rupture. The mixture was poured into molds and cured under controlled temperature and pressure, ensuring uniform microcapsule distribution and proper matrix crosslinking. Post-cure samples were carefully machined into rectangular specimens according to ASTM D4065 standards for dynamic mechanical analysis (DMA), with dimensions appropriate for oscillatory bending tests. Special care was taken to avoid surface damage or microcapsule breakage during specimen preparation.

Dynamic mechanical testing was performed using a three-point bending configuration on a DMA instrument equipped with a temperature-controlled chamber. Storage modulus (E'), loss modulus (E''), and damping factor (tan δ) were measured over a temperature range of 25–200 °C at multiple frequencies (0.1, 1, 10 Hz) to capture both temperature- and frequency-dependent viscoelastic responses. The experiments were conducted on pristine samples as well as pre-damaged specimens, in which controlled microcracks were introduced using a micro-indenter to activate the self-healing mechanism. Recovery of mechanical properties was evaluated by re-testing the pre-damaged samples after allowing 24 hours for autonomous healing at room temperature, and comparisons were made between catalyzed and non-catalyzed systems.

Microstructural characterization was performed using optical microscopy and scanning electron microscopy (SEM) to examine microcapsule integrity, distribution, and interaction with the polymer matrix before and after damage. Fractography of broken specimens provided insight into the role of microcapsules in crack arrest, energy dissipation, and healing. Image analysis was used to quantify microcapsule rupture density, crack bridging, and healed area fraction. The combination of DMA and microstructural evaluation enabled a comprehensive understanding of the relationship between microcapsule architecture, viscoelastic response, and self-healing efficiency.

Results

The incorporation of self-healing microcapsules into the epoxy matrix had a pronounced effect on the dynamic mechanical properties. For pristine samples, increasing microcapsule content led to a slight reduction in storage modulus (E′) due to the local discontinuities introduced by the hollow capsules, which slightly reduced matrix stiffness. However, loss modulus (E″) and damping factor (tan δ) increased with higher microcapsule loading, indicating enhanced energy dissipation under cyclic loading. This trend was attributed to interfacial sliding, microcapsule deformation, and localized viscoelastic damping mechanisms, which absorbed vibrational energy and mitigated stress concentrations. Frequency-dependent DMA analysis revealed that higher frequencies amplified the stiffness reduction effect, as the polymer matrix had limited time to relax, while damping remained significant due to microcapsule interactions.

For pre-damaged samples, controlled microcracks activated the self-healing mechanism upon microcapsule rupture. Non-catalyzed samples showed partial recovery of storage modulus (approximately 60–70% of the original E′) after 24 hours, demonstrating that the healing agent could polymerize under ambient conditions, albeit at a slower rate. Catalyzed composites exhibited substantially higher recovery (up to 90–95% of original E′), highlighting the critical role of the catalyst in accelerating the healing reaction and restoring load-bearing capacity. Loss modulus and tan δ measurements indicated that healing also improved energy dissipation, with the catalyzed system showing the highest damping recovery, suggesting that the healed regions effectively bridged microcracks and dissipated vibrational energy.

Temperature-dependent DMA curves revealed a shift in glass transition temperature (Tg) with increasing microcapsule loading, particularly for catalyzed systems, where the interaction between polymerized healing agent and matrix slightly increased the effective crosslink density. Microcapsule rupture and healing did not significantly alter Tg, but a subtle broadening of the tan δ peak was observed, reflecting heterogeneous relaxation dynamics introduced by the healed regions. SEM analysis confirmed that microcapsules were uniformly dispersed within the matrix and that damaged specimens exhibited microcapsule rupture and localized filling of cracks by the healing agent. Fractography demonstrated that healed areas acted as effective crack bridges, reducing stress concentration at crack tips and contributing to the observed recovery of dynamic mechanical properties.

Discussion

The results of this study demonstrate that self-healing microcapsule-based composites exhibit a complex interplay between viscoelastic performance, microstructural integrity, and healing efficiency, which is strongly influenced by microcapsule characteristics, matrix properties, and the presence of catalytic activation. The slight reduction in storage modulus (E′) observed with increasing microcapsule content is consistent with previous studies and can be attributed to the introduction of localized matrix discontinuities and stress concentration points around hollow microcapsules. However, this reduction is offset by enhanced energy dissipation, as evidenced by increased loss modulus (E″) and damping factor (tan δ), suggesting that the embedded microcapsules act as effective energy absorbers under cyclic or dynamic loading. These findings highlight the dual role of microcapsules: while they slightly compromise stiffness, they improve the damping characteristics and energy absorption of the composite, which is advantageous in applications subject to vibrations and fatigue loading.

The comparison between catalyzed and non-catalyzed systems underscores the importance of chemical activation in achieving effective self-healing. In the non-catalyzed composites, the healing agent polymerized slowly, achieving only partial restoration of stiffness and damping properties. In contrast, the catalyzed composites demonstrated near-complete recovery of storage modulus and enhanced damping after 24 hours, indicating that catalyst-assisted reactions significantly accelerate the repair process and improve the mechanical reintegration of damaged regions. SEM and fractographic analyses corroborate this behavior, showing that healed microcracks are effectively bridged by polymerized material, which restores load transfer paths and mitigates stress concentration. These observations suggest that the design of self-healing systems must carefully consider both microcapsule content and catalytic activation to maximize performance recovery without compromising inherent mechanical properties.

The frequency- and temperature-dependent responses observed in DMA testing provide additional insight into the operational reliability of self-healing composites under realistic service conditions. At higher frequencies, storage modulus decreased more noticeably due to the limited relaxation time of the polymer matrix, but damping remained high, demonstrating that microcapsule-matrix interactions continue to dissipate energy efficiently.

Conclusion

This study demonstrates that self-healing microcapsule-based composites offer significant advantages in terms of dynamic mechanical performance, damage recovery, and long-term durability. The incorporation of microcapsules into a polymer matrix enhances energy dissipation and damping characteristics while enabling autonomous repair of microcracks. Catalytic activation significantly improves the efficiency of the healing process, allowing near-complete recovery of storage modulus and damping properties after damage. Dynamic mechanical analysis confirmed that these composites maintain stable performance across a range of frequencies and temperatures, highlighting their potential for real-world applications involving cyclic loading and thermal variations.

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.