

Synthesis, Sintering, and Characterization of Composites

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Introduction

Composites, renowned for their lightweight nature, high strength, high specific modulus, high temperature resistance, and excellent wear resistance, have become indispensable key materials in fields such as aerospace, rail transportation, defense, and energy [1–3]. In recent years, the field of composites has developed rapidly, with emerging frontiers continuously expanding. They have begun to partially replace traditional structural materials, finding applications in extreme service environments characterized by ultra-high temperatures and ultra-high strain rates [4–8]. Composites can be classified by their matrix type into metal matrix composites (MMCs), polymer matrix composites (PMCs), ceramic matrix composites (CMCs), and carbon-based composites, among others. In terms of spatial architecture design, they can be configured as network, layered, island, or gradient structures [9–12]. Reinforcements include ceramic particles, whiskers, fibers, or other nanomaterials, such as zero-dimensional (e.g., nanodiamonds), one-dimensional (e.g., carbon nanotubes), and two-dimensional nanomaterials (e.g., graphene) [13–15]. Their performance is fundamentally determined by the complex interplay between the synthesis route, the densification process, and the resulting microstructural characteristics. Understanding the “process-structure-property” paradigm has become crucial for designing composites with tailored functionalities. This Special Issue (SI), “Synthesis, Sintering, and Characterization of Composites”, presents innovative research findings on several typical classes of composites, with a particular focus on innovative design in synthesis processes and microstructures, as well as the exploration of underlying mechanisms. This Editorial summarizes the five publications (four research articles and one review article) included in this SI.

Powder metallurgy is both a traditional and a dynamic advanced material forming technology. It offers mature techniques for preparing MMCs based on metals like titanium, copper, and aluminum, making it a preferred method for composite fabrication [16–18]. The process typically involves designing reinforced/metal composite powders, followed by consolidation or thermo-mechanical deformation, often requiring specialized conditions like high temperature and high pressure. Sintering is a primary consolidation technique, including methods such as spark plasma sintering (SPS), hot pressing (HP), hot isostatic pressing (HIP), and liquid phase sintering (LPS) [19–22]. How to precisely control the microstructure through reinforcement design, architectural design, and optimization of sintering processes to achieve tailored performance has always been a core challenge in this field [23–25].

Deepening the application of powder metallurgy techniques can further enhance the properties of MMCs to meet diverse material requirements. Pavkov et al. [26] utilized liquid phase sintering to introduce an environmentally friendly andesite basalt glass phase into a 316 L stainless steel matrix. Their work systematically reveals the influence of the



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glass phase content on the densification process, microstructural evolution, and mechanical properties of the composite.

Building upon existing sintering technologies to push the performance boundaries of MMCs, leveraging layered or gradient architectural design enables the precise construction of multi-scale structures and the cross-scale synergistic regulation of heterogeneous materials, synergistically enhancing strength and plasticity [27–29]. Duan et al. [30] employed field-assisted sintering technology (FAST) to successfully fabricate a bilayer composite plate, consisting of a high-strength-and-toughness “nacre-like” structured graphene nanoplatelet (GNP)/TC4 composite layer and a highly ductile TC4 layer. They conducted an in-depth analysis on the failure mechanism of this hierarchical heterogeneous structure under high-strain-rate impact. The study found that the hard layer dissipates energy by inducing multiple cracks, while the soft layer effectively arrests crack propagation, significantly enhancing the overall ballistic performance (V50 value). This provides a new paradigm for the integrated “processing-structure-property” design of high-performance MMCs intended for extreme impact service environments.

The nature of the interface in composites is critical in determining their integrity, reliability and mechanical properties [31]. The review by Zhu et al. [32] focuses on basalt fiber-reinforced polymer composites. It systematically summarizes various non-destructive surface modification techniques, such as treatment with silane coupling agents, rare-earth coupling agents, and plasma. It details how these methods introduce active functional groups, increase surface roughness, or construct nano-reinforced interlayers to effectively enhance the interfacial bonding strength between the fiber and the matrix.

Thermal spraying technology is an effective method for preparing functional ceramic matrix composites. Gadzhiev et al. [33] successfully used low-pressure plasma to melt and deposit β -Ga₂O₃ powder, forming a ceramic body with good crystallinity and luminescent properties. Their study accurately describes the heating and acceleration behavior of powder particles in the plasma jet, revealing the influence of process parameters on the phase composition, microstructure and photoluminescence properties of the final product.

In the realm of amorphous alloy composites designed for high-strain-rate impact environments, Wang et al. [34] synthesized a Ti_{42.3}Zr₂₈Cu_{8.3}Nb_{4.7}Ni_{1.7}Be₁₅ (at%) composite via vacuum melting. They conducted a detailed investigation into the synergistic deformation mechanism of this in situ formed metastable β -phase reinforced bulk metallic glass composite under tensile load. Beyond traditional shear banding, they observed localized amorphization and a stress-induced phase transformation from BCC β -Ti to HCP α -Ti at the crystalline/amorphous interface. This localized structural transition effectively relaxes stress concentration and leads to serrated flow behavior in the stress–strain curve, imparting excellent work-hardening capacity and tensile plasticity to the material.

Composites are a crucial material foundation supporting the development of advanced equipment manufacturing, and continuous performance improvements directly drive the evolution of next-generation high-end equipment [35,36]. In composite research and development, synthesis preparation, process control, and detailed characterization form the tightly interconnected core “process-structure-property” chain. The synergy among these three elements dictates the depth of material innovation and the breadth of engineering application. Optimal design must systematically consider how process parameters influence the evolution path of the microstructure and ultimately determine the macroscopic service behavior of the material [37]. Currently, the expansion of additive manufacturing technologies into metal, ceramic, and polymer matrix composites [38–41], the emergence of cold sintering processes for ceramic–polymer integration [42,43], and the maturation of energy-efficient methods like microwave sintering [44,45] are significantly broadening the design freedom and processing window for advanced composites. Simultaneously,

high-throughput characterization methods integrated with machine learning are providing quantitative support for deeply deciphering the intrinsic correlations within the “process-structure-property” paradigm. Future breakthroughs in composites will rely on the deep integration and closed-loop synergy of the aforementioned fields [46]. The trend points towards building an intelligent closed-loop ecosystem driven by advanced manufacturing, big data technologies, and AI foundation models [47–49]. In this vision, leveraging massive experimental and service data, large models can inversely design optimal architectures. Advanced manufacturing then precisely realizes these designed architectures through controlled processing. Meanwhile, big data technologies continuously learn from the entire manufacturing and service lifecycle, feeding back information to iteratively optimize the models. This will ultimately propel composite materials research and development from the traditional “trial-and-error” paradigm into a new era of “data-driven intelligent design and precision manufacturing” [50], meeting the increasingly demanding service requirements of aerospace, energy, and other critical sectors.

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References

1. Sarmah, P.; Gupta, K. Recent Advancements in Fabrication of Metal Matrix Composites: A Systematic Review. *Materials* **2024**, *17*, 4635. [CrossRef]
2. Chen, B.; Sun, H.; Ye, Y.; Ji, C.; Pan, S.; Wang, B. Research Status and Development Trends of Joining Technologies for Ceramic Matrix Composites. *Materials* **2025**, *18*, 871–897. [CrossRef]
3. Simões, S. High-Performance Advanced Composites in Multifunctional Material Design: State of the Art, Challenges, and Future Directions. *Materials* **2024**, *17*, 5997. [CrossRef] [PubMed]
4. Feng, Y.; Wang, W.; Lu, Y.; Li, X.; Wang, W.; Yang, J.; Cui, G.; Chen, W.; Zhuang, D. Research on the High-Temperature Wear Resistance of Columnar Network Reinforce TiBw/TA15 Composites with Varying TiB Volume Fractions. *Mater. Chem. Phys.* **2025**, *343*, 131043. [CrossRef]
5. Feng, Y.; Lu, Y.; Liu, X.; Cao, H.; Wang, W.; Yang, J.; Chen, W.; Cui, G. High Strength and Plasticity TiBw/TA15 Composites with a Novel Columnar Network Structure. *Scr. Mater.* **2023**, *229*, 115349. [CrossRef]
6. Zhang, C.; Hu, P.; Xun, L.; Zhou, Y.; Han, J.; Zhang, X. A Universal Strategy towards the Fabrication of Ultra-High Temperature Ceramic Matrix Composites with Outstanding Mechanical Properties and Ablation Resistance. *Compos. Part B* **2024**, *280*, 111485. [CrossRef]
7. Markovsky, P.E.; Janiszewski, J.; Stasyuk, O.O.; Bondarchuk, V.I.; Savvakina, D.G.; Cieplak, K.; Goran, D.; Soni, P.; Prikhodko, S.V. Mechanical Behavior of Titanium Based Metal Matrix Composites Reinforced with TiC or TiB Particles under Quasi-Static and High Strain-Rate Compression. *Materials* **2021**, *14*, 6837. [CrossRef] [PubMed]
8. Yi, C.; Xu, J.; Tian, L.; Zhang, C. Temperature and Strain Rate Related Deformation Behavior of UHMWPE Fiber-Reinforced Composites. *Polymers* **2024**, *16*, 1250. [CrossRef]
9. Zhu, Y.; Ameyama, K.; Anderson, P.M.; Beyerlein, I.J.; Gao, H.; Kim, H.S.; Lavernia, E.; Mathaudhu, S.; Mughrabi, H.; Ritchie, R.O.; et al. Heterostructured Materials: Superior Properties from Hetero-Zone Interaction. *Mater. Res. Lett.* **2021**, *9*, 1–31. [CrossRef]
10. Xiao, Y.; Song, C.; Liu, Z.; Liu, L.; Zhou, H.; Wang, D.; Yang, Y. In-Situ Additive Manufacturing of High Strength yet Ductility Titanium Composites with Gradient Layered Structure Using N₂. *Int. J. Extreme Manuf.* **2024**, *6*, 35001. [CrossRef]
11. Liu, H.; Li, S.; Li, S.; Liu, L.; Kondoh, K.; Hui, D.; Wang, S.; Li, X.; Cao, Y.; Zhang, X.; et al. Microstructure and Mechanical Properties of Heterogeneous Titanium Matrix Composites with Micro-Nano Reinforcement Control. *Mater. Sci. Eng. A* **2025**, *943*, 148826. [CrossRef]
12. Xiao, Y.; Yang, Y.; Wang, D.; Zhou, H.; Liu, Z.; Liu, L.; Wu, S.; Song, C. In-Situ Synthesis of Spatial Heterostructure Ti Composites by Laser Powder Bed Fusion to Overcome the Strength and Plasticity Trade-Off. *Int. J. Mach. Tools Manuf.* **2024**, *196*, 104117. [CrossRef]
13. Liu, X.-S.; Fu, Q.-G.; Wang, H.; Song, Q. Improvement of Mechanical Property and Ablation Resistance of Carbon/Carbon Composites by Adding Nano-Diamond Particles. *Diam. Relat. Mater.* **2020**, *104*, 107751. [CrossRef]

14. Han, L.; Xiao, C.; Song, Q.; Yin, X.; Li, W.; Li, K.; Li, Y. Nano-Interface Effect of Graphene on Carbon Nanotube Reinforced Carbon/Carbon Composites. *Carbon* **2022**, *190*, 422–429. [[CrossRef](#)]
15. Baimova, J.A.; Shcherbinin, S.A. Metal/Graphene Composites: A Review on the Simulation of Fabrication and Study of Mechanical Properties. *Materials* **2022**, *16*, 202–228. [[CrossRef](#)]
16. Liu, L.; Li, S.; Zhang, X.; Li, S.; Wang, S.; Li, B.; Gao, L.; Liu, H.; Hui, D.; Pan, D.; et al. Synthesis Mechanism of Pelleted Heterostructure Ti64-TiB Composites via an Interdiffusion and Self-Organization Strategy Based on Powder Metallurgy. *Compos. Part B* **2024**, *276*, 111366. [[CrossRef](#)]
17. Singh, K.; Khanna, V.; Chaudhary, V.; Jasrotia, R.; Prakash, C.; Al-Kahtani, A.A. Investigating the Potential of Powder Metallurgy for Fabricating Graphene Nanoplatelets Reinforced Copper Nanocomposites. *J. Mater. Res. Technol.* **2024**, *31*, 1258–1269. [[CrossRef](#)]
18. Akgümüş Gök, D.; Bayraktar, C.; Hoşkun, M. A Review on Processing, Mechanical and Wear Properties of Al Matrix Composites Reinforced with Al₂O₃, SiC, B₄C and MgO by Powder Metallurgy Method. *J. Mater. Res. Technol.* **2024**, *31*, 1132–1150. [[CrossRef](#)]
19. Wiśniewska, M.; Laptev, A.M.; Marczewski, M.; Krzyżaniak, W.; Leshchynsky, V.; Celotti, L.; Szybowicz, M.; Garbiec, D. Towards Homogeneous Spark Plasma Sintering of Complex-Shaped Ceramic Matrix Composites. *J. Eur. Ceram. Soc.* **2024**, *44*, 7139–7148. [[CrossRef](#)]
20. Liu, Z.; Luo, Z.; Zhang, X.; Feng, Y.; Wang, M.; Yang, J. Study on Microstructure and Mechanical Properties of (TiC+B₄C)/6061Al Composites Prepared by Vacuum Hot-Press Sintering Method. *J. Manuf. Process.* **2024**, *131*, 671–681. [[CrossRef](#)]
21. Markovsky, P.; Janiszewski, J.; Savvakina, D.; Stasyuk, O.; Fikus, B.; Samarov, V.; Ellison, V.; Prikhodko, S.V. Ballistic Performance of Titanium-Based Layered Composites Made Using Blended Elemental Powder Metallurgy and Hot Isostatic Pressing. *Def. Technol.* **2024**, *39*, 1–14. [[CrossRef](#)]
22. Xu, H.; Qi, Q.; Ji, W.; Wang, W.; Zhang, J.; Fu, Z. In-Situ Synthesis and Low-Temperature Fabrication of B₄C/TiB₂-Based Multilayer Graded Composites with B₄C and Ti-Al Intermetallics Mixtures through Transient Liquid Phase Sintering. *Ceram. Int.* **2021**, *47*, 24384–24392. [[CrossRef](#)]
23. Alem, S.A.A.; Sabzvand, M.H.; Govahi, P.; Poormehrabi, P.; Hasanzadeh Azar, M.; Salehi Siouki, S.; Rashidi, R.; Angizi, S.; Bagherifard, S. Advancing the next Generation of High-Performance Metal Matrix Composites through Metal Particle Reinforcement. *Adv. Compos. Hybrid Mater.* **2025**, *8*, 3–70. [[CrossRef](#)] [[PubMed](#)]
24. Xie, J.; Wu, Y.; Liang, Y.; Chen, T.; Zhang, J.; Zhang, X.; Liu, R. Dual-Heterostructure Realizes Synergistic Enhancement of Strength and Ductility in Particle Reinforced Aluminum Matrix Composites. *Mater. Charact.* **2025**, *225*, 115127. [[CrossRef](#)]
25. Murali, P.; Chattopadhyay, K.; Jindal, V. Effect of Hot-Pressing Sintering Temperature and Pressure on the Densification and Properties of Ti-TiB Composites. *J. Alloys Metall. Syst.* **2024**, *8*, 100132. [[CrossRef](#)]
26. Pavkov, V.; Bakić, G.; Maksimović, V.; Stopić, S. Synthesis and Characterisation of Metal-Glass Composite Materials Fabricated by Liquid Phase Sintering. *Materials* **2025**, *18*, 4622. [[CrossRef](#)]
27. Markovsky, P.E.; Janiszewski, J.; Savvakina, D.G.; Stasiuk, O.O.; Cieplak, K.; Baranowski, P.; Prikhodko, S.V. Mechanical Behavior of Bilayer Structures of Ti64 Alloy and Its Composites with TiC or TiB under Quasi-Static and Dynamic Compression. *Mater. Des.* **2022**, *223*, 111205. [[CrossRef](#)]
28. Ji, M.; Huang, L.; Zhang, R.; Wang, S.; Sun, F.; Wang, C.; Geng, L. Microstructure Evolution and Bending Fracture Mechanism of As-Rolled Gradient-Laminated Network Titanium Matrix Composites. *Mater. Charact.* **2024**, *212*, 113976. [[CrossRef](#)]
29. Guo, Z.; Tan, Z.; Li, X.; Zhang, X.; Fan, G.; Li, Z. Progress and Perspective on Heterostructure Design and Strength-Ductility Synergy in Aluminum Matrix Composites. *Mater. Today Commun.* **2025**, *48*, 113497. [[CrossRef](#)]
30. Duan, H.; Li, X.; Zhang, H.; Cheng, X.; Mu, X.; Zheng, K. The High-Strain-Rate Impacts Behaviors of Bilayer TC₄-(GNPs/TC₄) Composites with a Hierarchical Microstructure. *Materials* **2024**, *17*, 5589. [[CrossRef](#)]
31. Zhang, M.; Ma, D.; Wang, J.; Dai, S.; Xue, Y.; Zhu, L. Enhancing Interfacial Bonding in Metal Matrix Composites: Challenges, Methods, and Future Prospects. *Crit. Rev. Solid State Mater. Sci.* **2025**, *1*–54. [[CrossRef](#)]
32. Zhu, M.; Zhu, M.; Zhai, R.; Zhu, W.; He, J. Research Progress on the Surface Modification of Basalt Fibers and Composites: A Review. *Materials* **2025**, *18*, 1164. [[CrossRef](#)] [[PubMed](#)]
33. Gadzhiev, M.K.; Muslimov, A.E.; Yusupov, D.I.; Il'ichev, M.V.; Kulikov, Y.M.; Chistolov, A.V.; Venevtsev, I.D.; Volchikov, I.S.; Kanevsky, V.M.; Tyuftyaev, A.S. Gas-Thermal Spraying Synthesis of β-Ga₂O₃ Luminescent Ceramics. *Materials* **2024**, *17*, 6078. [[CrossRef](#)] [[PubMed](#)]
34. Wang, H.; Chen, N.; Cheng, H.; Wang, Y.; Zhao, D. Tensile Deformation Mechanism of an In Situ Formed Ti-Based Bulk Metallic Glass Composites. *Materials* **2024**, *17*, 4486. [[CrossRef](#)]
35. Khan, F.; Hossain, N.; Mim, J.J.; Rahman, S.M.; Iqbal, M.J.; Billah, M.; Chowdhury, M.A. Advances of Composite Materials in Automobile Applications—A Review. *J. Eng. Res.* **2025**, *13*, 1001–1023. [[CrossRef](#)]
36. Zhang, Y.; Cui, X.; Chen, L.; Gao, N.; Zhang, X.; Wang, Z.; Cong, G.; Zhai, X.; Luo, J.; Zhang, Y.; et al. Simultaneously Enhancing Room-Temperature Strength-Ductility Synergy and High-Temperature Performance of Titanium Matrix Composites via Building a Unique Bimodal Architecture with Multi-Scale Reinforcements. *Int. J. Plast.* **2025**, *187*, 104283. [[CrossRef](#)]

37. Li, X.; Zhao, H.; Ren, J.; Lv, H.; An, Y.; Zhang, C.; Zhao, E. In-Situ Characterization of Microstructure Evolution Mechanism of TiB Reinforced Titanium Matrix Composites at Different Cooling Rates. *Mater. Charact.* **2025**, *223*, 114910. [\[CrossRef\]](#)
38. Ngo, T.D.; Kashani, A.; Imbalzano, G.; Nguyen, K.T.Q.; Hui, D. Additive Manufacturing (3D Printing): A Review of Materials, Methods, Applications and Challenges. *Compos. Part B* **2018**, *143*, 172–196. [\[CrossRef\]](#)
39. Zeng, Y.; Wang, J.; Liu, X.; Xue, Y.; Tang, L.; Tong, Y.; Jiang, F. Laser Additive Manufacturing of Ceramic Reinforced Titanium Matrix Composites: A Review of Microstructure, Properties, Auxiliary Processes, and Simulations. *Compos. Part A* **2024**, *177*, 107941. [\[CrossRef\]](#)
40. Liu, C.-W.; Li, J.; Gao, X.; Mu, Y.; He, Z.; Wang, H.; Jia, Y.; Yuan, B.; Wang, G.; Peng, H.-X. Fundamental Approach to Superior Trade-off between Strength and Ductility of TiB/Ti64 Composites via Additive Manufacturing: From Phase Diagram to Microstructural Design. *J. Mater. Sci. Technol.* **2025**, *221*, 221–232. [\[CrossRef\]](#)
41. Scheithauer, U.; Johne, R.; Gottlieb, L.; Weingarten, S.; Wiemer, H.; Holtzhausen, S. Recent Developments in the Field of Additive Manufacturing of Ceramic-Based Multi-Material Components Open the Door to Highly Functionalized Components. *Prog. Addit. Manuf.* **2025**, *10*, 4051–4059. [\[CrossRef\]](#)
42. Zhang, J.; Gomez, E.; Sun, H. Interface Engineering and Integration of Ceramic-Polymer Composites via Cold Sintering Process. *Compos. Part B Eng.* **2025**, *2025*, 112929. [\[CrossRef\]](#)
43. Marín-Cortés, S.; Biesuz, M.; Bhandari, S.; Franchin, G.; Enríquez, E.; Fernández, J.F.; Sglavo, V.M. Cold Sintering of Complex-Shaped Ceramic Materials. *J. Eur. Ceram. Soc.* **2024**, *44*, 116813. [\[CrossRef\]](#)
44. Lin, M.-S.; Chu, K.-R. On the Non-Thermal Mechanisms in Microwave Sintering of Materials. *Materials* **2025**, *18*, 668–688. [\[CrossRef\]](#) [\[PubMed\]](#)
45. Li, Y.; Cheng, Y.; Liu, Y. Evolution Mechanism of Ti(C,N)-Based Cermet Microstructure under Microwave Sintering. *Ceram. Int.* **2024**, *50*, 54976–54987. [\[CrossRef\]](#)
46. Zhong, Z.; An, J.; Wu, D.; Gao, N.; Liu, L.; Wang, Z.; Meng, F.; Zhou, X.; Fan, T. A Machine Learning Strategy for Enhancing the Strength and Toughness in Metal Matrix Composites. *Int. J. Mech. Sci.* **2024**, *281*, 109550. [\[CrossRef\]](#)
47. Wei, W.; Zhang, Q.; Wu, W.; Cao, H.; Shen, J.; Fan, S.; Duan, X. Agglomeration-Free Nanoscale TiC Reinforced Titanium Matrix Composites Achieved by in-Situ Laser Additive Manufacturing. *Scr. Mater.* **2020**, *187*, 311–316. [\[CrossRef\]](#)
48. Masrouri, M.; Qin, Z. Towards Data-Efficient Mechanical Design of Bicontinuous Composites Using Generative AI. *Theor. Appl. Mech. Lett.* **2024**, *14*, 100492. [\[CrossRef\]](#)
49. Cheung, H.L.; Uvdal, P.; Mirkhalaf, M. Augmentation of Scarce Data—A New Approach for Deep-Learning Modeling of Composites. *Compos. Sci. Technol.* **2024**, *249*, 110491. [\[CrossRef\]](#)
50. Kibrete, F.; Trzepieciński, T.; Gebremedhen, H.S.; Woldemichael, D.E. Artificial Intelligence in Predicting Mechanical Properties of Composite Materials. *J. Compos. Sci.* **2023**, *7*, 364–399. [\[CrossRef\]](#)

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