

Materials Science

Mesoporous graphitized carbon materials: Dilemma between graphitization and porosity

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As one of the most prevalent functional materials, carbon materials exhibit a broad range of applications owing to their inherent physicochemical properties. The primary strengths of these materials originate from their superior electronic conductivity and chemical stability [1–3]. The design of mesoporous structures with high interconnectivity can confer exceptional mass transport capabilities and ionic conductivity, thereby further broadening their application potentials [4]. Current research on mesoporous carbon mainly focuses on the construction of unique nanostructures and the augmentation of specific surface area and connectivity, while fewer investigations delve into the control of carbon atom arrangement at smaller scales, specifically graphitization.

A major barrier is associated with the unbearably high temperature required for maintaining the mesostructure. Conventional mesoporous carbon materials are synthesized via the pyrolysis of organic polymers, typically displaying an amorphous atomic arrangement and exhibiting a low degree of graphitization, which are termed as hard carbon. Compared to hard carbon, graphitized carbon exhibits higher specific surface area, electrical conductivity, and thermal conductivity within the same nanostructure. However, in the industrial system, graphitization typically requires continuous heating at high temperatures ranging from 2000 to 3000 °C to activate and rearrange carbon atoms under an inert atmosphere [5]. Even after the design of nanostructures under laboratory conditions, a graphitization temperature of 1600 °C is still required [6]. From the viewpoint of mesoporous materials, it is undeniable that a high graphitization temperature can induce the collapse of mesostructure and reduction in porosity [7], making the synthesis of mesoporous graphitized carbon (MGC) a formidable challenge (Figure 1).

In comparison to the synthesis of amorphous mesoporous carbon, the synthetic process of MGC essentially encompasses merely an additional graphitization step. Current progress indicates that this step can be accomplished via two distinct pathways. One approach involves instantaneous heating, wherein a substantial quantity of thermal energy is rapidly supplied to the amorphous carbon system within an extremely brief time, which is termed thermal graphitization. The other pathway through the carbothermic and carbonization reactions occurred between metal precursors and carbon atoms at approximately 1000 °C. During this reaction process, the metal precursor plays the role of a catalyst, denoted as catalytic graphitization.

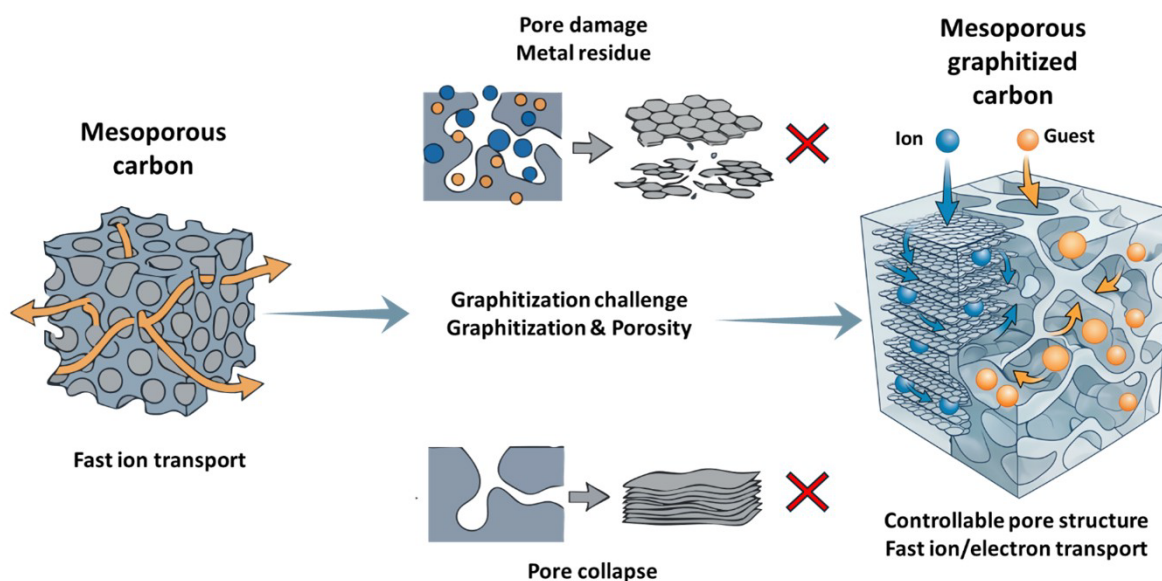


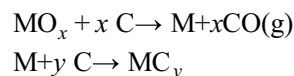
Figure 1 Scheme of the incompatibility between the high-temperature catalytic graphitization and thermally unstable mesostructure.

Thermal graphitization is a process that exhibits a strong dependence on heating technology, demanding the swift release of a substantial amount of heat energy within an extremely brief time. Joule heating emerges as the most appropriate technique to meet this requirement. In 2020, a flash Joule heating (FJH) technique was reported, which entails a rapid application of high voltage to the conductive system, inducing the generation of considerable heat [8]. Consequently, the temperature is elevated to over 3000 K within milliseconds to seconds, thereby promoting the atomic rearrangement of carbon materials to form graphene. This technology has gradually matured in recent years, with further expansion upon the basic heating graphitization by constructing specific nanostructures [9] or doping with synergistic elements [10]. Moreover, employing reactive metals can also facilitate rapid exothermic heating. For example, utilizing metallic lithium as the exothermic agent and blending it with organic polymer precursors, followed by gentle heating to 200 °C to melt the lithium, the molten lithium undergoes a lithium-thermal reaction within the system to swiftly release a substantial amount of heat, causing the system to rapidly heat up to over 3000 K within milliseconds for ultimately obtaining highly graphitized carbon materials [11]. Overall, thermal graphitization offers the advantages of straightforward operation and high production yield; however, it also presents notable drawbacks, including high requirements for equipment and environmental conditions, as well as severe structural deformation incapable of maintaining specific nanostructures.

Alternatively, catalytic graphitization can be achieved through a chemical reaction between carbon and metal precursors at approximately 1000 °C. This approach demands relatively low energy and avoids the need for aggressive temperature-ramping strategies, thereby exhibiting minimal equipment dependency. Consequently, it has garnered significant research attention. The earliest research in the mesoporous field was reported in 2009, wherein the authors emulated the reversed template replication pathway of CMK-3 [12]. Graphitized mesoporous carbon was synthesized by heating the hard template and nickel phthalocyanine complex, followed by acid washing to remove the hard template. It was observed that the complexes of three magnetic transition metals, iron, cobalt, and nickel could all undergo pyrolysis to synthesize graphitized

carbon. Subsequently, Jiao *et al.* [13] further developed this approach by utilizing magnetically induced assembly of Fe₃O₄ particles to serve as hard templates, onto which oleic acid was modified as a precursor. Following the carbonization of oleic acid at 1000 °C, the iron template was etched away using hydrochloric acid, resulting in the formation of graphitized mesoporous carbon. As pioneers of the hard template method, Ryong Ryoo and colleagues employed this method to reverse replicate various types of zeolites by placing lanthanum ions into zeolite pores through ion exchange, then introducing ethylene to deposit carbon, and finally removing the zeolite template to obtain the replicated carbon zeolite [14]. The resulting carbon zeolite product displays a G peak with an intensity comparable to that of graphite, which might be associated with the fact that lanthanum ions, which promote graphitization, reside in carbide-forming elements. Moreover, by further employing molybdenum, a classic carbide-forming element, as the catalyst and KIT-6 as the template, ordered mesoporous graphitized carbon can be synthesized at a lower temperature of 800 °C [15].

Based on the above progress, a detailed catalytic graphitization process is presented in this perspective. As the temperature rises during annealing, the initial step is the pyrolysis of metal precursors, resulting in the formation of metal oxides. Subsequently, the organic precursors undergo carbonization upon being heated to a specific temperature, generating amorphous carbon. A further increase in temperature activates carbothermic and carbide reactions, which can be depicted as follows:



where M represents the carbide-forming element. The carbide reaction results in interstitial carbides, wherein carbon atoms exist in interstitial positions in the metal lattice. Besides, carbon is the excessive component; thus, the amorphous carbon remains in the system after carbide reaction. As amorphous carbon atoms undergo free diffusion into the carbide lattice at a high temperature, the carbide lattice continuously sustains a supersaturated state, which subsequently precipitates. This process is similar to the growth of supersaturated crystals, despite the fact that the ultimate precipitates are crystallized carbon atoms at a high degree of graphitization. However, the removal of active metal sites for solid-state reaction is difficult and inevitably causes pore damage due to atomic reconstruction.

Although there is no elaboration on the types of carbides, it is apparent that the interstitial diffusion capacity of carbon atoms during the catalytic process is crucial for achieving graphitization. Catalytic graphitization can only be attained when interstitial carbides are generated, which means the employed catalyst must contain transition metals. In contrast, ionic carbides derived from elements like Li, Na, Ca, or covalent carbides from B, Si, exhibit limited capabilities in catalyzing graphitization under 1000 °C. Elevating the reaction temperature to 3000 °C enables good graphitization capability through another mechanism [16]. The mainstream for catalytic graphitization primarily employs iron-based catalysts [17], rather than more stable carbide-forming elements (W, Mo). This is related to the thermal stability of the formed carbides. Molybdenum carbide is thermally stable and merely serves as a catalytic intermediate that needs to be removed after calcination, whereas iron carbide represents an unstable carbide at high temperature and tends to decompose into metallic iron and graphite. This process is specifically termed “graphitization” in metallurgy [18], while it is a feasible tool in the synthesis of highly graphitized carbon frameworks.

It is foreseen that the future advancements in MGC will primarily focus on the flourishing of versatile properties, architecture and pore engineering, which could show great potential in electrochemical devices

owing to both rapid mass and ion transport, as well as catalysis systems as exceptionally high-surface-area metal supports with no agglomeration. Currently, the inherent conflict lies in the contradiction between graphitization temperature and the stability of mesoporous structures. Thermally graphitized products generally exhibit an absence of a defined nanostructure, with mesopores primarily being stacked pores. Catalytic graphitization highly relies on the corresponding hard templates, yielding pores that are neither controllable nor reproducible. So far, there has been quite limited success for the synthesis via the soft-templating method [19]. Current research also lacks a comprehensive understanding of the sophisticated assembly mechanisms at integrated multiscale systems involving atomic graphitization and mesoscale assembly. These limitations in fundamental synthesis severely impede the profound technological possibilities. Decoupling molecular interactions from the nano-environment, which involves delimiting catalytic reaction zones or recruiting hard-templated porosity to ensure multiple equilibria, would provide possibilities to mitigate the shortcomings of existing methodologies. With more ongoing explorations devoted to the future, it is envisaged that a variety of mesoporous graphitized carbon materials with diverse structures at multiple scales will be prevalent and valuable for cutting-edge applications in the next generation.

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Conflict of interest

The authors declare no conflict of interest.

References

- 1 Zhao Y, Wan J, Ling C, *et al.* Acidic oxygen reduction by single-atom Fe catalysts on curved supports. *Nature* 2025; **644**: 668–675.
- 2 Pan J, Sun Z, Wu X, *et al.* Mechanically robust bismuth-embedded carbon microspheres for ultrafast charging and ultrastable sodium-ion batteries. *J Am Chem Soc* 2025; **147**: 3047–3061.
- 3 Lan N, Li J, Zeng L, *et al.* Hyper-crosslinking to customize ultrathin-wall closed pores in pitch-derived carbon for sodium-ion batteries. *Adv Mater* 2025; **37**: 2419528.
- 4 Peng L, Peng H, Li W, *et al.* Monomicellar assembly to synthesize structured and functional mesoporous carbonaceous nanomaterials. *Nat Protoc* 2022; **18**: 1155–1178.
- 5 Burket CL, Rajagopalan R, Foley HC. Overcoming the barrier to graphitization in a polymer-derived nanoporous carbon. *Carbon* 2008; **46**: 501–510.
- 6 Darmstadt H, Roy C, Kaliaguine S, *et al.* Pore structure and graphitic surface nature of ordered mesoporous carbons probed by low-pressure nitrogen adsorption. *Microporous Mesoporous Mater* 2003; **60**: 139–149.
- 7 He Y, Li R, Tong H, *et al.* Emerging compositions in functional mesoporous materials. *Chem Soc Rev* 2025; **54**: 6927–6972.
- 8 Luong DX, Bets KV, Algozeeb WA, *et al.* Gram-scale bottom-up flash graphene synthesis. *Nature* 2020; **577**: 647–651.
- 9 Wang L, Zhu S, Huang Z, *et al.* Rapid and up-scalable flash fabrication of graphitic carbon nanocages for robust potassium storage. *Adv Funct Mater* 2024; **34**: 2401548.
- 10 Sun Y, Ma G, Liu Z, *et al.* High-sulfur-doped cathodes enable efficient chloride conversion in rechargeable Na-Cl₂

- batteries. *Nano Energy* 2026; **150**: 111745.
- 11 Zhang H, Qiu J, Pang J, *et al.* Sub-millisecond lithiothermal synthesis of graphitic meso-microporous carbon. *Nat Commun* 2024; **15**: 3491.
 - 12 Lee K, Ji X, Rault M, *et al.* Simple synthesis of graphitic ordered mesoporous carbon materials by a solid-state method using metal phthalocyanines. *Angew Chem Int Ed* 2009; **48**: 5661–5665.
 - 13 Jiao Y, Han D, Liu L, *et al.* Highly ordered mesoporous few-layer graphene frameworks enabled by Fe₃O₄ nanocrystal superlattices. *Angew Chem Int Ed* 2015; **54**: 5727–5731.
 - 14 Kim K, Lee T, Kwon Y, *et al.* Lanthanum-catalysed synthesis of microporous 3D graphene-like carbons in a zeolite template. *Nature* 2016; **535**: 131–135.
 - 15 Baek DS, Lee KA, Park J, *et al.* Ordered mesoporous carbons with graphitic tubular frameworks by dual templating for efficient electrocatalysis and energy storage. *Angew Chem Int Ed* 2020; **60**: 1441–1449.
 - 16 Ōya A, Ōtani S. Catalytic graphitization of carbons by various metals. *Carbon* 1978; **17**: 131–137.
 - 17 Hunter RD, Ramírez-Rico J, Schnepf Z. Iron-catalyzed graphitization for the synthesis of nanostructured graphitic carbons. *J Mater Chem A* 2022; **10**: 4489–4516.
 - 18 Zhu M, Zhang L, Zhao H, *et al.* Modeling of microstructural evolution during divorced eutectic solidification of spheroidal graphite irons. *Acta Mater* 2015; **84**: 413–425.
 - 19 Robertson M, Guillen-Obando A, Barbour A, *et al.* Direct synthesis of ordered mesoporous materials from thermoplastic elastomers. *Nat Commun* 2023; **14**: 639.