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Hybrid-Filler and Structural Strategies for Self-Lubricating Epoxy Composites and Coatings: A Focused Review

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ABSTRACT

Self-lubricating epoxy (EP) composites and coatings are required in bearings, gears, and structural tribo-components that must operate with low friction and stable wear across dry, boundary, mixed, and corrosion-coupled environments. The uploaded literature converges on three synergistic strategies: solid-lubricant nanofillers and hybrids (graphite/graphene/GO, h-BN, MXene, ZnS–GO) that form robust transfer films and provide thermal/electrical pathways; encapsulated and vascular lubrication that releases liquids on demand; and fiber/architected reinforcements (carbon fabrics, filament winding, substrate engineering) that deliver load-bearing capacity and anisotropic transport. This review synthesizes mechanisms and trends strictly from the uploaded sources, embeds research-style tables summarizing systems, processes, test contexts, and outcomes, and discusses open issues around dispersion and interfacial bonding, film stability under heat and shear, corrosion–tribology coupling, dosing/triggering in on-demand lubrication, test comparability, and manufacturing scale-up. We conclude with future directions emphasizing multi-scale hybridization, adaptive lubrication networks (capsule+vascular), thermal/anti-corrosion co-design, oriented architectures, and application-driven substrate/process choices for water-lubricated and oscillatory bearings.

KEYWORDS

Epoxy; Self-lubricating Composites; Tribology; 2D Nanofillers; Microcapsules; Vascular lubrication; Carbon Fiber Laminates.

1. INTRODUCTION

Epoxy resins (EP) are widely used due to their adhesion, chemical resistance, and processability; yet their intrinsic brittleness and modest wear resistance motivate composite solutions for tribological service. Early work using particles and fibers illustrates that multiphase EP can arrest cracks and resist erosive/abrasive damage while maintaining structural integrity [1]. Within this line, graphite-filled EP showed that suitable loading can minimize friction and wear compared with neat EP, highlighting the trade-off between interfacial film formation and matrix embrittlement at high filler contents [2]. Building upon these foundations, the research corpus represented in the uploaded materials emphasizes three complementary routes: Two-dimensional (2D) solids and hybrids. Hexagonal boron nitride (h-BN) and graphene-family materials (graphite, graphene nanoplatelets (GNPs), graphene oxide (GO)) exploit lamellar shear and help build transfer films; functional hybrids (BNNSs/g-C3N4, GO–h-BN) are reported to improve dispersion and interfacial bonding, enabling stronger, smoother films and enhanced barrier effects [3]. Emerging MXene-based systems further strengthen load sharing and thermal pathways. A ZnS–GO hybrid represents a synergy case with improved tribological outcomes. Encapsulated/vascular lubrication. Oil-filled microcapsules (SiO_2 shells; or PAO with Cu NPs@m-SiO_2) release liquid lubricant under stress or frictional heating, stabilizing boundary films and counteracting starvation [4]. Bio-inspired vascular EP embedded in

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carbon-fiber (CF) laminates supplies silicone oil through micro-channels ruptured during wear, with oil flux governed by vascular density and fabric weave. Fiber/architected and ceramic/MAX reinforcement. Carbon-fiber cloth (CFC) laminates provide mechanical backbone and, when combined with oriented GNPs, create in-plane lubricating highways that stabilize films until extreme shear/temperature triggers delamination. Filament-winding processes enable scalable, repeatable laminates for tubular/bearing substrates, while water-lubricated bearing substrates impose additional constraints on swelling, hydrodynamics, and start–stop wear behavior [5]. For harsh, corrosion-coupled service, EP coatings filled with Ti_3AlC_2 (MAX phase) and B_4C demonstrate dense microstructures and film resilience at moderate temperature, though film stability degrades at elevated temperatures.

2. SOLID COMPOSITE MATERIAL

2.1. Solid-Lubricant Nanofillers and Hybrids

Combining fibers/particles with EP enhances not only mechanical toughness but also the resistance to surface damage under erosive/abrasive environments. This sets the stage for carefully balancing micro-/nano-scale phases to support both structure and tribology. Classical graphite/EP already demonstrated that solid-lubricant films can be maintained without excessive loss of matrix integrity when the loading window is appropriate an idea that reappears in later 2D systems[6].

The h-BN and h-BN-based hybrids. Dispersion/bonding issues can cause local pull-out and surface cracking, undermining tribology. Hybridizing BN with g-C3N4 (BNNSs/g-C3N4) yielded smoother, stronger transfer films on EP coatings, with conspicuously reduced friction and wear compared to neat EP, attributable to improved dispersion and interfacial compatibility ; lamellar shear of BN; and enhanced load-sharing and thermal conduction through the hybrid network [7]. A complementary journal study on GO–h-BN/EP reports a dual benefit—low friction/wear and increased corrosion resistance—suggesting that a percolating 2D network both shares load and interrupts corrosive ingress, consistent with barrier-film mechanisms.

Other hybrid fillers and 2D carbons. The ZnS–GO hybrid brings a 0D–2D perspective, where ZnS nanoparticles stiffen/strengthen the matrix and GO lamellae provide low-shear planes; the synergy yields reduced friction and wear compared to neat EP. MXenebased EP is further highlighted for interfacial bonding via surface terminations and for superior load-sharing/thermal pathways compared to typical GO/oxide baselines. Together, these studies converge on a core principle: interfacially engineered lamellar networks (GO, BN, MXene; alone or hybrid) distribute contact stress, protect the polymer from direct metal contact, and stabilize low-shear transfer films[8].

Oriented lamellae in fiber laminates. Within CF laminates, aligning GNPs in the plane of sliding can markedly affect film continuity and heat removal. The thesis shows that at moderate shear/temperature the oriented lamellae keep friction low and films coherent; as speed and temperature rise, thermal softening and interfacial shear can trigger delamination, echoing a universal stability window for 2D-based films under aggressive conditions [9].

2.2. Encapsulated and On-Demand Lubrication

Microcapsules. Silica-shelled microcapsules embedded in EP provide reservoirs of lubricating oil that can be released when capsule shells crack under contact stress or when frictional heating raises local temperature. The released oil forms a boundary film, suppressing spikes in friction and stabilizing wear in transient or intermittent contact conditions. The design problem shifts to “dose and trigger”: shells must be strong enough to survive processing/handling yet fragile enough to release oil where and when needed.

Metal-assisted capsules. PAO/Cu NPs@m-SiO_2 capsules add multi-physics benefits to oil release: the metal nanoparticles can act as nano-rollers and heat sinks, potentially lowering contact temperature and helping oil distribution. The combination of liquid lubrication and nano-rolling complements EP's limited toughness under local heating.

Vascular delivery. A vascular EP with embedded channels within CF laminates stores silicone oil and releases it as the channels fracture during wear. The oil flux depends on vascular density and CF weave ratio; tribological performance shows marked reductions in friction and wear when these parameters are tuned to match the duty cycle[10]. The architecture introduces a recoverable, spatially distributed lubricant delivery mechanism—distinct from capsules in capacity and refill potential (depending on design).

2.3. Fiber and Architected Reinforcement

Carbon-fiber cloth with oriented 2D fillers. CF cloth for stiffness and aligns GNPs to create in-plane low-shear paths. This co-optimizes load transfer and tribology, provided heat generation remains controlled; at excessive speeds/temperatures, films delaminate and friction rises, suggesting a processing–service window where orientation pays off. Such observations generalize to other 2D fillers (BN, MXene) once interfacial compatibility is secured.

Process and substrate design via filament winding. Filament winding ensures regular fiber placement, steady resin infiltration, and compact consolidation, directly relevant to bearing sleeves/tubes. Because defects (porosity, resin-rich layers, fiber waviness) can erode tribological benefits, winding parameters and in-process quality control are critical.

Water-lubricated bearing substrates. For start–stop, low-speed marine environments, hydrodynamic films are hard to sustain; substrate swelling, water ingress, and compressive behavior determine friction and wear more than pure dry-contact mechanisms. The winding-type substrate study frames property targets and evaluation routes specific to wet bearings, reinforcing that matrix/substrate choice is a first-order decision for these applications[11].

2.4. Ceramic/MAX-Reinforced and Corrosion-Resistant Coatings

The Ti_3AlC_2–B_4C/EP coating study provides a distinct perspective: for environments that combine corrosion and lubrication, a dense, well-bonded coating with layered MAX phase (Ti_3AlC_2) and hard B_4C can support a robust transfer film at moderate temperatures; however, as temperature rises, wear scars widen and ploughing becomes evident, pointing to a temperature-dependent film stability threshold. Such coatings are promising for structural parts exposed to corrosive fluids and intermittent sliding, provided the temperature envelope is respected and interfacial adhesion remains high[12].

2.5. Bearing-Oriented Epoxy Materials and Components

Joint bearings. Consolidates an EP-based self-lubricating material for oscillatory contacts. Compared with coupon tests, component metrics capture recovery of transfer films and friction stability under oscillation, guiding material recipes and counterface choices for real bearings.

Self-lubricating sliding EP bearings + FE coupling. Tribological testing with finite-element (FE) models, allowing the mapping of friction reductions (r-GO/TiO_2-modified layers) to stress/strain field changes in bearing geometries. Such coupling moves design from "material-only" thinking toward material–geometry–load co-design[13].

Water-lubricated winding substrates.The substrate complements by highlighting the dominance of swelling and hydrodynamics at low speed; together with winding process evidence, this underlines that bearing-oriented EP systems are just as much about substrate/process as about fillers.

3. CHALLENGES AND OPEN ISSUES

Dispersion and interfacial load transfer for 2D fillers. Agglomeration in high-surface-area fillers (BN, GO, MXene) creates stress concentrators and interrupts tribo-films; weak interfacial bonding leads to pull-out and ploughing. Interface-designed hybrids (BNNSs/g-C3N4, GO–h-BN) expand processing windows, but the optimal content is typically narrow—and context-dependent across bulk/coating, dry/corrosive, and temperature regimes. Aligning lamellae in CF laminates improves pathways but demands compatible chemistries to avoid debonding under cyclic shear [14].

Transfer-film robustness versus heat and shear. Nearly every 2D-enabled system exhibits a stability window: at modest speeds/temperatures the film remains coherent, whereas at elevated speeds/temperatures delamination or thermal softening causes friction rebound and deeper grooves. This is explicit in oriented GNP laminates and MAX/ceramic coatings, implying that thermal management (conductive pathways, heat sinks, controlled duty cycles) must be co-designed with the solid-lubricant architecture.

Corrosion–tribology coupling. GO–h-BN/EP simultaneously lowers friction/wear and raises corrosion resistance, but in aggressive acids/salts micro-crack networks can still nucleate from scratches; hence, barrier effects must be balanced with matrix toughness and adhesion. Ceramic/MAX coatings add hardness and barrier properties, but high-temperature exposure still weakens transfer films—demanding co-optimization between anti-corrosion layers and solid-lubricant functionality.

On-demand lubrication: dosing and triggers. For microcapsules and PAO/Cu@m-SiO_2, the key questions are capsule loading, shell thickness/strength, and release thresholds that correlate with real duty cycles; excessive dosing risks softening surfaces, while insufficient dosing fails to arrest friction spikes. Vascular EP introduces geometric parameters (channel size/density; weave ratio) whose optimization must reconcile mechanical integrity with sufficient oil flux.

Testing comparability and application fidelity. Coupon tests often use ball-on-disk or pin-on-disk at steady loads/speeds; bearings seldom see such simplicity. The oscillatory joint-bearing study, FE-coupled sliding-bearing work, and water-lubricated substrate study show the necessity of component-relevant evaluations (oscillation, start–stop in water, corrosive media, contaminated contact). Without these, lab metrics may not transfer to service[15].

Manufacturing constraints and scale-up. Filament winding is a route to reproducible laminates, yet defects (porosity, resin-rich layers) immediately degrade wear resistance. Coating processes for MAX/ceramic systems must ensure dense microstructures and strong adhesion; otherwise, tribological gains evaporate under thermal/corrosion cycling. Process monitoring and in-line quality assurance are therefore first-class design variables, not afterthoughts.

4. FUTURE DIRECTIONS

Multi-scale hybridization with targeted functions. Combine lamellar 2D phases (GO, h-BN, MXene) with hard/temperature-resistant particles (Ti_3AlC_2, B_4C) and 0D nanoparticles to co-optimize low-shear planes, load bearing, heat dissipation, and barrier properties. The aim is a hierarchical network that sustains low friction while resisting thermal and corrosive degradation[16].

Adaptive lubrication architectures (capsules + vascular). Stage lubricant delivery: capsules address early-life and transient spikes; vascular networks handle sustained boundary lubrication as wear exposes channels. Metal-assisted capsules can add nano-rolling and thermal benefits. System-level design should map release rate vs. duty cycle to keep the coefficient of friction within a specified band for the full service window.

Thermal and corrosion co-design. Tie tribology to electrochemical/corrosion protocols to quantify film breakdown onset and barrier synergy under service-like fluids/temperatures. MXene and GO–h-BN pathways suggest high-conductivity/barrier architectures; overlay these with ceramic/MAX particles to resist groove formation at higher temperatures[17].

Oriented 2D and fiber architectures. Scale magnetic/compression alignment from laboratory coupons to laminates and sleeves. Use CF fabrics as carriers for anisotropic lubricating networks; incorporate toughening interlayers to absorb shear without delamination. Process–structure–property maps should target the "safe" shear/temperature domain where films remain intact.

Application-driven substrates and processes. For water-lubricated bearings, prioritize low swelling, compressive stability, and hydrodynamic compatibility in winding laminates; for oscillatory joint and sliding bearings, use FE-informed duty-cycle maps to position materials within acceptable stress/strain envelopes. Embed process controls (void fraction, consolidation pressure, cure schedule) as design variables alongside filler content[18].

Standardization and data richness. Encourage reporting of counterface materials/roughness; ramped speed/temperature protocols;film thickness/chemistry (Raman/EDS); and corrosion-tribology combined metrics.

5. SUMMARY

Self-lubricating EP systems coalesce around three pillars: interfacially engineered 2D/hybrid fillers, adaptive liquid-delivery architectures, and load-capable fiber/ceramic frameworks. h-BN and GO hybrids (BNNSs/g-C3N4, GO–h-BN) create smooth and tough transfer films with improved dispersion; MXene and ZnS–GO widen the design space to stronger interfacial bonding and 0D–2D synergies. Capsule and vascular strategies transform EP from a passive matrix to an active lubricant reservoir, stabilizing COF during transients and wear progression. Structural solutions—CF laminates with oriented lamellae and filament-wound substrates—connect tribology to manufacturability and component realities, especially in water-lubricated and oscillatory scenarios. For corrosion-coupled conditions, MAX/ceramic-reinforced EP coatings withstand moderate temperatures before film stability declines, illustrating the need for temperature-aware designs. Persistent gaps—dispersion control, film endurance under heat/shear, corrosion synergy, dosing/triggering, test fidelity, and process QA—define actionable research frontiers. We advocate multi-scale hybridization, capsule+vascular integration, thermal/barrier co-design, laminate orientation with toughening interlayers, and application-driven substrate/process selection, ready for translation to bearing-grade EP systems.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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