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# Fabrication Technology of SiC Particle Reinforced Aluminum Matrix Composite Brake Discs for High-Speed Trains Research Progress

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## ABSTRACT

With low density, high specific strength, favorable thermal conductivity and wear resistance, SiC particle-reinforced aluminum matrix composites are highly promising candidate materials for lightweight brake discs of high-speed trains. This paper summarizes the fundamental theories, various preparation technologies and existing engineering challenges of brake discs made from such composites. It illustrates strengthening mechanisms including load transfer, thermal mismatch and dislocation obstruction, and analyzes the influences of SiC/Al interfacial reactions, particle agglomeration and pore defects on the thermo-mechanical fatigue, fracture and wear properties of materials. The control essentials, advantages and disadvantages, as well as engineering adaptability of processes such as powder metallurgy, stir casting, pressure infiltration, friction stir processing and additive manufacturing are compared. It is indicated that stir casting is suitable for large-size components; friction stir processing can construct gradient wear-resistant microstructures; dual-configuration microstructures and particle surface coatings can achieve synergistic improvement of strength and ductility. Current material applications mainly face bottlenecks including difficult particle dispersion, formation of interfacial brittle phases, initiation of thermal fatigue cracks, and conflicts between manufacturing scale and cost. The research demonstrates that brake discs require coordination between material microstructure regulation and structural thermo-mechanical coupling design, which provides references for subsequent process optimization and engineering development of SiCp/Al brake discs for high-speed trains.

## KEYWORDS

SiC/Al interfacial reaction; Pore defect; Thermo-mechanical coupling

## 1. INTRODUCTION

The safety and reliability of high-speed train braking systems directly determine the upper limit of train operating speed and operational economy. As a key load-bearing and heat-dissipating component in friction pairs, brake discs need to maintain structural integrity under conditions of high contact pressure, high friction power, and complex thermo-mechanical coupled cycles. Compared with traditional cast iron brake discs, aluminum matrix composite brake discs have become an important candidate for lightweight and high-performance applications due to their low density, superior specific strength and specific stiffness, considerable thermal conductivity, and synergistically improved wear resistance and thermal fatigue resistance via reinforcing phases [1]. In actual service environments, brake discs are subjected to alternating temperature rises and stresses

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induced by braking, as well as the coupled effects of abrasive debris, invading particles from track or braking environments, damp heat corrosion, salt spray, and other multiple factors. Therefore, the microstructural stability, interfacial bonding quality and tribological response of materials become decisive factors. Relevant studies indicate that composite material design and process optimization can significantly improve wear and friction performance, demonstrating potential technical maturity under urban rail bench simulation conditions [2].

There remain multiple challenges in the practical application of SiC particle reinforced aluminum matrix composites to high-speed train brake discs. First, poor wettability, agglomeration and unstable dispersion of SiC particles in the aluminum matrix lead to local pores and stress concentration. Second, interfacial reactions and thermal mismatch between SiC and Al induce the evolution of reinforcing phases, generation of brittle phases or interfacial degradation, which impair toughness and durability. Third, braking conditions involve thermal loads of 150–400°C or even higher; materials must retain stable strength and wear resistance under thermal cycles and thermo-mechanical coupled fatigue. Fourth, brake disc structures (vent ribs, spokes, bolt holes, etc.) amplify temperature gradients and deformation, resulting in directional and localized initiation sites of thermal fatigue cracks, which requires comprehensive evaluation from the perspective of thermo-mechanical coupling [3-5].

As a typical hard ceramic reinforcing phase, SiC particles feature high hardness and favorable thermal stability, and can participate in forming a third-body/debris layer during friction, thus enhancing wear resistance and friction coefficient stability. Meanwhile, the introduction of SiC particles achieves multiple strengthening effects through load transfer, dislocation multiplication induced by thermal mismatch, and dislocation motion blocking by particles. Adopting specific particle sizes/content as well as gradient or heterogeneous microstructure strategies can alleviate the trade-off between strength and ductility and modify crack propagation paths. For instance, dual-scale or dual-configuration reinforcement designs realize coordinated improvement of strength and ductility, and the underlying strengthening mechanisms are mainly associated with hetero-deformation induced (HDI) strengthening, enhanced dislocation accumulation capacity and crack blunting effect [6]. In addition, thermo-mechanical coupling analysis and finite element simulation provide physical basis for material selection and structural optimization targeting friction heat input and thermal stress distribution of brake discs. For example, theoretical and numerical models of wear-resistant layers containing 3D $Al_2O_3$-SiC can explain the evolution of maximum friction temperature and thermal stress reduction mechanisms, and further illustrate the role of material thermal conductivity and cooling capacity in temperature field uniformity. On this basis, this paper reviews the fabrication technologies, microstructures and engineering challenges of SiC particle reinforced aluminum matrix composite brake discs.

# 2. BASIC THEORIES OF SIC PARTICLE REINFORCED ALUMINUM MATRIX COMPOSITES

## 2.1. Matrix and Reinforcing Phases

SiC particle reinforced aluminum matrix composites (SiCp/Al MMCs) generally adopt aluminum alloys (such as A356, A6061, A2024, 6013, Al-Si series alloys, etc.) as the matrix and SiC particles as the reinforcing phase. Aluminum alloy matrices instead of pure aluminum are selected in engineering because aluminum alloys offer solid-solution strengthening/precipitation strengthening potential, enabling composites to possess stronger matrix load-bearing capacity at room and medium-high temperatures. At the same time, the incorporation of SiC particles not only improves hardness and wear resistance, but also stabilizes friction pairs and inhibits local plastic deformation. For brake disc applications, materials also need to satisfy high thermal conductivity, relatively low thermal expansion and high interfacial stability to reduce risks of thermal stress and thermal fatigue cracks.

From a microstructural perspective, the dispersion state of SiC particles in the matrix determines the effective strengthening volume fraction and actual load transfer efficiency of composites. Particle size, content and morphological distribution affect particle agglomeration tendency and wettability at the particle-melt/matrix interface; agglomeration and local pores significantly reduce macroscopic plasticity and raise the probability of fatigue crack initiation. Studies on particle distribution and transfer efficiency show that smaller particle sizes aggravate agglomeration, impairing particle transfer efficiency and final dispersion quality. In addition, molten surface oxide films and particle-melt interactions affect transfer behavior, so stirring head parameter design during stirring must ensure the elimination of agglomerates [7]. Furthermore, random particle size distribution exerts a critical influence on fracture morphology and damage evolution.

Friction heat input during brake disc service causes remarkable temperature rise and stress cycling, so composites are simultaneously constrained by static strength, dynamic softening, thermal fatigue and third-body debris formation. Thermo-mechanical fatigue (TMF) studies reveal that spray-deposited SiCp/Al-Si composites exhibit continuous cyclic softening within 150–400°C, and increasing SiC particle size and content aggravate softening, which originates from dislocation generation triggered by differential thermal shrinkage at Al matrix/second-phase interfaces. Meanwhile, in terms of TMF life and stress amplitude, SiCp/Al-7Si composites possess superior TMF life and bearing capacity compared with monolithic matrix alloys, and TMF life rises with increasing particle size due to load sharing mechanisms. Therefore, both the strengthening and wear-resistance effects of reinforcing phases must be considered in brake disc material selection and process optimization.

## 2.2. Strengthening Mechanisms

Strengthening of SiCp/Al composites mainly includes load transfer strengthening, thermal mismatch strengthening, and dislocation blocking/Orowan-type mechanisms. Load transfer strengthening refers to the phenomenon that reinforcing phases bear partial external loads, increasing the equivalent strength of composites. Load transfer efficiency improves when particles are well dispersed and interfacial bonding is sufficiently strong. Finite element and pore sensitivity studies indicate that reinforcing phases still maintain effective load transfer trends even with pores, but pores reduce stress concentration capacity, lower effective elastic modulus, and composite elastic properties are more sensitive to pores far away from reinforcing particles [8]. This implies that pore control must be a core indicator in brake disc manufacturing processes; otherwise, macroscopic defects will weaken effective strengthening despite the high intrinsic strength of particles.

Thermal mismatch strengthening arises from thermal strain differences between SiC (high modulus, distinctly lower coefficient of thermal expansion than Al) and aluminum matrices during temperature variation, which further induce thermally driven dislocations, geometrically necessary dislocations (GNDs) and local stress fields. Relevant fracture and damage model studies show that particle size effects affect material response through plastic strengthening induced by GNDs, and random particle size distribution plays an important role in fracture morphology. Moreover, TMF research further confirms that differential thermal shrinkage generates dislocations at interfaces between Al matrix and Si phases or SiC particles, aggravating continuous cyclic softening. Thus, a competitive relationship exists between thermal mismatch strengthening and thermal cycle softening under cyclic thermal service conditions of brake discs: the dislocation multiplication generated by thermal mismatch is utilized to strengthen the matrix, while interfacial degradation and early crack initiation induced by brittle phases must be suppressed.

Regarding dislocation blocking and the Orowan mechanism, although the references cited in this review mainly focus on thermo-mechanical coupling and macroscopic properties, particles can improve hardness and resistance to plastic deformation at the microscale by pinning dislocations and increasing the resistance to dislocation traversal. In particular, surface coating modification to

optimize interfacial bonding enables full utilization of hard particles. For example, friction stir processing (FSP) of copper-coated SiC particles enhances interfacial bonding and achieves multi-strengthening via Cu diffusion, dispersed Cu debris, formation of Al-Cu intermetallic compounds, solid-solution strengthening and dislocation mechanisms [9]. Such routes combining interfacial engineering and process strengthening are especially vital for brake discs, as interfaces bear coupled shear and thermal stresses under braking conditions, and weak interfaces lead to debonding and accelerated wear.

### 2.3. Interfacial Characteristics and Their Effects on Material Properties

Interfaces between SiC particles and aluminum matrices are the dominant factor governing composite performance. Excessively strong interfacial reactions or continuous brittle phase networks degrade fracture toughness and accelerate crack propagation along interfaces; insufficient interfacial bonding reduces load transfer efficiency and triggers particle debonding wear. Studies on SiC particle surface states demonstrate that adsorbed layers on SiC surfaces affect wettability, infiltration and final mechanical properties during pressure-free infiltration fabrication, and ultrasonic cleaning is adopted to investigate their influences on composite forming processes.

Interfacial reactions are also related to in-situ reactions of SiC particles. Selective laser melting (SLM) studies show that intense chemical reactions occur between SiC particles and Al matrices during laser forming, generating micron-scale acicular $Al_4SiC_4$ strips in situ. In contrast, no interfacial reactions take place between TiC particles and Al matrices, and semi-coherent TiC/Al interfaces possess favorable bonding strength. This research also points out that abundant acicular $Al_4SiC_4$ strips constitute the primary factor causing premature fracture failure of composites [10]. This suggests that interfacial reactions significantly alter the composition of reinforcing and interfacial phases during high-energy additive manufacturing or melting processes, affecting toughness under service conditions.

Furthermore, to avoid SiC surface decomposition and mitigate adverse reactions, physical vapor deposition (PVD) is employed to fabricate thin metal coatings (e.g., tungsten films) on SiC particles, followed by spark plasma sintering (SPS) to prepare Cu/Al matrix composites for improved interfacial stability. Results reveal that material wear behavior changes after corrosion and thermal shock, while coating strategies help maintain uniform interfacial layers and modulate thermodynamic performance [11]. In transient liquid phase (TLP) diffusion bonding with Cu interlayers, the Cu interlayer promotes wettability and interfacial connection via Al-Si-Cu and Al-Cu eutectic reactions, and regulates the generation and aggregation of $CuAl_2$ phases to adjust shear strength levels.

Therefore, clear interfacial design targets should be defined for brake disc materials: on one hand, surface coating or alloying methods are adopted to facilitate effective wettability and load transfer; on the other hand, the morphology and volume fraction of interfacial reaction products must be controlled to avoid rapid crack propagation driven by continuous brittle phases. Meanwhile, pores, agglomeration and microstructural inhomogeneities generated during fabrication superpose with interfacial reactions to form synergistic damage paths of pores-interfaces-brittle phases, which will be further elaborated in subsequent discussions on mechanical, frictional and thermal fatigue performance [12].

## 3. RESEARCH PROGRESS OF FABRICATION TECHNOLOGIES

Fabrication technologies determine the dispersion uniformity and pore level of SiC particles in aluminum matrices, as well as the degree of interfacial reactions, grain morphology, residual stress and microstructural gradients. For large-size brake discs for high-speed trains featuring high near-net-shape requirements and severe cyclic thermal service loads, the scalability, controllability and repeatability of processes are equally important as material performance. This section reviews

research progress and key control indicators of powder metallurgy, stir casting, pressure infiltration, spray deposition and novel additive manufacturing technologies.

## 3.1. Powder Metallurgy

### 3.1.1. Process Principles and Procedures

Fabrication of SiCp/Al composites via powder metallurgy generally includes powder mixing (mechanical ball milling/stirring), forming (cold pressing/hot pressing/isostatic pressing), degreasing and sintering (or melting-solidification variants), and optional plastic working such as extrusion/rolling after heat treatment to improve microstructural homogeneity. The advantage of powder systems lies in the stable retention of initial reinforcing phase dispersion during subsequent forming and sintering, reducing deterioration of dispersion caused by agglomerate migration in molten melts.

Powder metallurgy also enables multi-scale particle or heterogeneous structural design of reinforcing phases. For example, pre-mixing SiC particles of different sizes with corresponding aluminum alloy powders and assembly followed by powder metallurgy yields heterogeneous grain structures and dual-configuration reinforcing phase distributions. Relevant studies indicate that dual-configuration strategies (submicron SiCsm/Al and micron SiCm/2024Al) produce alternating coarse-grained and ultra-fine-grained heterogeneous structures, ultimately achieving coordinated improvement of strength and ductility while maintaining high modulus, with primary strengthening mechanisms associated with HDI strengthening and crack blunting.

### 3.1.2. Effects of Process Parameters on Microstructure

Key powder metallurgy parameters include ball milling time/rotational speed, forming pressure, sintering temperature and holding time, as well as post-extrusion ratio and hot working parameters. Although systematic ball milling parameter laws targeting brake discs are less abundant in the collected data compared with stirring processes, fundamental material rules can be extended for comprehension: inter-particle contact, interfacial diffusion and agglomeration tendency jointly determine final dispersion and interfacial reaction levels during sintering. Studies on the influence of SiC particle size on hot workability show that particle size significantly affects hot deformation activation energy and dynamic softening mechanisms, further defining the processing window. For SiCp/6013 composites, hot deformation activation energy Q rises with decreasing SiC particle size, and the transition of dynamic softening from dynamic recovery to dynamic recrystallization depends on particle size and temperature. This indicates that matched processing maps must be established according to particle sizes for extrusion or hot working after powder metallurgy fabrication [13].

In addition, random particle size distribution affects fracture behavior and macroscopic damage propagation. Combined experimental-numerical research based on the Gurson–Tvergaard–Needleman (GTN) damage model verifies that random particle size distribution exerts a remarkable influence on fracture morphology, which implies that powder mixing uniformity and agglomeration control during powder metallurgy are reflected in macroscopic fracture characteristics.

### 3.1.3. Technical Characteristics and Application Scope

Powder metallurgy exhibits potential in precise interfacial regulation and multi-scale microstructure construction, and is more suitable for small and medium-sized components requiring elaborate microstructural design. However, brake discs are generally large and complex-shaped parts, and traditional powder metallurgy faces limitations in cost, production capacity and component dimension. If near-net shaping is realized via powder stacking/composite assembly, interfacial defects, incomplete diffusion and pores still need to be resolved. For instance, studies on sandwich-type solid-state forming point out that although SiC particles can realize certain dispersion within layers and form interfacial carbides/local microvoids, such processing-induced defects lead to limited improvement in macroscopic tensile strength [12]. Therefore, applying powder metallurgy to brake

discs requires special attention to whether layered/sandwich structures form defect channels detrimental to macroscopic fracture, and whether hot pressing/densification post-processing can eliminate fabrication voids.

## 3.2. Stir Casting

### 3.2.1. Process Principles and Procedures

Stir casting and its variants adopt molten aluminum alloy as the matrix; stirring heads disperse SiC particles in the melt to promote wettability and particle transfer, followed by pouring and solidification to form composite castings. Compared with powder metallurgy, stir casting possesses superior scalability for manufacturing large-size components, thus holding greater engineering potential. Particle transfer and dispersion efficiency during stirring are strongly affected by particle size, molten surface oxide films, stirring head motion and process parameters.

### 3.2.2. Uniformity Control of SiC Particle Distribution

Regarding particle agglomeration, water model and special stirring head device studies analyze particle transfer efficiency and dispersion mechanisms in melts. Results show that thermal pretreatment often facilitates particle wettability but may induce agglomeration before feeding; early agglomerates reduce transfer efficiency and final dispersion uniformity, and interactions between particles and molten upper-surface oxide films constitute a critical influencing factor. In addition, finer particles aggravate agglomeration, and matrix alloy compositions (e.g., rare earth elements) modify melt properties to affect particle dispersion. Therefore, the coupled effects of wettability enhancement, agglomeration suppression and oxide film control must be considered when applying stir casting to brake disc production.

Local reinforcement and gradient structures can also optimize performance during stirring-based processes. For example, research on friction stir processing (FSP) forming local reinforced layers reveals that stirring electroplated copper-coated SiC particles into A6061 matrices improves interfacial bonding and enhances hardness/strength. Unlike integral casting, this local strengthening concept provides insights for fabricating wear-resistant layers on brake disc friction surfaces. Furthermore, molten pool flow dynamics and particle migration rules observed in spray deposition or TIG-assisted deposition reflect cross-process common laws governing dispersion uniformity in both stir casting and additive manufacturing [14, 15].

### 3.2.3. Technical Characteristics and Application Scope

The advantages of stir casting lie in its scalable production capacity and cost competitiveness, enabling fabrication of composite brake discs close to engineering scale. Corresponding drawbacks include particle floating/sedimentation, agglomeration and solidification shrinkage-induced pores. Pore content directly affects elastic modulus and overall performance, and may act as fatigue crack initiation sources under thermo-mechanical coupled cycles. Meanwhile, excessively high volume fractions of reinforcing particles increase interfacial reactions and brittle phase formation, impairing toughness and fracture behavior; comprehensive balance via particle content, size and interfacial engineering is required.

## 3.3. Pressure Infiltration

### 3.3.1. Process Principles and Procedures

Pressure infiltration (including pressure-free and pressure-assisted infiltration) generally relies on porous preforms with SiC particle skeletons. Under specific atmospheric or protective environments, molten aluminum alloy infiltrates and encapsulates particles under applied pressure to form composites. The core of this route lies in wettability and infiltration capacity: melts must fully

penetrate pores and form favorable interfacial bonding with particle surfaces to guarantee densification and load transfer efficiency.

#### 3.3.2. Preform Fabrication and Infiltration Processes

A key variable of infiltration is the cleanliness and adsorbed layers on SiC particle surfaces. Studies fabricating SiCp/Al composites via pressure-free infiltration adopt ultrasonic cleaning to investigate the influences of surface adsorbates on infiltration and mechanical properties. Results indicate that SiC particles carry adsorbed layers of certain mass fractions, which alter infiltration behavior and final performance. This demonstrates that surface contamination, adsorbed gas/organic residues and oxide films must be effectively controlled for SiC particle systems used in brake discs.

#### 3.3.3. Technical Characteristics and Application Scope

Compared with full melting stir casting, pressure infiltration readily forms relatively controllable pore structures and realizes uniform particle "skeleton constraint" via infiltration paths. However, it features high sensitivity to particle preform shaping, stable infiltration flow, gas discharge and densification, and strongly depends on surface wettability. Therefore, engineering scaling must consider the influences of preform pore size distribution on infiltration pressure drop, consistency of surface treatment, and regulation of interfacial reactions via post-heat treatment.

### 3.4. Novel and Composite Fabrication Technologies

#### 3.4.1. Friction Stir Processing for Local Strengthening and Gradient Microstructures

Friction stir processing (FSP) is a severe plastic deformation method under solid or near-solid states, which disperses reinforcing particles to form local composite layers in designated regions. Studies on FSP-manufactured hybrid-layer brake discs show that the upper layer is A357/SiC aluminum matrix composite and the lower layer is AA6082 alloy; full-scale bench braking tests verify outstanding wear and friction performance. Performance improvement originates from thermally stable hardening of SiC particles, microstructural refinement via uniform particle distribution, reduced crack initiation from secondary particles, and gradient hardness mitigating external impact and internal thermal stress.

In addition, incorporating copper-coated SiC particles during FSP significantly strengthens interfacial bonding and elevates hardness and tensile strength. Electroplated copper coatings realize diffusion and reactions between Cu films and Al matrices, and microscopic evidence interprets four primary strengthening mechanisms: diffusion enhancement, dispersed Cu debris, formation of Al-Cu intermetallic compounds, solid-solution strengthening and dislocation penetration mechanisms. Corresponding FSP studies verify interfacial atomic diffusion and intermetallic compound formation via optical microscopy (OM) and transmission electron microscopy (TEM), further proving the feasibility of copper-coated SiC reinforcement.

#### 3.4.2. Additive Manufacturing and Droplet Deposition: Flow Dynamics of Particle Migration

During TIG-assisted droplet deposition additive manufacturing, molten pool flow and particle migration determine the final uniformity of deposited layers. Numerical model studies show that the deposition process includes four stages: impact, coalescence, spreading and rebound. Remelting occurs near impact points; droplet impact generates V-shaped depressions at molten pool centers and crown bulges at edges. Driven by melt drag force, SiC particles tend to distribute on both sides of deposited layers, while local high pressure induced by droplet impact and bottom convection suppress SiC sedimentation at molten pool bottoms [14]. Further three-dimensional transient numerical analysis emphasizes the coupling of heat transfer, flow and particle migration; the volume of fluid (VOF) method is adopted to calculate free surface fluctuations and simulate particle trajectories and final distribution states. Numerical models are verified by microstructural characterization, and particle distribution and solidification morphology of deposited layers match experimental results [15].

### 3.4.3. Hot Workability: Hot Deformation Windows of Multi-Size SiC Reinforced Composites

Brake discs require post-processing such as extrusion, rolling or forging to achieve target dimensions and surface quality. Hot workability research on 6013 aluminum matrix composites reinforced with multi-size SiC particles reveals that rising deformation temperature and decreasing strain rate reduce flow stress, which can be described by the sine-hyperbolic Arrhenius equation. Activation energy Q correlates with SiC particle size and processing window. Constructed hot processing maps show unstable regions mainly locate at high strain rates, and the optimal processing window ranges from 450–500°C with strain rates of 0.03–0.25 $s^{-1}$[16]. Further studies on particle size effects on hot workability indicate that finer SiC particles lead to higher hot deformation activation energy Q and variable dynamic softening mechanisms dependent on particle size and temperature; smaller SiC particles expand the area of unstable processing regions. This implies that matched hot deformation windows must be formulated after selecting particle sizes and fabrication routes to avoid pore expansion or abnormal microstructures during deformation, which would degrade subsequent service performance of brake discs.

### 3.4.4. Material Joining and Local Interfacial Control: Diffusion Bonding and Interlayer Design

Local joining operations may be required during brake disc manufacturing (e.g., bonding different material layers, repair patches or structural assembly). Transient liquid phase (TLP) diffusion bonding studies show that Cu interlayers promote interfacial wettability and connection via eutectic reactions at 550°C under argon atmosphere, and modulate the generation and aggregation of $CuAl_2$ phases to adjust shear strength. Shear strengths of two material systems reach 85.4 MPa and 73 MPa respectively, and differences in interfacial reaction product content dominate performance variation.

## 3.5. Comprehensive Comparison and Analysis of Different Fabrication Technologies

Overall, Table 1 gives a comprehensive comparison of various preparation technologies, which exhibit distinctions in particle dispersion mechanism, interfacial reaction control, densification and scale-up capability. Stir casting is suitable for large-size components but highly sensitive to molten oxide films, particle agglomeration and flow parameters. Powder metallurgy enables controllable dispersion, yet post-forming densification, layered defects and macroscopic performance transformation require special attention. Pressure infiltration is extremely sensitive to surface wettability, and surface adsorbed layers significantly alter infiltration processes and mechanical properties. Spray deposition delivers potential for wear-resistant layers/gradient functional structures, while softening risks under thermo-mechanical fatigue need optimization via particle size and deposition parameters. FSP demonstrates bench-verified engineering application prospects in local strengthening and gradient structure construction, and multi-strengthening mechanisms are realized via interfacial coatings such as Cu coatings. Meanwhile, particle enrichment at specific positions in additive manufacturing layers leads to localized performance differences, which must be regulated via process parameters to control molten pool flow patterns and particle migration [17-20].

In terms of brake disc application evaluation, these differences are ultimately reflected in performance indicators: mechanical strength and hardness, toughness/fracture behavior, wear resistance, thermal stability and thermo-mechanical coupled fatigue life. The following sections systematically elaborate these indicators and correlate fabrication differences with performance variations.

**Table 1.** Analysis of Different Preparation Technologies

| Preparation Route | Control Mechanism | Performance Target |
|---|---|---|
| Stir casting | Regulate melt agglomeration and flow | Form large-size components |
| Powder metallurgy | Realize densification and suppress delamination defects | Homogenize microstructure |
| Pressure infiltration | Improve wettability and regulate surface adsorption layer | Optimize interface and mechanical properties |
| Spray deposition | Optimize particle and deposition parameters | Construct gradient wear-resistant layers |
| Friction-Stir Processing (FSP) | Gradient-structure construction + Cu-coating modification | Improve thermo-mechanical fatigue resistance |
| Additive manufacturing | Control melt-pool flow and mitigate particle segregation | Eliminate local performance discrepancy |

# 4. CONCLUSIONS

## 4.1. Conclusions

Overall, SiC particle reinforced aluminum matrix composites exhibit promising development prospects for high-speed train brake disc applications, with core advantages originating from hard reinforcement, thermal stability and tunable friction and wear behavior provided by SiC particles. Full-scale bench tests prove that constructing hybrid gradient layers of aluminum matrix composite/Al alloy via friction stir processing achieves excellent friction and wear performance, which is closely associated with thermally stable hardening of SiC particles, microstructural refinement from uniform particle distribution, gradient hardness and reduced thermal stress. From a mechanical perspective, dual-configuration heterogeneous microstructure strategies realize coordinated strength-ductility improvement via HDI strengthening and crack blunting; FSP combined with copper-coated SiC particles elevates hardness and tensile strength through multiple mechanisms including diffusion reactions, dispersion strengthening and dislocation effects. From a thermo-mechanical fatigue perspective, spray-deposited SiCp/Al-Si composites possess superior fatigue life and bearing capacity compared with monolithic matrix alloys within 150–400 °C thermal cycles, and particle size and content modulate softening degree and TMF behavior. From a thermo-mechanical coupled structural response perspective, temperature gradients and edge stresses around bolt holes constitute high-risk regions for thermal fatigue crack initiation, requiring collaborative optimization of material and structural design. These conclusions collectively indicate that the key to SiC particle reinforced aluminum matrix composite brake discs lies not merely in increasing hardness, but in systematic realization via fabrication process optimization, microstructural homogeneity improvement, interfacial reaction control, pore defect reduction and thermo-mechanical coupled service life extension.

## 4.2. Main Existing Problems

Several critical bottlenecks remain unresolved at present. First, controlling particle dispersion and agglomeration remains difficult, especially during stir casting and melting processes; early agglomeration induced by thermal pretreatment coupled with oxide film interactions reduces particle transfer efficiency and deteriorates dispersion quality. Second, interfacial reactions exert dual effects: excessive reactions generate brittle acicular $Al_4SiC_4$ strips leading to premature failure, while insufficient interfacial bonding causes inadequate load transfer and risks of debonding wear. Third, pores and defects weaken stress concentration capacity and lower effective elastic modulus; macroscopic defects alter fracture morphology and accelerate damage evolution. Fourth, the complex service environment of brake discs requires coupled evaluation of material performance and structural

thermo-mechanical response. Thermo-mechanical coupling analysis confirms larger stress variations around bolt holes and specific orientations, which easily trigger thermal fatigue cracks and raise higher requirements for composite microstructural homogeneity and local defect tolerance. Fifth, engineering manufacturing faces trade-offs between cost and component scale. Powder metallurgy and additive manufacturing enable controllable performance yet incur high costs, while defect control of stir casting/infiltration processes requires mature processing windows.

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