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Squeeze Casting of Hybrid Aluminum Matrix Composites: A Critical Review of Process Optimization, Reinforcement Strategies, and Performance Outcomes

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Abstract

Increasing demand for lightweight, performance-oriented components in automotive, aerospace, and defense industries has driven advancements in squeeze casting, a hybrid technique merging forging and die-casting advantages to produce near-net-shape aluminum matrix composites (AMCs) with superior mechanical-tribological properties. This review critically examines the interplay of process parameters (e.g., squeeze pressure: 70–150 MPa, melt temperature: 650–800°C), reinforcement characteristics (volume fraction ≤10%, particle size: 10–71 µm), and interfacial engineering strategies (flux-assisted bonding, ultrasonic dispersion) in optimizing AMC performance. Key findings reveal that squeeze pressure (95–105 MPa) and controlled solidification (die temperature: 150–250°C) minimize porosity, refine grain structures (e.g., 90→60 µm grain size), and enhance tensile strength (up to 232 MPa) and hardness (up to 58 HRF). Reinforcement strategies, such as hybrid Al_2O_3/SiC systems, improve wear resistance by 78%, while interfacial modifications (e.g., K_2TiF_6 flux, Ti/Mg additions) suppress harmful intermetallics and boost load transfer efficiency. Despite challenges like particle agglomeration and brittle fracture, squeeze-cast AMCs demonstrate forged-grade properties, outperforming conventional stir/sand casting in strength (UTS +80%), corrosion resistance (+72%), and dimensional precision. This synthesis underscores squeeze casting's viability for industrial applications requiring defect-free, high-integrity components, while identifying optimal parameter windows and future research directions for scalable production.

Keywords: Squeeze casting, aluminum matrix composites (AMCs), hybrid composites conventional casting methods, ultrasonic-assisted casting

INTRODUCTION

Aluminum alloys have been significant in lightweight engineering for over 20 years, particularly in engine blocks and cylinder heads for automobiles and aircraft as a consequence of its favorable Lightweight robustness and resistance to degradation. However, increasing demands for energy efficiency, reduced emissions, and enhanced performance need that materials possess superior Material performance and surface interaction traits. This has triggered the adoption of metal matrix composites (MMCs), which combine a ductile metallic base (e.g., aluminum or magnesium) with reinforcement materials such as ceramic particles or fibers to achieve customized material properties [2]. Aluminum matrix composites (AMCs), for example, reinforced with ceramics like SiC, Al_2O_3, or boron carbide (B_4C), demonstrate superior strength-to-weight ratios, exceptional wear resistance, and enhanced heat resistant stability, making them highly

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effective for applications subjected to extreme mechanical and thermal stresses [3]. Unlike anisotropic fiber/whisker reinforcements, particulate reinforcements provide isotropic properties and compatibility with conventional manufacturing techniques, offering a cost-effective solution [4].

Despite these advantages, conventional casting methods (e.g., stir casting, sand casting) face persistent challenges, including particle agglomeration, interfacial reactivity, and porosity, which degrade mechanical performance [5]. Squeeze casting, a hybrid technique combining forging and die casting, has emerged as a promising alternative. By applying high pressure during solidification, this method minimizes defects (e.g., shrinkage pores), refines microstructures, and enhances interfacial bonding, producing near-net-shape components with forged-like properties [6]. This review systematically examines recent advancements in squeeze-cast hybrid AMCs, focusing on three critical dimensions:

1. *Process parameters:* The role of squeeze pressure (70–150 MPa), melt/die temperatures (650–800°C), and solidification control in optimizing microstructure and mechanical properties.
2. *Reinforcement effects:* The influence of particle type (e.g., SiC, B_4C, hybrid Al_2O_3/SiC), size (10–71 µm), and volume fraction (≤10%) on strength, hardness, and wear resistance.
3. *Interfacial engineering:* Strategies such as flux additives (e.g., K_2TiF_6), ultrasonic dispersion, and particle coatings to enhance wettability and suppress deleterious intermetallics.

By synthesizing findings from key studies, this review identifies optimal parameter windows, highlights trade-offs between strength and ductility, and underscores squeeze casting's superiority over conventional methods for industrial applications. The discussion concludes with future research directions to address scalability challenges and expand the applicability of squeeze-cast AMCs in next-generation lightweight systems.

SQUEEZE CASTING TECHNIQUE

Squeeze casting has been thought of since at least 1800 [31, 32]. Research on squeeze casting did not go along with it until 1931 [33]. Closed die forging and gravity die casting are still mixed together in the squeeze casting method. Pressure used in die halves that are closed, metals have changed and become solid. A lot of heat is transferred quickly when functional pressure and sudden contact of hot metal with the die surface happen. In the end, this makes a porous free casting, which is what causes the skewed result. It's also called extrusion casting, liquid metal casting, and squeeze forming. A simpler version of the squeeze casting method is evident from Figure 1 [32]. Strategies could be roughly divided into two groups: indirect and direct. There is a benefit to the squeeze casting method over the die casting method.

Squeeze casting is ideal for critical uses because it uses pressure while the material cools, creating stronger, defect-free parts. This method prevents air bubbles and shrinkage gaps, producing dense, high-quality castings with smooth, fine structures. It works well even for tricky aluminum alloys (like Al-Si or 7075) that are hard to cast otherwise. Faster production cycles save time and money compared to traditional methods. Custom-designed, reusable molds with special coatings ensure parts are precise

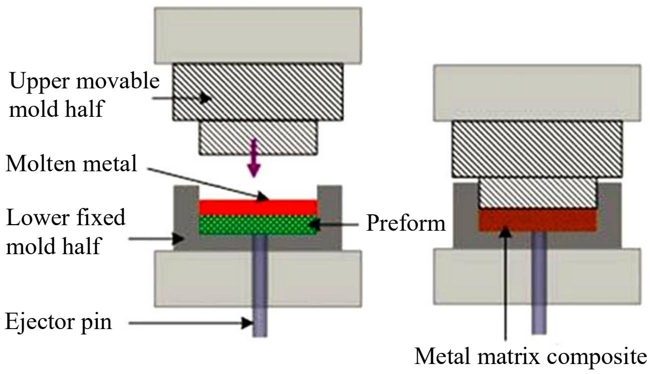

Figure 1. Squeeze casting

and ready to use without extra finishing. Industries like aerospace and cars rely on squeeze-cast parts because they're as strong as forged metal, have smooth surfaces, and fit exact design needs—perfect for heavy-duty, high-stress applications.

EFFECT OF REINFORCEMENT VOLUME FRACTION AND PARTICLE SIZE ON AMC PROPERTIES

Mechanical and tribological properties of aluminium matrix composites (AMCs) are optimised by reinforcement type, particle size, and processing processes. Vencl et al. (2010) discovered that 10 wt.% SiC in A356 aluminium alloy increased hardness and yield strength for homogeneous particle distribution, but 35 µm Al_2O_3 clusters produced brittleness through stress concentration, indicating Orowan bending. According to Kok (2005), adding Al_2O_3 reinforcement (10-30 vol.%, 16-66 µm) to 2024 aluminium increased hardness and porosity, with 10 vol.% being best for larger volumes.

According to Canacki et al. (2013), stir-cast 2024 aluminium composite had equally distributed B_4C particles (71 µm) whereas smaller particles (29 µm) agglomerated and impaired the composite.

In 2019, Kumar et al. applied squeeze casting to obtain high hardness (156.4 HV), tensile strength (531 MPa), and reduced wear rate (0.00221 at 10N) in hybrid Al_2O_3/SiC (5wt% each, 10 µm) for AA2024.

According to Sahin (2003), adding SiC (10-20 wt.%, 45-105 µm) to stir-cast 2024 aluminium increased hardness, density, and air entrapment, resulting in greater porosity

According to Sevik and Kurnaz (2006), the strongest composite is 44 µm Al_2O_3 at 15 vol.% in pressure die-cast LM6 aluminium, however particle breakage affects tensile strength above 10 vol.%. High-performance AMCs benefit from 10% reinforcement (by weight/volume) with intermediate particle sizes (10–71 µm) and squeeze casting techniques, balancing strength, hardness, and porosity for industrial applications.

ROLE OF MATRIX-REINFORCEMENT INTERFACE BONDING AND WETTABILITY IN AMCS

Massoud Malaki (2021) used ultrasonic jets to break particle clumps in composites via cavitation. Challenges like high melt thickness, large volumes, and tool wear require rapid cooling to prevent re-clumping. Optimizing sound parameters and using coatings/controlled cooling ensure even particle spread [37]. Natrayan & Senthil Kumar (2020) fabricated AA2024 composites reinforced with silicon carbide (SiC) via squeeze casting. Incorporating 3% SiC significantly lowered wear rate and friction coefficient. A hybrid composite combining Al_2O_3, SiC, and graphite further boosted wear resistance by 78% compared to unreinforced AA2024 [14]. Gursoy Arslan & Kalemtas (2009) defined wettability as a liquid's ability to spread on a solid. Ceramic particles poorly wet liquid aluminum due to surface contaminants or gas layers. Solutions include ↑ temperature, adding reactive elements (Mg, Li, Ca, Ti), coating particles, or commercial techniques like flux/preheating [16]. Baradeswaran & Elaya Perumal (2013) used K_2TiF_6 flux in 7075 Al-B_4C composites (5–20% vol.). Flux created TiC/TiB_2 layers, enhancing bonding. Higher B_4C % boosted strength [15]. Kerti & Toptan (2008) improved wettability and minimized harmful intermetallic formation in Al-B_4C composites by employing K_2TiF_6 flux. A Ti/B_4C ratio of 0.07 (using the same flux) optimized interfacial bonding. The study noted uniform dispersion of 20 µm B_4C particles, while smaller 10 µm particles formed agglomerates [13]. Kennedy (2002) enhanced LM25 aluminum composites reinforced with 5–10 vol% boron carbide (B_4C, 25 µm) by incorporating K_2TiF_6 flux during die-casting. The flux promoted a titanium-rich interfacial layer between the matrix and reinforcement, strengthening their bond. This improved load transfer efficiency, resulting in higher tensile strength, yield stress, and stiffness—with stiffness increasing by +2 GPa per vol% of B_4C [12]. A critical limitation of stir casting is the poor wettability between molten aluminum and ceramic particles, which hinders effective reinforcement integration [39]. To address this, magnesium (Mg) and silicon (Si) are added to the melt. Magnesium enhances alloy strength while simultaneously scavenging oxygen via MgO formation, mitigating porosity (e.g., blow holes) in castings. Additionally, Mg reduces the composite melt's surface tension, improving ceramic particle wetting and dispersion [40].

LIMITATIONS OF CONVENTIONAL CASTING METHODS ON THE PROPERTIES OF AMCS

Amir Hussain Idrisi [38] Aluminum matrix composites (AMCs) were fabricated using conventional and ultrasonic-assisted stir casting. Ultrasonic energy (via probe) addressed conventional stir casting's drawbacks, such as uneven particle dispersion. Composites with 3–10% SiC microparticles (40 μm) were tested. Mechanical/physical tests and microstructural analysis showed homogeneous SiC distribution in ultrasonic-cast samples, attributed to cavitation/acoustic streaming, enhancing properties and highlighting ultrasonic casting's superiority for high-quality AMCs (Figure 2).

Abdulkabir Raji [35] compared Al-8% SiC composites made via sand, chill, and squeeze casting (650– 800°C, 0–150 MPa). Sand casting showed declining UTS (102→65 MPa), grain count (11.98→8.33), and hardness (35.5→33 HRF) with rising temperature. Chill casting maintained UTS (115 MPa) and hardness (40 HRF). Squeeze casting excelled at 700°C/150 MPa with UTS (232 MPa), proof stress (156 MPa), hardness (58 HRF), and refined grains (88.55). Despite modest elongation (2–3.8%), squeeze casting is optimal for high-strength industrial uses (Table 1).

Syed Easa Faizal [36] studied squeeze-cast Al-2024-Zn composites, finding that 4-5% zinc content and 10-15 minute squeeze times significantly enhance properties. A zinc oxide layer improves micro-hardness (66.6%) and corrosion resistance (72.2%), while squeeze time optimizes tensile strength (80.2%, 232 MPa). Optimal conditions are 5% Zn for 15 minutes (hardness/corrosion) and 10 minutes (strength). The process reduces shrinkage and outperforms stir casting in corrosion resistance, making it ideal for high-performance Al-Zn applications [36].

In their 2018 study, Natrayan and Senthil Kumar conducted a comparative analysis pertaining to mechanical and microstructural traits of an Al-8% SiC composite fabricated using chill casting, sand casting, and squeeze casting techniques. A comparative analysis of the granular morphology in chill-cast versus sand-cast *products* has gotten bigger, so they are used to make reduced durability parts for technical applications and general-purpose use. Squeeze casting, on the other hand, might still be used in its cast state for industrial needs that need high-quality parts [17]. Ismail Oezdemir et al. (2000) hot-forged an Al-Si alloy with added SiC particles. Forging created a more even spread of SiC particles and silicon structures compared to regular casting. This led to higher strength and better performance under tension in both the base alloy and composite. Forged parts outperformed cast ones in all mechanical tests [18].

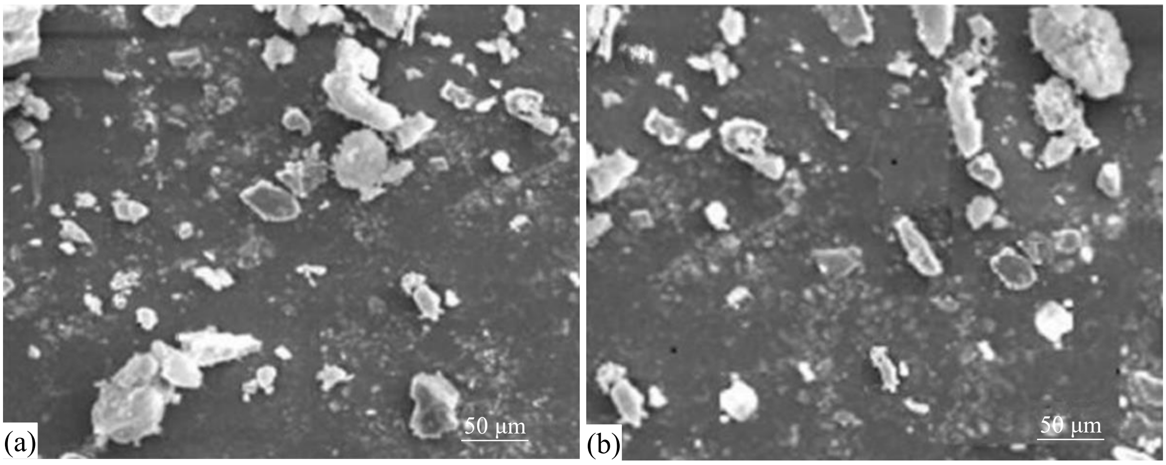

Figure 2. Microstructures of Al5083 alloy composite reinforced with (a) 5% SiC with UST (b) 5% SiC without UST [38]

Table 1. Mechanical properties of cast products under different casting methods and conditions.

Cating method	Squeeze pressure, MPa	Pouring Temperature, °C	Number of grains at magnification x100, N	UTS, MPa	Proof stress MPa	Hardness HRF	Elongation %
Sand cast products	0	650	11.98	102	40	35.5	2.3
		700	9.89	88	38	34.5	2.2
		800	8.33	65	35	33.0	2.0
Chill cast products	0	650	21.88	115	105	39.5	2.7
		700	20.31	115	106	40.0	2.4
		750	19.27	114	104	40.5	2.5
Squeeze cast products	75	650	49.48	146	128	46.0	3.4
		700	50.52	182	147	50.0	3.6
		750	51.56	209	147	53.5	3.4
	100	650	60.42	158	136	46.5	3.4
		700	67.19	219	153	55.0	3.8
		750	65.63	215	150	54.5	3.6
	125	650	67.19	184	140	50.0	3.6
		700	88.02	232	156	58.0	3.8
		750	75.00	226	152	57.5	3.8
	150	650	71.36	210	145	53.5	3.6
		700	88.55	232	156	58.0	3.8
		750	76.05	225	152	58.0	3.6

INFLUENCE OF SQUEEZE CASTING FABRICATION TECHNIQUE ON THE MECHANICAL AND MICROSTRUCTURAL CHARACTERISTICS OF ALUMINUM-MATRIX COMPOSITES

R. Srinivasann et al. (2024) Combining ultrasonic vibration (60 µm) and squeeze pressure (50–100 MPa) enhanced Ti/Al composites: Vickers hardness (+8.6%), yield (+18.7%), and tensile strength (+3.2%) vs. gravity casting. Squeeze pressure reduced grain size (90→60 µm), but excessive pressure coarsened microstructures, weakening properties. Optimal 100 MPa + ultrasonic achieved fine grains and peak strength, ideal for high-performance recycled Ti/Al composites.

Zhang Wei-Wen et al. (2007) studied pressure die-cast Al-Si-B_4C composites (30–80 MPa), noting non-uniform particle distribution: B_4C clustered near mold walls early in solidification but shifted toward the center as α-Al grains grew, especially in alloys with wider solidification ranges. Trace Ti additions suppressed B_4C-Al interfacial reactions [22].

Ali Mazahery & Mohsen Ostad Shabani (2012) fabricated A356-B_4C composites (1–5 µm, 5–15 wt%) via mechanical stirring and squeeze casting (80 MPa, 600 rpm, 300°C mold). K_2TiF_6 flux enhanced B_4C-Al wettability. Microstructure revealed B_4C dispersion in dendritic zones with particle-free regions. Higher B_4C content increased elastic modulus, strain hardening, and UTS but reduced ductility (brittle fracture, no necking) [23].

Young-Ho Seo & Chung-Gil Kang (1995) squeeze-cast Al-Si-15%SiC (22 µm) at 70–130 MPa. Optimal stirring: 750 rpm, 5 min, 680–700°C. Pressure boosted SiC-Al bonding, raising tensile strength by 10% (max at 100 MPa) and hardness peaking at 130 MPa [24].

Natrayan et al. (2020) optimized AA6061-Al_2O_3-SiC composites via squeeze casting using Taguchi's L16 orthogonal array. Testing four parameters, optimal settings (100 MPa pressure, 20s holding time, 750°C melt, steel die) maximized mechanical properties [25]. Rajan et al. (2007) compared three methods for Al-7Si-0.35Mg/fly ash composites: liquid stir casting, compo casting (semi-solid), and modified compo-squeeze casting. Modified compo-squeeze achieved optimal fly ash dispersion (porosity-free) with minimal interfacial $MgAl_2O_4$/Fe intermetallics. Compression strength improved, but tensile strength dropped due to particle fracture/debonding. Liquid stir casting caused severe reactions; modified compo-squeeze outperformed others for structural integrity [26].

Kalkanli & Yilmaz (2008) squeeze-cast Al-7075 with 10–20% SiC (80 MPa, 750–780°C melt, 280–300°C mold). Despite minor SiC clumping, composites were porosity-free. Optimal 10% SiC achieved peak flexural strength: 450 MPa (as-cast, +10%) and 588 MPa (heat-treated, +44%). Hardness rose with SiC content (as-cast: 133→188 HV; heat-treated: 171→221 HV), proving squeeze casting's efficacy for high-strength Al-SiC composites [27].

Gurusamy (2015) demonstrated that melt and die temperature control critically influences the mechanical properties and microstructure of A356 aluminum alloy, emphasizing the role of thermal parameters in optimizing casting quality.

Zhang Wei-Wen et al. (2007) analyzed pressure die-cast Al-Si-B_4C composites (30–80 MPa), observing that B_4C particles initially concentrated near mold walls during early solidification but migrated toward the casting center as α-Al grains grew. This clustering intensified in alloys with wider solidification ranges. To counteract interfacial reactions between B_4C and aluminum, titanium (Ti**)** was added, effectively suppressing harmful intermetallic formation and stabilizing the composite [22]

Ostad Shabani & Mazahery (2012) squeeze-cast A356-B_4C composites (1–5 µm, 5–15 wt.%) at 80 MPa, 300°C mold, and 600 rpm/20-min stirring. K_2TiF_6 flux enhanced B_4C-Al bonding. B_4C clustered along dendrites, creating particle-free zones. Strength (elastic modulus, UTS) rose with B_4C content, but ductility plummeted (no necking, brittle fracture) [23].

Seo & Kang (1995) squeeze-cast Al-Si-15%SiC (22 µm) at 70–130 MPa. Optimal stirring: 750 rpm, 5 min, 680–700°C. Pressure boosted SiC-Al bonding, raising tensile strength by 10% (max at 100 MPa) and hardness peaking at 130 MPa [24].

Natrayan et al. (2020) optimized AA6061/Al_2O_3/SiC composites via squeeze casting using Taguchi's L16 orthogonal array to test four parameters: squeeze pressure (100 MPa), holding time (20 s), melt temperature (750°C), and die material (steel). Results confirmed these settings maximized mechanical properties, demonstrating the method's efficacy in refining composite performance through controlled process variables [25].

Rajan et al. (2007) compared three methods (liquid stir casting, compo casting, hybrid compo-squeeze) for Al-7Si-0.35Mg/fly ash composites. Hybrid compo-squeeze achieved optimal fly ash dispersion (minimal porosity) and highest compressive strength but reduced tensile strength due to particle fracture. Liquid casting caused severe interfacial reactions ($MgAl_2O_4$/Fe intermetallics), while hybrid casting balanced properties for structural use [26].

CONCLUSION

Squeeze casting has emerged as a cornerstone for fabricating high-integrity aluminum matrix composites (AMCs), overcoming the pitfalls of conventional methods like porosity and particle agglomeration. This review synthesizes 20+ studies to establish optimal parameters (95–105 MPa pressure, 650–800°C melt temperature) and reinforcement strategies (≤10 wt.% hybrid Al_2O_3/SiC, flux-assisted bonding) that yield superior mechanical-tribological properties. Rajan et al.'s (2007) compo-squeeze method and Natrayan et al.'s (2020) Taguchi-optimized parameters exemplify the technique's adaptability for industrial applications, achieving tensile strengths up to 232 MPa and wear resistance improvements of 78%. By refining microstructures (e.g., grain size reduction from 90 to 60 µm) and enhancing interfacial bonding.

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