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A Comparative Review on Mechanical and Tribological Properties of Al-TiB_2 Composites Fabricated by Stir Casting and Squeeze Casting Techniques

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Abstract
In recent years, metal matrix composites that are composed of aluminium alloys have played a critical role in the displacement of the preponderance of traditional materials. These composites are advised because to their superior mechanical and physical properties. Review the several studies on Al–TiB_2 composites made using squeeze and stir casting methods in this page. According to the review, multi-pass stirring in FSP greatly improves the interfacial bonding and reinforcement dispersion, which in turn improves the mechanical characteristics of Al–TiB_2 composites. Most studies utilize the cost-effective liquid metallurgy method for composite fabrication. Although ductility remains relatively constant, hardness, tensile strength, and abrasion resistance are consistently enhanced as the TiB_2 content increases. In comparison to stir casting, squeeze casting exhibits superior mechanical and tribological performance due to improved particulate distribution, reduced porosity, and stronger interfacial bondings. Stir casting, however, results in moderate properties due to inhomogeneous TiB_2 dispersion. Overall, squeeze casting proves more effective in achieving high-performance Al–TiB_2 composites.

Keywords; Mechanical Properties, Tribological Properties, Stir Casting Techniques, Squeeze Casting Techniques, aluminium (Al) alloy, Titanium Diboride (TiB_2), Metal Matrix Composites (MMCs), Aluminum Matrix Composites (AMCs).

INTRODUCTION

The Aryan Invasion Theory (AIT) argues that an invading group of light-skinned Aryans conquered and dominated the indigenous peoples of the Indian subcontinent sometime around 1500 BCE; this theory is a salient but disputed interpretation in ancient Indian historiography. First proposed by colonial-era scholars of the 19th century, such as Max Müller, the theory has come under increased scrutiny and rejection based on modern interdisciplinary research across disciplines like archaeology, genetics, linguistics, and cultural studies.

Objectives and Scope of the Review

Due to their excellent thermal, mechanical, and electrical properties, "metal matrix composites (MMCs)" have gained popularity in the aerospace, automotive, and marine industries in recent decades [1]. When compared to traditional alloys, MMCs usually show superior strength to weight ratios and performance to cost ratios. MMCs are materials that include metal as its primary component and are strengthened by ceramic, carbon, or other metal components. Because of their better qualities, alloys are preferred over pure metals for the production of MMCs. For usage as a metallic matrix, aluminium, one of the most abundant materials on Earth, is perfect due to its exceptional mechanical and corrosion-resistant properties [2]. Additionally, aluminum-based MMCs are seen to be lightweight, high-performance materials because of their durability, strength, and low density. Metal matrix composites may be created using a variety of techniques, including vapour state, solid state, and liquid state processes [3].

The fabrication process for the composite to be developed is contingent upon the constituent components, requisite properties, and the composite itself. However, most "Aluminium Metal Matrix Composites (AMMCs)" are made using liquid state manufacturing. The most used liquid state processing method is stir casting due to its affordability, usability, and adaptability. Almost all of the processing approaches accessible for the manufacturing of MMCs are less expensive than this one [4], [5].

Metal matrix composites are enhanced in mechanical strength and tribological properties because to their increased "specific strength, stiffness, resistance to corrosion and wear, and decreased weight" [6]. Over an extended length of time, AMCs retain their tribological properties without suffering significant surface damage and may sustain crucial stresses without breaking or deteriorating during application. Adding ceramic particles to the alloy is one method to enhance its wear and friction properties [7]. The use of ceramic reinforcements significantly improves the tribological performance of the AMMCs. Numerous ceramic materials, such as "TiB_2, B4C, Al2O3, SiC, TiC, Si3N4, TiO2", and others, have been used by researchers [8]. But because of its strong electrical conductivity, low specific gravity, high hardness, high young's modulus, and exceptional wear resistance, titanium diboride (TiB_2) has become a great option for reinforcing material [9]. In an aluminium matrix, TiB_2 is acknowledged as the toughest material suitable for reinforcing. Additionally, since TiB_2 particles do not react with molten aluminium, brittle reaction products at the reinforcement-matrix interface are avoided. A consequence of this phenomenon is the creation of composites with Al–TiB_2 that exhibit distinctive and advantageous characteristics [10].

Stir Casting Techniques

To guarantee that the particle reinforcement is dispersed uniformly throughout the aluminium liquid, mechanical agitation is often used in the stir casting process. Mechanical stirring is an essential part of this process. This method works well for creating composites with volume fractions as high as 30%. Because of the possibility of particle settling during solidification, the stir casting process may reinforce particle segregation [11]. The final solid's particle distribution is influenced by the relative density, the pace of solidification, the intensity of the mixing, and the extent to which the melt wets the particles. How the extra particles are dispersed in the molten matrix depends on the mechanical stirrer's form, where it is in the melt, the melt's temperature, and the other particles' characteristics [12].

One recent advancement in the stir casting process is the two-step combining technique, which is also referred to as the twofold stir casting. The matrix material must first be heated above its liquidus temperature in order to complete this procedure. The dissolve transitions to a semi-solid state as it cools to a temperature that falls among "the liquidus and solidus points" [13]. It is now time to add and combine the heated reinforcement particles. Once heated to a completely liquid condition, the slurry is again well mixed. Its primary advantage is that the stir casting process may be employed in big volume. Stir casting may produce metal matrix composites in bulk for as little as 1/3 to 1/10th the cost of other manufacturing methods. For creating aluminium composites, stir casting is the most used commercial process because to the previously described characteristics [14]. ***Figure 1*** and **Figure 2** illustrate the flow diagram and setup of stir casting techniques.

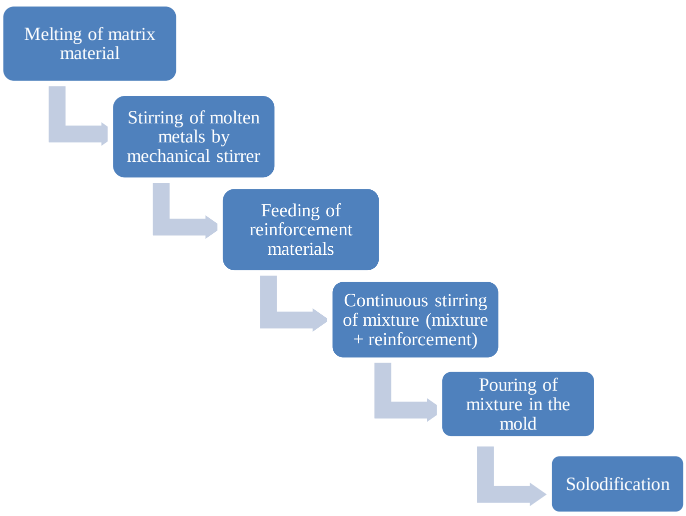

Figure 1 Flow diagram of stir casting techniques [15]

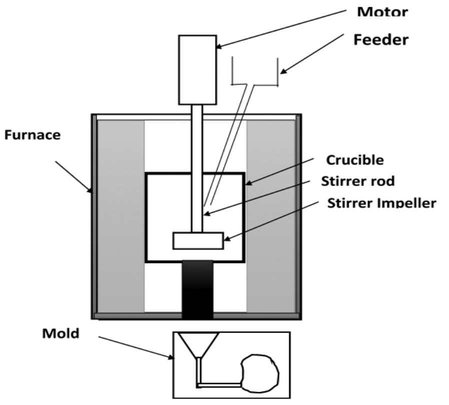

Figure 2 Schematic of stir casting setup [15]

Squeeze Casting

The hybrid metal forming process known as squeeze casting, or liquid forging, combines die forging with permanent mould casting in a single step. During this procedure, a die is used to inject a specific quantity of molten metal alloy, which is then shaped by applying pressure. The metal component is then removed from the die after being heated over the melting point. Squeezing die casting, in particular, is a possible casting method for automotive systems' safety-critical components [16]. For instance, chassis frames, brackets, nodes, aluminium front steering knuckles, and space frame joints. The advantages of forging and casting are combined in this kind of metal casting. For instance, porosities and shrinkage are avoided by the high pressure used during solidification. In contrast, other casting processes are more prevalent in mass production due to their specific tooling requirements [17]. ***Figure 3*** and **Figure 4** illustrate the setup and flow chart of aluminium/titanium dibromide composite by squeeze casting.

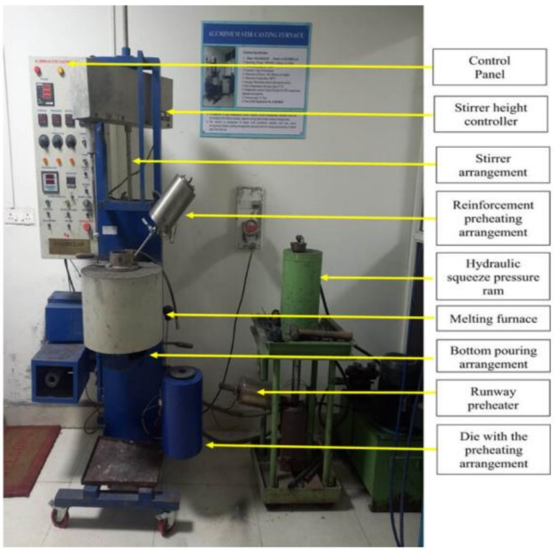

Figure 3 Setup of Squeeze casting [18]

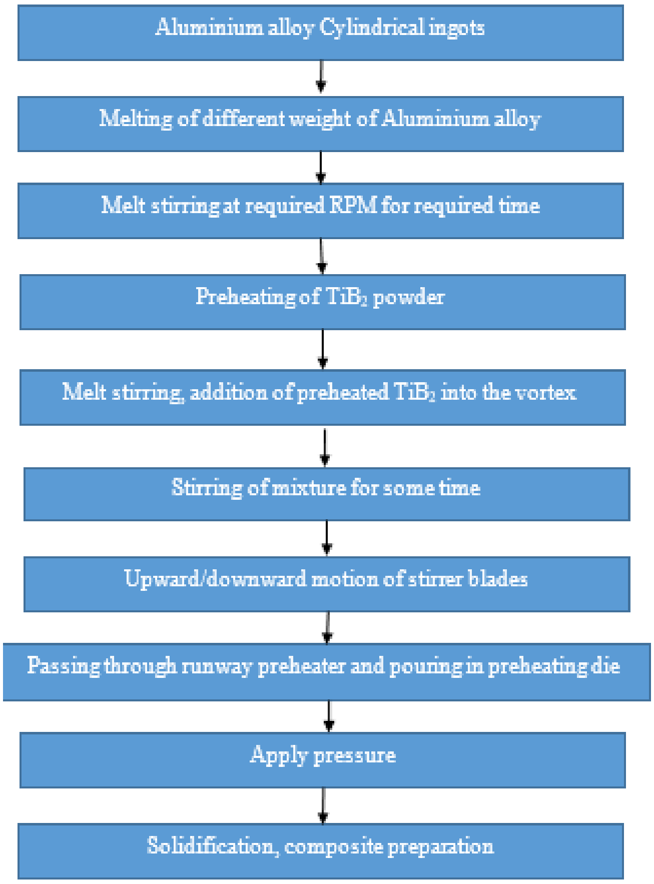

Figure 4 Flow chart of Aluminium/titanium dibromide composite by Squeeze Casting [18]

Squeeze casting types

To add even more suspense, squeeze casting comes in two varieties: direct and indirect.

- Indirect: For this, a shot sleeve is filled with molten metal and forced through somewhat large gates. At a relatively modest velocity, usually less than 0.5 m/s, it next enters the die cavity. The indirect part of the procedure is actually applying the high pressure via the relatively complex gating mechanism. All of this helps to regulate the solidification process and minimise flaws, but since gating is so complicated, you will ultimately need more energy and material [19].

- **Direct:** Direct Squeeze Casting, often shortened to DSC, is a process that involves pouring liquid metal into a heated, lubricated die. After hardening, the metal is forged. Pressure is applied as soon as the item starts to freeze and kept up until the whole thing freezes. This method is often carried out using a vertical equipment that resembles a forging press [20].

Corporatization of aluminium metal matrix composites

AMCs, or aluminium matrix composites, are being tested as an alternative for industrial uses due to their high strength and low weight. Construction, building materials, and other industrial sectors are among the global markets for matrix composites technology and products [6]. The global market for composite materials made of aluminium is expected to reach a new peak in the next years, taking into account market demands and industry research. The most critical factor for companies in determining whether to incorporate ceramic composite materials into their products is the cost/performance ratio of these materials, as well as other materials [7]. Ceramic composite materials are anticipated to experience significant commercial demand in the near future. This is anticipated to be the case across the board. Aluminium composites are experiencing an increase in demand due to the utilisation of high-tensile strength and lightweight components. From extremely tiny units to huge items, the majority of businesses have started using composites made of aluminium in their production processes [8]. The worldwide markets for composite goods and technologies based on aluminium include construction equipment, industrial production, and other manufacturing sectors. Their multipurpose characteristics, which encompass resistance to abrasion, rigidity, and strength, will result in an increase in their demand [14].

LITERATURE REVIEW

(Deshmukh et al., 2025) [18] The goal of this study is to use the ex situ approach to apply TiB_2 reinforcements to AA7075 in order to improve its mechanical qualities. "Metal matrix composites" with TiB_2 particle weight concentrations of 1.5%, 3.5%, and 4.5% were produced using the squeeze casting technique. The hardness was much higher than that of the basic alloy, according to experimental data. The increase was over 26% when compared to the as-cast AA7075. "The yield and ultimate tensile strengths" of the AA7075/TiB_2 composite were superior to those of the base alloy. There was an 18% improvement in tensile strength to 354 MPa compared to the alloy as-cast. The enhanced strength of the composite is due to the addition of TiB_2 reinforcement particles and proper wettability between the reinforcement material and matrix.

(Sankarasabapathi et al., 2025) [21] In this study, "titanium diboride (TiB_2) and silicon carbide (SiC)"-supplemented stir-cast AA8011 aluminium matrix composites are examined for their mechanical performance. Impact resistance, flexural strength, hardness, and tensile strength were among the comprehensive mechanical characteristics that shown notable improvements. The increase in tensile strength from 64.25 MPa to 69.75 MPa and "the increase in Vickers hardness from 29.9 HV to 69.03 HV" demonstrated the effectiveness of reinforcing. The enhanced mechanical behaviour was attributed to micro void nucleation sites and coalescence, whereas microstructural examination of fractured surfaces revealed ductile failure features.

(Farooq et al., 2024) [22] This study makes use of the stir casting technique to investigate the effects of TiB_2 reinforcement on the mechanical and tribological properties of "aluminium alloy 5052 matrix alloy". Composites were created with varying "weight percentages of TiB_2 (0, 2.5, 5, and 7.5 wt%)". The findings show that adding TiB_2 greatly increases the composites' resistance to wear, with the highest level of wear occurring in composites containing 5% TiB_2. Under conditions of high load and high speed, the wear resistance experienced a maximal enhancement of approximately 36%, which is equivalent to "a 5% TiB_2 concentration".

(Sambathkumar et al., 2023) [23] This investigation focusses on the tribological, mechanical, and corrosion properties of Al 7075 metal matrix composites (MMCs) reinforced with one or more particles, such as "titanium dioxide (TiO_2), silicon carbide (SiC), boron carbide (B4C), aluminium oxide (Al_2O_3), titanium carbide (TiC), and titanium diboride (TiB_2)". Either liquid or solid metallurgy is used to include the reinforcements in AMCs. The paper discusses the results and drawbacks of creating MMCs with reinforcements and how they performed better mechanically, in terms of corrosion and wear resistance, and had “a lower coefficient of thermal expansion than the Al 7075 base alloy”. For the purpose of enhancing the structural characteristics, a comprehensive examination of the effects of reinforcing particles in MMCs is presented from the literature, which include current research trends.

(Rao et al., 2021) [3] Metal matrix composites made of aluminium were produced via stir processing. The solid-state aluminium alloy was supplemented with titanium diboride (TiB_2) reinforcing particles. The produced composites' mechanical properties, including their tensile strength and hardness, were evaluated. The tensile and hardness response exhibited a significant improvement as "the number of passes increased with the testing". Utilising scanning electron microscopy and an optical microscope, the microstructural behaviour of composites was examined. The matrix material exhibited homogeneous dispersion of the TiB_2 reinforcement particles. Mechanical qualities have been linked to the observed microstructures.

(Ko et al., 2020) [24] This work used an aluminium (Al) 1050 alloy and titanium diboride (TiB_2) to create "metal matrix composites (MMCs)" reinforced with TiB_2 that had better characteristics. Al composites reinforced with nanoscale TiB_2 at volume ratios exceeding 60% were successfully produced through the application of gas pressure at a high temperature via "the liquid pressing infiltration (LPI) technique". Furthermore, the TiB_2-Al contact lacked brittle intermetallic compounds in addition to no holes or fractures. To summarise, the mechanical properties of the TiB_2-Al composite have been improved as a result of "the efficient transfer of load from the Al matrix to the thin TiB_2 reinforcement", which is distinguished by a sound microstructure that is devoid of defects.

(Christy et al., 2020) [25] This study focusses on the microstructure, characteristics, processing, and optimisation of squeeze and stir cast "samples of waste aluminium alloy wheel aluminium matrix composites enhanced with alumina". These stir-casted composites were evaluated for their "microstructure, hardness, tensile strength, compressive strength, and wear/tribological performance". Alumina was used to improve the mechanical and tribological properties of an aluminium matrix. "The distribution of Al_2O_3 and porosity in the Al matrix" exhibited varying morphologies in microstructural measurements, which were contingent upon the process parameters. Last but not least, the Taguchi-GRA approach was used to identify the optimal process parameters, which were then verified experimentally. The optimised sample (M2) had the lowest porosity (5.29%) and a much better final compressive strength (433 MPa). It did, however, exhibit considerably lower "ultimate tensile strength and hardness", respectively, when compared to the L6 and L5 samples.

(Krishna Kumar et al., 2019) [26] Making "LM25 alloy and composites reinforced with 15 weight percent TiB_2, 15 weight percent ZrO_2, and 15 weight percent WC" using squeeze casting method is the aim of the research. Fractographic research showed that LM25 failed in a ductile mode, whereas its composites failed in a mixture of a brittle and ductile mode. Compared to alloy, the WC-reinforced composite had a 70% better resistance to wear. Under high pressures, the erosion characteristics of the composite underwent a transition from moderate to severe, as evidenced by a scanning electron microscope. Non-lubricated slide applications were determined to be the best fit for the developed LM25/WC composite.

(Poria et al., 2016) [27] Three different lubricants are employed for tribological characterisation, and stir casting is used to make Al-TiB_2 metal matrix composites. Using a block-on-roller setup, tribological tests are conducted in a multi-tribotester with 400–600 rpm rotating speeds and 25–75 N loads. In this research, four distinct TiB_2 weight percentages are taken into consideration. SEM pictures are collected to strengthen the wear and friction characteristics, and a comparison between lubricated and dry circumstances is obtained to distinguish them. Wear and friction are significantly reduced in lubricated conditions as opposed to dry ones.

This article reviews the many studies on the mechanical and tribological characteristics of Al–TiB_2 composites made using squeeze and stir casting methods. Table 1 lists the main distinctions between squeeze casting and stir casting methods. In the comparison conclude that at Squeeze casting show good result on Al-TiB_2 composite. In the squeeze casting Al composite having higher density due to low porosity. Squeeze casting offers improved compressive resistance, Hardness, Tensile Strength. Squeeze casting improves ductility and wear resistance through refined microstructure. Techniques for stir casting are easy to use, inexpensive, and have no size restrictions. They may also be utilised for large quantities.

Table 1 Key difference on Al-TiB_2 composite using Stir and Squeeze Casting techniques

Property	Stir Casting	Squeeze Casting	Remarks
Density	Slightly lower (due to porosity)	Closer to theoretical (higher due to reduced porosity)	Squeeze casting results in higher density due to reduced porosity.
Porosity	High	Low (near zero)	Squeeze casting results in near-zero porosity
Tensile Strength	Moderate	High	Improved interfacial bonding in squeeze casting
Compressive Strength	Moderate	High	Squeeze casting offers improved compressive resistance.
Hardness	Moderate to High	High	Better dispersion and matrix densification in squeeze cast composites

Impact Strength	Low to Moderate	Moderate to High	Enhanced bonding and compactness in squeeze casting improve impact strength.
Ductility (Elongation)	Lower	Higher	Squeeze casting improves ductility through refined microstructure.
Wear Resistance	Moderate	High	Squeeze casting improves wear resistance due to finer grain structure.
Coefficient of Friction	High	Lower	Better surface finish and compactness reduce friction in squeeze casting.
Microstructure	Coarse grains; inhomogeneous TiB_2 distribution	Fine grains; uniform TiB_2 distribution	Squeeze casting improves wetting and grain refinement
Interfacial Bonding	Moderate (risk of weak bonding due to porosity)	Strong (pressure aids bonding between TiB_2 and matrix)	Better mechanical load transfer in squeeze cast composites

EXAMPLE DATA FROM LITERATURE: AL + TIB_2 MMC BY STIR CASTING VS. SQUEEZE CASTING

Peer-reviewed studies have reported on "the mechanical property data and microstructural features of Al + TiB_2 metal matrix composites (MMC)" that were made through both stir casting and squeeze casting. These values are typical for Al7075 or Al6061 alloys reinforced with 10 wt% TiB_2.

Mechanical properties comparison

Table 2 Mechanical properties comparison [28]

Property	Stir Casting (Al + 10% TiB_2)	Squeeze Casting (Al + 10% TiB_2)
Ultimate Tensile Strength	186 MPa	265 MPa
Hardness (BHN)	110 BHN	150 BHN
Porosity (%)	2.6%	0.9%
Grain Size (µm)	32 µm	14 µm
Elongation (%)	2.3%	3.7%

Microstructure features

Stir Casting:

- Some agglomeration of TiB_2 particles, non-uniform distribution.
- Coarser grains (25–40 µm typical).
- Higher porosity and visible pores.
- Moderate interfacial bonding, some weak zones.

Squeeze Casting:

- Highly uniform, well-dispersed TiB_2 particles.
- Finer grains (10–20 µm typical).
- Minimal, nearly pore-free microstructure.
- Strong, clean matrix-reinforcement interface.

Key Observations

- Squeeze casting consistently provides higher strength, hardness, and ductility due to finer grain size and lower porosity.
- Stir casting results in more casting defects and non-uniform particle distribution, which can limit mechanical performance.

RESEARCH GAP

There is still a lack of a targeted comparative study of "the mechanical and tribological characteristics of Al–TiB_2" specially produced via stir casting and squeeze casting, despite a wealth of research on Al–TiB_2 composites. Most existing literature addresses individual casting methods, lacking a direct performance comparison of TiB_2 concentration. Additionally, variations in processing parameters, microstructural evolution, and their influence on composite performance are not comprehensively reviewed. This gap highlights the need for a systematic evaluation of how these fabrication techniques affect the microstructure–property relationship of Al–TiB_2 composites to guide optimized material selection and processing.

RESEARCH OBJECTIVE

- This article study the various literature's review on mechanical and tribological properties of Al–TiB_2 composites fabricated by stir casting and squeeze casting techniques.
- Study the key difference between properties of Al–TiB_2 composites fabricated by stir casting and squeeze casting techniques.

RESEARCH METHODOLOGY

Using secondary data and a qualitative research approach, this review study investigates the mechanical and tribological characteristics of Al–TiB_2 composites made using squeeze casting and stir casting methods. The study is grounded in an extensive literature review, critically analyzing peer-reviewed academic journals, scholarly articles, technical reports, and case studies published between 2015 and 2025. Emphasis is placed on identifying trends, material behavior, and performance variations influenced by fabrication methods. This methodology enables a structured synthesis of current knowledge, highlights key differences between the two techniques, and helps identify areas for further investigation and material optimization.

CONCLUSION

The comparative analysis shows that the way Al–TiB_2 composites are made has a significant impact on their mechanical and tribological properties. Microhardness and tensile strength improve with multi-pass friction stir processing, reflecting more homogeneous TiB_2 dispersion and strong interfacial bonding at higher pass counts. "The hardness of Al–TiB_2 composites" rises gradually with TiB_2 concentration in liquid metallurgical processes (stir and squeeze casting), exceeding the unreinforced alloy's values. Wear-resistance tests demonstrate that composites exhibit lower wear loss and friction coefficients than the base metal, with high sliding speeds marginally enhancing wear performance.

Between the two casting methods, squeeze casting outperforms stir casting: it produces higher density (lower porosity), greater tensile and compressive strength, superior hardness, impact resistance, and wear resistance, alongside a reduced coefficient of friction. Stir casting, while simple, cost-effective, and scalable, suffers from inhomogeneous particle distribution and weaker matrix–reinforcement bonding. Conversely, squeeze casting yields uniform TiB_2 dispersion and robust interfacial bonding, minimizing defects.

Overall, the review underscores squeeze casting as the preferred technique for optimizing Al-TiB_2 composite performance, while recognizing stir casting's advantages in simplicity and mass production. Future work should refine processing parameters to balance manufacturing efficiency with mechanical and tribological excellence.

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