IN-SITU STIR CASTING OF ALUMINUM-BASED METAL MATRIX COMPOSITES: A COMPREHENSIVE REVIEW

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ABSTRACT

Aluminum (Al) composites have emerged as a promising material for high-performance applications due to their exceptional strength-to-weight ratio, affordability, and excellent wear resistance. These composites are widely used in structural applications, such as aerospace and automotive industries, where their unique properties offer significant advantages.The simplicity and cost-effectiveness of the manufacturing process are crucial for expanding their applications. Ceramic reinforcements like ZrB_2, TiC, and Al_2O_3 can be easily incorporated into molten metal using the in-situ stir casting method, resulting in enhanced mechanical and tribological properties.This review aims to summarize the current developments in Al composite processing via in-situ stir casting, highlighting the benefits of reinforced particles in improving the material's performance.

Key words: Aluminum composite; In-situ method; Reinforcement.

INTRODUCTION

The automotive and aerospace industries demand materials with exceptional strength-to-weight ratios. Aluminum (Al) matrix composites, fabricated through casting, meet this requirement with their outstanding mechanical properties, workability, surface finish, corrosion resistance, and wear resistance [1].Aluminum-based composites are leading materials in this field, produced using various methods, including casting, powder metallurgy, and forming processes. The in-situ process allows for easy control of material properties by adjusting reinforcement volume fractions or weight ratios [2-3].

Components made from Al composites, formed through shape casting and in-situ reaction, exhibit superior mechanical properties. Elements like grain refinement and eutectic modification enhance these properties.In-situ synthesis of reinforcements in the metal matrix offers advantages like thermodynamic stability, strong reinforcement-matrix interfaces, and low fabrication costs [4-5]. For instance, Al6061 alloy, with low density and high thermal conductivity, is reinforced with TiB_2 to improve hardness, Young's modulus, and wear resistance [6-7].

In-situ metal matrix composites (MMCs) demonstrate excellent mechanical properties at room and high temperatures, surpassing conventional engineering alloys. The in-situ formed reinforcements ensure strong interfacial bonding, free from contamination [8-9].Al composites have proven useful in various engineering fields, including functional and structural applications, due to their tailored mechanical properties. The cost-effective in-situ stir casting process has emerged as a relatively economical and easy-to-use method for manufacturing composites [10].This paper provides a comprehensive review of Al composite synthesis, focusing on their enhanced mechanical and tribological properties.

PROCESSING METHOD

STIR CASTING

The stir casting process involves distributing reinforcing phases, typically in powder form, into molten aluminum through mechanical stirring. This method was first introduced in 1968 by S. Ray who mixed alumina particles into molten aluminum alloys using ceramic powders.Mechanical stirring in the furnace is a crucial step in this process. The resulting molten alloy, containing ceramic particles, can be used for various casting methods, including:Die casting, Permanent mold casting and Sand casting.

Stir casting is suitable for producing composites with up to 30% volume fractions of reinforcement. To enhance the material's properties, the cast composites may undergo additional processing, such as:Extrusion to reduce porosity, Microstructure refinement and Homogenization of reinforcement distribution.

Stir casting is a liquid-state method for fabricating composite materials. It involves mixing a dispersed phase (ceramic particles or short fibers) with a molten matrix metal using mechanical stirring. The resulting liquid composite material can be cast using conventional methods and further processed using traditional metal forming technologies.

IN-SITU PROCESS

In recent years, a new in-situ process has emerged for fabricating Metal Matrix Composites (MMCs), aiming to overcome the limitations of traditional ex-situ methods. This innovative approach utilizes both liquid and solid phase routes to produce in-situ particle reinforced MMCs. The reinforcements are formed in-situ through an exothermic reaction between the matrix and precursor elements or compounds, resulting in (i) Clean and impurity-free interfaces, (ii) Finer reinforcement sizes, (iii) Uniform distribution and (iii) Enhanced mechanical properties.

In-situ processing offers significant technical and economic advantages over conventional methods, including stronger bond between matrix and reinforcement, avoidance of interfacial defects and improved mechanical behavior due to combined thermal and chemical effects. In-situ composites are multiphase materials where the reinforcing phase is synthesized within the matrix during fabrication, unlike ex-situ composites where the reinforcing phase is synthesized separately and inserted into the matrix later.

In-situ processes can create various reinforcement morphologies, including discontinuous to continuous reinforcements and ductile or ceramic phases. The potential advantages of in-situ composites over discontinuous metal ceramic composites produced by ex-situ methods are significant, making this innovative approach a promising direction for MMC fabrication.

PROCESS OF FABRICATION

3.1 REINFORCED OF ZRB_2-AL MMC

Recent studies have investigated the reinforcement of Aluminum (Al) matrix composites with Zirconium Boride (ZrB_2) particles. Dinaharan et al. [11] developed Al composites reinforced with ZrB_2 particles through an in-situ reaction between K_2ZrF_6 and KBF_4 salts and molten AA6061 alloy. The resulting composites exhibited refined microstructures and enhanced mechanical properties, with improvements observed in proportion to the increase in ZrB_2 content.

Further characterization of AA6061/ZrB_2 composites was conducted by [12] using Differential Thermal Analysis (DTA), X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM), and Transmission Electron Microscopy (TEM). The results showed that the density and hardness of the composites increased with the amount of reinforcement. The ultimate tensile strength improved continuously with the volume fraction of ZrB_2 particles up to 9 vol.%, beyond which strength decreased.Additionally, Yida Zeng et al. [13] developed Al6061/ZrB_2 composites through a direct melt chemical reaction using an Al-KBF_4-K_2ZrF_6 system. A laser surface melting strategy was employed to enhance the surface strength of the in-situ ZrB_2p/6061Al composite. The results demonstrated improved wear resistance in the laser-melted layer compared to the substrate and matrix AA6061. Notably, the wear mass loss of laser-melted composites decreased from 61 to 56 mg under a load of 98 N for 60 minutes, indicating a significant improvement in wear resistance.

3.2 REINFORCED OF TIC-AL MMC

Synthesis and Characterization of Al-TiCp Composites

In-situ synthesis of Al-TiCp composites was achieved through the reaction of K_2TiF_6 and graphite in molten aluminum. This process generates K-Al-F salts, which clean the particle surfaces and remove oxide layers, promoting the formation of TiC particles. Holding the melt at 1000 °C replaces Al_3Ti particles with TiC particles, resulting in improved wear resistance [14].

Optimized Synthesis of TiC/Al Composites

A novel method employing quick preheating treatment and high-intensity ultrasonic vibration was used to develop TiC/Al composites. This approach reduces the synthesizing temperature by approximately 150 °C compared to conventional methods. The resulting composites exhibit uniform TiC particle distribution, porosity below 1%, improved microhardness, and refined microstructure [15].

Mechanical Properties of Al-Cu Matrix Composites Reinforced with In-Situ TiC Particles Al-4.5 wt. % Cu matrix composites were reinforced with in-situ TiC particles synthesized via direct reaction synthesis (DRS). The results show that the formation of Al_3Ti phase increases hardness and improves tensile properties, attributed to grain refinement of the matrix [16].

3.3 REINFORCED OF MG_2SI-AL MMC

Synthesis and Characterization of Mg_2Si/Al Composites

Guangzhu Bai et al. synthesized an in-situ Mg_2Si/Al composite with the addition of lanthanum (La) and ultrasonic stirring at different powers during solidification. The results showed that the composite with 0.4 wt.% La and 150 W ultrasonic stirring exhibited improved mechanical properties such as Hardness: 132 HB, Tensile strength: 201 Mpa and Elongation: 5.28%

In contrast, the composite without La addition or ultrasonic stirring showed lower mechanical properties. This study demonstrated the potential of modifying the microstructure and enhancing the mechanical properties of in-situ Mg_2Si/Al composites for industrial applications [17].

Microstructural Evolution of Al-Cu/Mg_2Si Composites

The Al-Cu/Mg_2Si based in-situ composite was studied to understand the evolution of primary and secondary reinforcement phases. Scanning electron microscopy revealed the mechanical fragmentation, thermal disintegration, micro-buckling, coalescence, and spheroidization of primary and secondary particles [18].

Characterization of Al-15 wt. % Mg_2Si Composites

Al-15 wt. % Mg_2Si composites were prepared by in-situ casting and characterized for microstructure, hardness, and sliding wear behavior. The results showed that increasing the extrusion ratio improved hardness and wear resistance, accompanied by a decrease in average Mg_2Si particle size and porosity. The dominant wear mechanism was abrasion in extruded composites and a combination of adhesion and delamination in as-cast composites [19]

3.4 REINFORCED OF TIB_2- AL MMC

Fabrication and Characterization of Aluminum Metal Matrix Composites

Aluminum metal matrix composites were fabricated by reinforcing an Al-6Cu-0.2Mg-1Mn matrix with in-situ TiB_2 particulates. The composites underwent a series of heat treatments, including solution treatment and aging, which revealed that the in-situ TiB_2 particulates improved the matrix structure by retarding directional growth of matrix grainsand forming isometric grains in the matrix. The hardness of the treated composites was higher than that of the corresponding Al-6Cu-0.2Mg-1Mn alloys [20].

Mechanical Properties and Fatigue Analysis of Al6061-TiB_2 Composites

Al6061-TiB_2 in-situ composites exhibited high specific modulus and strength, excellent wear resistance, and high fatigue life. Fatigue analysis was performed using commercial FEA software (MSC-Patran, MSC-Nastran, and MSC-Fatigue), with material properties data experimentally determined. The results validated the MSC-Fatigue tool and showed that increasing the number of cycles decreases the component's life and Extruded samples have a longer life compared to cast counterparts [21]

Friction Stir Processing of AA6063/TiB_2 Composites

S.Y. Zhong et al. developed a homogeneous redistribution of nanosized TiB_2 particles in a fine-grained in-situ AA6063/TiB_2 composite using friction stir processing (FSP). The average microhardness in the nugget zone of the FSPed 6063/TiB_2 composite was higher than that of the FSPed 6063 alloy [22].

3.5 REINFORCED OF AL_2O_3-AL MMC

Development and Characterization of Al_2O_3-Reinforced Aluminum Matrix Composites

An aluminum matrix composite reinforced with Al_2O_3 particles was developed using the in-situ stir casting method by adding NH4AlO (OH) HCO_3 to molten aluminum. The study investigated the effects of mechanical properties and wear behavior of the as-fabricated composites. The results showed that (i) Stirring formed γ-Al_2O_3 particles via decomposition reaction of NH_4AlO (OH) HCO_3, (ii) Al_2O_3 particles were more uniformly distributed in the matrix aluminum compared to direct addition, (iii) Tensile strength and wear rate decreased with increasing particle volume fraction and (iv) In-situ formed Al_2O_3/Al composite exhibited superior mechanical and wear behaviors compared to directly added Al_2O_3 particles [23]

In-Situ Formation of Al_2O_3/Al Composite via CuO/Al Composite

An in-situ Al_2O_3/Al composite was produced by adding CuO to aluminum and subsequent remelting. The study investigated the chemical reaction evolution and fractography. The results showed that (i) Al_2O_3 was successfully formed in-situ by adding CuO to aluminum, (ii) Fracture mechanism changed from interfacial debonding in copper oxide/Al composite to particle cracking in Al_2O_3/Al composite and (iii) Interfacial bonding strength increased between in-situ Al_2O_3 particles and Al matrix, attributing to the change in fracture mechanism [24]

3.6 REINFORCED OF AL_3TI-AL MMC

Fabrication and Characterization of Al_3Ti-Reinforced Aluminum Matrix Composites

Titanium tri-aluminide (Al_3Ti) particles were homogeneously dispersed into a castable aluminum alloy matrix via aluminothermic reduction of hexafluorotitanate (K_2TiF_6) under varying conditions. The effects of temperature, holding time, alloying elements, and reinforcement dispersion on Al_3Ti particle morphology and size were examined using SEM and X-ray diffraction techniques. The results were attributed to differences in Al_3Ti particle growth behavior and dispersion, as well as Al/Al_3Ti interfacial bonding [25].

In-Situ Synthesis of Al/Al3Ti Composites

Al/Al_3Ti composites were prepared using a direct reaction method, where Al_3Ti was formed through the reaction of Ti and Al in aluminum alloy melt. The morphology of Al_3Ti changed significantly with increasing Al_3Ti content, from fine particles to needle-like and large block shapes. The addition of 3 wt. % Mg resulted in homogeneous distribution and refined microstructure of the Al/Al_3Ti composites [26].

CONCLUSION

In conclusion, the comprehensive review of in-situ stir casting aluminum-based metal matrix composites reveals several key findings as follows:

- The in-situ stir casting method is a viable and effective technique for fabricating metal matrix composites with tailored properties, offering a high degree of control over particle distribution and matrix-reinforcement bonding.
- Aluminum and its alloys exhibit excellent compatibility with ceramic reinforcement particles, resulting in uniform distribution and strong interfacial bonding, which is essential for enhancing mechanical properties.
- The incorporation of various reinforcement particles, such as ZrB_2, TiC, Mg_2Si, TiB_2, Al_2O_3, and Al_3Ti, into aluminum metal composites significantly improves hardness, yield strength, and tensile strength. However, this enhancement comes at the cost of reduced ductility, which must be carefully considered in the design and application of these composites.

Overall, the in-situ stir casting method offers a promising approach for developing high-performance aluminum-based metal matrix composites with tailored properties for various industrial applications.

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