



Review

Sustainable and Industry-Ready Metal Matrix Composites Produced by Stir Casting and Cryorolling: Process–Property Insights Enabled by Machine Learning—A Review

Haitham M. Alswat 

Department of Mechanical Engineering, College of Engineering, Shaqra University,
Dawadmi 11911, Riyadh, Saudi Arabia; halswat@su.edu.sa

Abstract

Metal matrix composites (MMCs) are one of the significant engineering materials for many industrial applications. The growing interest in MMCs stems from their strong mechanical properties, including their higher specific mechanical strength and excellent corrosion and wear resistance. From an industrial viewpoint, the ability of MMCs to undergo secondary processing is significant. This review aims to clarify the effects of cryorolling on the microstructure, mechanical properties and wear behavior of different aluminum-based MMCs. In particular, aluminum matrix composites (AMCs) produced through the stir-casting approach experience an additional cryorolling procedure to enhance their tensile mechanical strength and wear resistance. This hybrid manufacturing approach has shown promise in creating effective structural components. This review covers the production of ex situ aluminum-based composites formed by stir casting and then cryorolling. It also highlights how the particle size, volume fraction, and the cryorolling procedure affect the microstructure, wear, and mechanical properties. This approach could broaden the uses of hybrid manufacturing by demonstrating its practical advantages and efficiency. Furthermore, this review highlights the importance of implementing machine learning (ML) models and life cycle assessment (LCA) in evaluating MMCs produced through stir casting.

Keywords: metal matrix composites; aluminum matrix composites; stir casting; cryorolling; mechanical properties; tribological properties; strength; wear resistance

1. The Production and Requirements of MMCs

Composite materials consist of two or more dissimilar constituents that do not dissolve into each other. This process enhances mechanical properties beyond those of the individual materials. The classification of composites is determined by the nature of the matrix and reinforcement. Based on the matrix material, composites are categorized into metal–matrix composites (MMCs), ceramic–matrix composites (CMCs), and polymer–matrix composites (PMCs). MMCs are recognized for resisting high temperatures and moisture. They also have better mechanical properties compared to other composites [1]. These composites employ a ductile metal or alloy matrix reinforced with metallic, non-metallic, organic, and inorganic materials. The different combinations of matrix and reinforcement used in MMC fabrication are shown in Figure 1. MMC fabrication targets improved specific strength, stiffness, and wear and corrosion resistance at reduced density [2]. Because of these valuable properties, MMCs are becoming increasingly significant in the aerospace,



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automotive, defense, and marine industries. This has led to significant research on MMCs, especially involving new manufacturing techniques [3]. Al and Mg are the most commonly used matrices in ceramic-reinforced MMCs. In addition, MMCs based on Fe, Cu, and Ti matrices reinforced with ceramics have been successfully fabricated. Ceramic-reinforced aluminum MMCs are generally favored over fiber-reinforced systems owing to their better cost-effectiveness. Additionally, fiber and whisker-based MMCs often show more uniform properties and less variation in their microstructure. Common ceramic reinforcements include SiC, B₄C, TiC, TiB₂, and Al₂O₃ (see Figure 1 for various types of reinforcements used). Ceramic-reinforced Al-MMCs show excellent wear and corrosion resistance due to their strong structure–property relationship. As the amount of reinforcement increases, tensile mechanical strength improves, but this comes with a significant reduction in elongation.

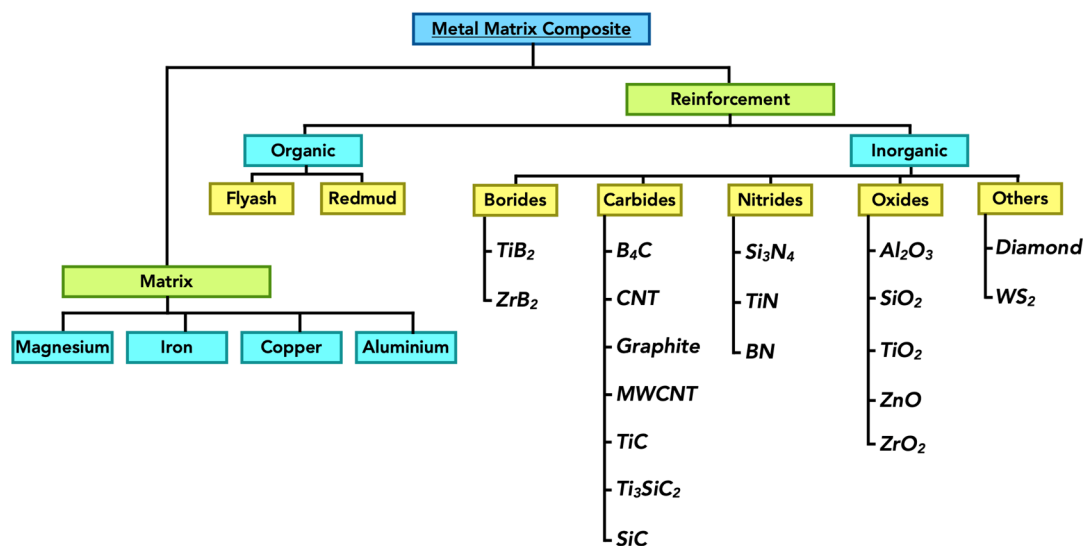


Figure 1. Different combinations of matrix and reinforcement are used in MMC fabrication.

2. Diverse Manufacturing Techniques for Al-MMCs and Their Corresponding Hurdles

Al-MMCs are produced based on the matrix state: liquid, solid, semi-solid, or in situ routes. MMCs with ceramic reinforcements have been produced by solid-state methods such as mechanical alloying and powder metallurgy. Liquid-state methods, such as stir casting, squeeze casting, centrifugal casting, infiltration, and various deposition techniques, have also been used. Solid-state methods face limitations in size and shape, higher costs, density variations, and sintering-related distortion, which can affect mechanical strength. In contrast, liquid-state methods provide advantages such as better bonding of matrix particles, easier processing, and improved control over the microstructure. Casting techniques generally produce well-bonded MMCs with great mechanical and wear-resistant properties. Stir casting has been widely adopted owing to its relatively low processing cost, ease of implementation, controllable reinforcement incorporation within the matrix, and feasibility for manufacturing large-volume metal matrix composites.

3. Stir Casting

Stir casting is a liquid-state manufacturing approach often used to generate metal matrix composites (MMCs). A simple setup for stir casting is shown in Figure 2. This procedure involves melting the metal matrix while mixing in reinforcement particles. As the mixture cools, it solidifies into MMCs. Several factors are significant for successful MMC production, according to Ramanathan et al. [2]:

- **Particle Size:** Smaller reinforcement particles are preferred to achieve better mechanical properties.
- **Temperature:** An ideal melt temperature is crucial. Higher temperatures enhance wettability but can diminish the viscosity of the metal matrix, which may lead to particle clustering. Conversely, lower melt temperatures can also cause clustering.
- **Stirring Speed and Duration:** The stirring speed must be controlled to prevent excessive resistance to particle movement. Finding a balance is essential since both very high and very low speeds can impact how well particles stay suspended. A longer stirring time helps achieve an even distribution of particles.
- **Impeller Profile:** The shape of the impeller significantly influences the stirring speed and duration. It also helps generate the vortex needed to blend the matrix and reinforcement materials effectively.

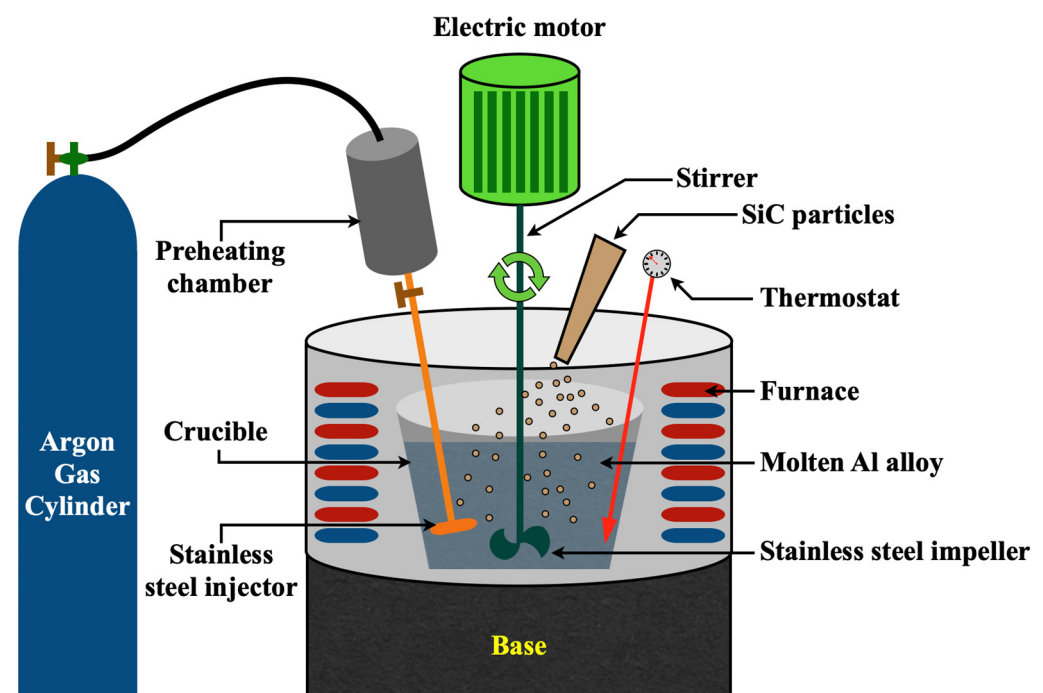


Figure 2. Stir-casting setup.

The steps involved in making MMCs through stir casting are:

1. Selection of metal matrix;
2. Charging the furnace;
3. Melting the matrix;
4. Continuous stirring of matrix metal;
5. Adding reinforcement particles to the molten metal matrix;
6. Continuous stirring of the metal matrix with reinforcement;
7. Pouring the mixture into a mold to solidify.

4. Requirements for Subsequent Post-Processing After Stir Casting

While stir casting has been effective for creating micro-sized Al-MMCs, producing nano-scale reinforced particles in Al-MMCs using the same approach has some limitations. These issues stem from poor wettability and the tendency of ceramic particles to clump together [2]. In addition, producing Al-MMCs containing nano-scale reinforcement particles is more challenging due to their increased surface area relative to micron-scale reinforcements [4]. A gaseous layer is formed on the surfaces of the reinforcement particles, leading to the creation of an interfacial gap between the molten matrix and the particles [5].

Both stirring and ultrasonic treatment have limited success in breaking up clusters of nano-sized reinforcement particles in the molten aluminum matrix, making it difficult to eliminate these clusters [6]. These challenges can lead to lower mechanical properties of Al-MMCs. Post-processing operations such as extrusion and rolling contribute to further improvements in the mechanical properties of Al-MMCs, enabling their use in aerospace, automotive, precision instrumentation, and other engineering applications [7].

In recent years, considerable research attention has been directed toward the development of Al-MMCs with ultra-fine-grained (UFG) microstructures. Such UFG Al-MMCs are typically fabricated using severe plastic deformation (SPD) techniques, including equal channel angular extrusion (ECAE), high-pressure torsion (HPT), friction stir processing (FSP), and accumulative roll bonding (ARB). While these methods can achieve a uniform distribution with a more consistent grain structure, their application is often limited to laboratory settings due to size constraints. Although large-scale production is possible with ARB, establishing strong bonding between layers in Al-MMCs remains a challenge.

Processing through powder metallurgy also has its challenges, such as an uneven distribution of reinforcement particles and the need for completely dense compacts. However, hybrid manufacturing methods that combine stir casting and cryorolling show promise in producing UFG Al-MMCs, as they can diminish dynamic recovery. Furthermore, this approach allows for the production of Al-MMCs suitable for large-scale industrial components without size limitations.

5. Cryorolling

Cryorolling is a rolling process performed at cryogenic temperatures (sub-zero), mostly using liquid nitrogen, in order to improve the mechanical properties of the material. The cryorolling procedure is shown in Figure 3. Before cryorolling, the material is placed in a liquid nitrogen bath maintained at $-196\text{ }^{\circ}\text{C}$ for about 30 to 45 min, depending on the thickness. Each rolling pass involves minimal rolling reduction (e.g., 0.1 mm) to minimize heating effects. After cryorolling, samples are stored in a deep freezer to prevent atmospheric influences, particularly in aluminum alloys. Throughout the rolling procedure, the roll speed is kept constant. The typical thickness reduction per pass was in the range of 5–10%, and the number of passes (20–40) was reported for cryorolled Al alloys and Al-MMCs. In addition, the total accumulated true strain can fall between $(\epsilon) \approx 2$ and 3, which is comparatively smaller when compared with other severe plastic deformation techniques [8].

Ultra-fine-grained materials with grain sizes less than $1\text{ }\mu\text{m}$ can be obtained through cryorolling. It is known for causing less deformation and forming a higher density of dislocations. Quantitative ranges of dislocation density (10^{14} – 10^{15} m^{-2}) are achieved under cryogenic rolling, contrasted with room-temperature rolling. Due to its improved mechanical properties, the cryorolled products are commonly used in the automotive and aerospace industries [9]. Rolling metallic materials at cryogenic temperatures reduces dynamic recovery. This approach achieves a higher level of dislocation density compared to rolling at room temperature. Cryorolling has become a significant approach for producing nanocrystalline or UFG pure metals like copper, aluminum, and nickel from bulk materials. This approach is advantageous due to its scalability, lower load demands, ease of processing, and suitability for producing long-length products. According to Wang et al. [10], cryorolling enables the fabrication of ultra-fine-grained copper at relatively lower temperatures than those required by other SPD methods. Shanmugasundaram et al. [11] studied the mechanical properties of cryorolled and post-annealed AA2219 alloy. They reported substantial improvements in yield strength (485 MPa) and ultimate tensile strength (540 MPa). Reduced-temperature ageing treatments of cryorolled age-hardenable alloys,

including AA7075 and AA2024, were investigated by Zhao et al. [12] and Cheng et al. [13], leading to notable improvements in mechanical properties. In recent studies, Sc-alloyed 5xxx aluminum alloys (Al–Mg–Sc–Zr) processed in cryogenic environments have garnered interest owing to their superior mechanical strength, ductility, and fracture toughness [14]. Cryorolled products, usually in the form of sheet metal, are effective structural materials in aviation, automotive parts, and storage tanks, among other uses. The contribution of various strengthening mechanisms to the yield strength of Al–MMCs produced through stir casting followed by cryorolling is given in Table 1.

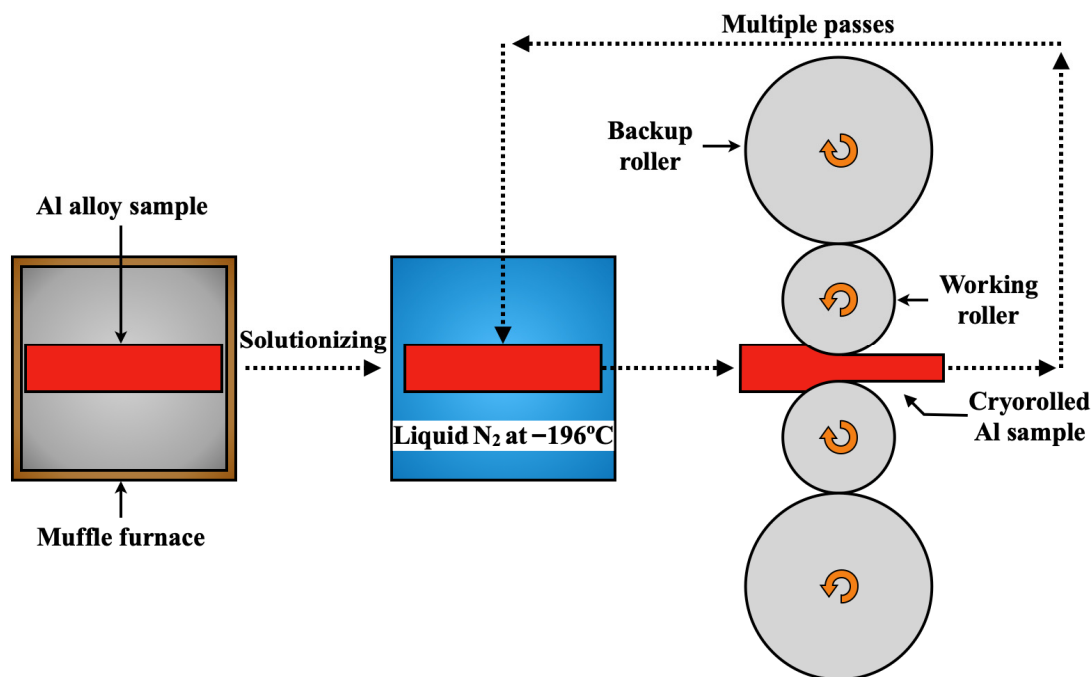


Figure 3. Cryorolling procedure.

Table 1. Contribution of various strengthening mechanisms to the total yield strength of Al–MMCs produced through stir casting followed by cryorolling based on the work of Krishna et al. [15].

S. No.	Mechanism	Typical Strength Contribution (MPa)	Sensitivity to Cryorolling
1	Solid Solution Strengthening ($\Delta\sigma_{ss}$)	20–50	Low
2	Grain Boundary Strengthening (Hall–Petch, $\Delta\sigma_{gb}$) $\Delta\sigma_{gb} = k_y d^{-1/2}$	120–180	High
3	Dislocation Strengthening ($\Delta\sigma_{dis}$) $(\Delta\sigma_{dis}) \propto Gb \sqrt{\rho}$	150–250	High
4	Dispersion Strengthening ($\Delta\sigma_{disp}$) $\Delta\sigma_{disp} = \eta V_r \sigma_m$	40–100	Moderate
5	Orowan Strengthening ($\Delta\sigma_{Or}$) $(\Delta\sigma_{Or}) = \frac{0.13Gb}{\lambda} \left(\frac{d_p}{2b} \right)$	20–70	Moderate

Figure 4 shows a schematic of the hybrid manufacturing route for making Al–MMCs. The MMCs are first produced by stir casting and then processed through cryorolling. The microstructural characteristics, wear behavior, and tensile properties of the Al–MMCs obtained via this hybrid approach are examined in the following sections.

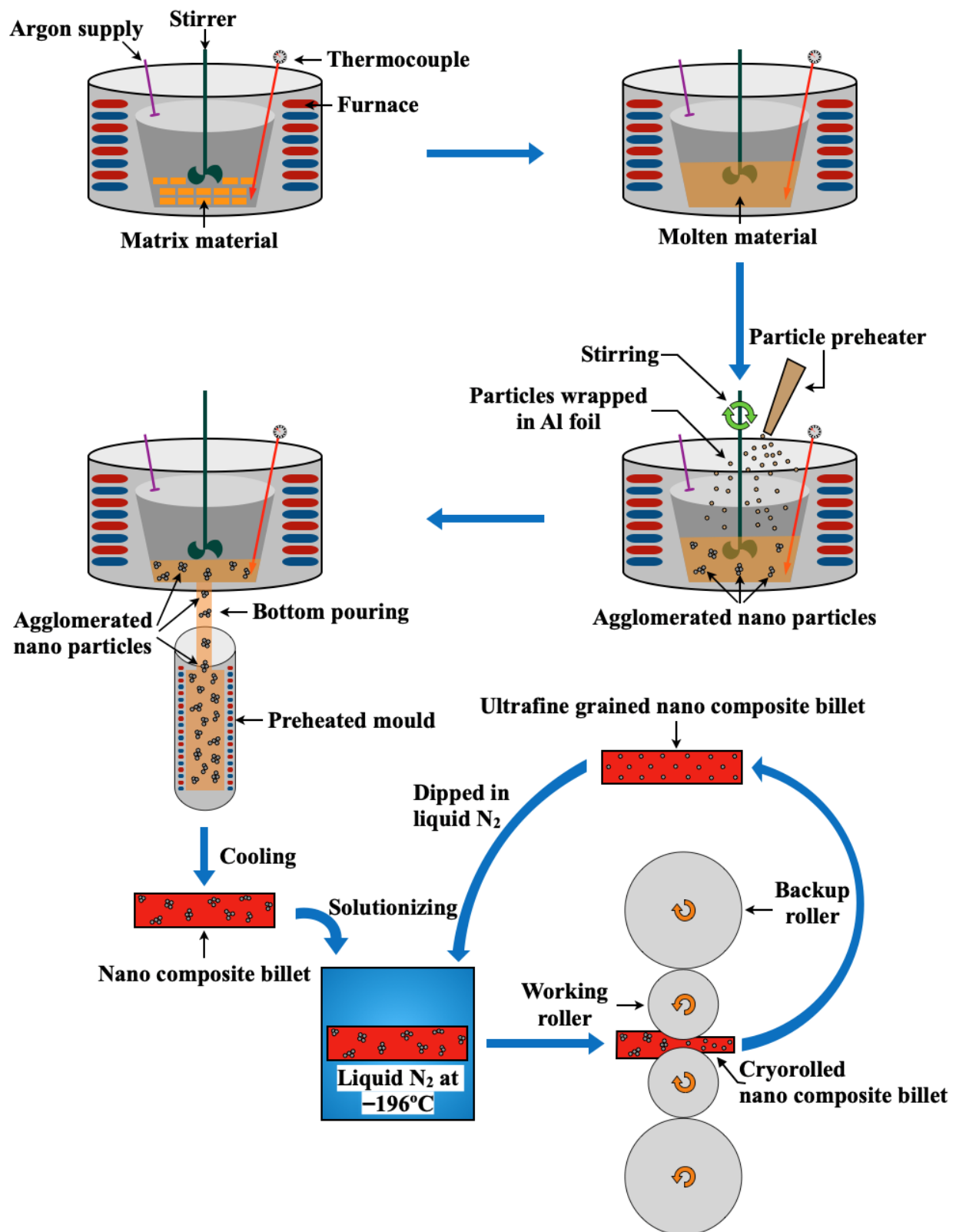


Figure 4. The sequence of operations involved in the fabrication of Al-MMCs, followed by cryorolling.

Despite a growing body of experimental studies on stir-cast and cryorolled Al-MMCs, the reported outcomes remain fragmented across different alloy systems, reinforcement types, and processing conditions. A consolidated understanding of how individual strengthening mechanisms evolve and interact under cryogenic deformation is still lacking, and most studies report mechanical improvements without quantitatively separating the

relative contributions of grain refinement, dislocation strengthening, load transfer, Orowan looping, and thermal mismatch effects. This limits the ability to rationally design processing routes or to generalize findings across material systems.

Furthermore, recent advances in data-driven manufacturing, sustainability assessment, and digitalization have introduced new perspectives into materials processing research. While sustainability metrics, machine-learning-based process modeling, and digital twins are increasingly discussed in the broader manufacturing literature, their integration into Al-MMC processing studies—particularly those involving stir casting combined with cryorolling—remains at an early stage. Most existing works treat these aspects qualitatively, without systematically connecting them to the underlying process–microstructure–property relationships.

This review critically synthesizes stir casting combined with cryorolling as a hybrid processing route for aluminum metal matrix composites, with an emphasis on microstructure–property relationships and strengthening mechanisms. Unlike existing reviews that address these topics separately, the present work integrates cryogenic deformation effects within composite processing using a unified quantitative framework. It further incorporates recent sustainability metrics and a structured assessment of machine-learning-enabled digital twins as forward-looking tools, providing a coherent and timely reference for future Al-MMC design and processing.

The literature reviewed in this work was collected through a systematic and structured search strategy to ensure a comprehensive coverage and technical relevance. Major scientific databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar, were used to identify peer-reviewed journal articles. The search was conducted using combinations of keywords such as “aluminum metal matrix composites”, “stir casting”, “cryorolling”, “cryogenic deformation”, “microstructure–property relationships”, “strengthening mechanisms”, “sustainability”, “life-cycle assessment”, “machine learning” and “digital twin”.

The primary time span of the reviewed literature covers 2000–2025, with a particular emphasis on recent publications (2015 onward) to capture advances in cryogenic processing, quantitative strengthening models, sustainability assessment, and data-driven manufacturing approaches. Only peer-reviewed journal articles published in reputed international journals were considered. Conference proceedings, theses, patents, and non-refereed reports were excluded unless they provided essential background information.

Inclusion criteria focused on studies that (i) investigated aluminum or aluminum-based MMCs fabricated via stir casting and/or post-solidification deformation routes, (ii) reported microstructural, mechanical, or thermo-mechanical behavior under ambient or cryogenic conditions, or (iii) presented quantitative models, sustainability analyses, or data-driven approaches relevant to MMC processing. Studies with insufficient experimental detail, non-reproducible data, or limited relevance to the discussed processing routes were excluded. This structured approach ensured that this review provides a balanced, rigorous, and up-to-date synthesis of the state of the art.

6. Microstructural Characteristics of Al-MMCs Produced via Stir Casting and Subsequent Cryorolling

Deb et al. [16] utilized a hybrid processing strategy to produce bulk ultrafine-grained (UFG) AA1050 nanocomposite sheets. The Al–SiC MMCs were fabricated by stir casting and subsequently subjected to cryorolling. The relationship between the microstructure and properties was evaluated at two processing stages: (i) after stir casting and (ii) after cryorolling the stir-cast composite. After the stir casting, the researchers noted a steady reduction in grain size, which started at micron levels, as the volume fraction of SiC increased (0, 0.5, 1, 2 wt.%). SEM images of stir-cast AA1050 + SiC MMC with varying

wt.% of SiC demonstrated many micropores and particle agglomeration from the stir casting, as reported by Deb et al. [16]. Also, cryorolling reduced the grain size to the nanoscale. Moreover, cryorolling reduced the pores and reduced particle agglomeration in the matrix. This change resulted from cryorolling, as the rolling pressure forced the matrix through particle clusters and deformed the composite. Cryorolling further aided in dispersing clustered particles and improving the uniform distribution of SiC in the Al matrix. Moreover, the limitation of dynamic recovery led to an increased dislocation density [17].

Bembalge and Panigrahi [18] employed a hybrid stir casting–cryorolling route to fabricate bulk ultrafine-grained (UFG) AA6063–SiC nanocomposite sheets, in which the SiC particle size was varied between 12 μm , 1 μm , and 45 nm. The AA6063 + SiC composite was created through stir casting with a volume fraction fixed at 4 wt.% for all particle size combinations. The dendrites were formed in the developed composites, and the size of the dendrites reduced proportionally with a decrease in particle size. As the particle size reduces, the particles gather along the grain boundaries, which inhibits grain growth. Some micro-porosity was observed in the stir-casted microstructure. To remove porosity, the researchers performed room-temperature rolling (1 mm thickness reduction). Then, solutionizing at 530 °C for a 2 h duration resulted in a more uniform distribution of particles with equiaxed grains. Cryorolling was then applied to the solutionized composites, achieving a 90% reduction in thickness. The cryorolling procedure produced a high density of dislocations and UFGs in the matrix material (without particle), as reported by Bembalge and Panigrahi [18]. In contrast, the cryorolled composite (with coarse SiC) showed dislocations at the matrix–particle interface. The composites showed a finer microstructure, and this refinement was due to cryorolling, which restricted grain elongation along the rolling direction due to the higher volume fraction of nano-SiC particles.

In another study by Deb et al. [19], they studied the crystallization behavior and thermal stability of AA1050–SiC MMC, which was produced with nano-sized particles (45 nm). They produced the composite using stir casting and then cryorolling, reducing its original thickness of 10 mm by 90%. After that, they conducted annealing trials at temperatures ranging from 150 °C to 300 °C to investigate the relationship between structure and mechanical properties. The cryorolled composite sheets had a highly deformed grain structure, with changes in the grain orientation after the annealing procedure. The cryorolled composite sheet, which was annealed at 150 °C, displayed a diffused microstructure similar to the unannealed cryorolled composite. When the annealing temperature increased to 200 °C, the researchers observed a gradual growth in sub-grains. Annealing at 250 °C resulted in a recrystallized microstructure, although the average grain size stayed at 507 nm, still within the ultrafine range. Beyond 250 °C, rapid grain coarsening occurred, and annealing at 300 °C produced a fully recrystallized microstructure with an average grain size of about 6 μm . The authors indicated that recrystallisation occurred before the recovery phase was completed. Due to aluminum's higher stacking fault energy, it recovers quickly even at reduced annealing temperatures. Additionally, the high dislocation density provided stored energy, which helped with recrystallisation. In contrast, the same material without reinforcement showed a larger grain size. Fine SiC reinforcements in the Al matrix aided in pinning grain boundaries and partially suppressing grain growth during annealing.

7. Wear Performance of Al-MMCs Fabricated via Stir Casting and Subsequent Cryorolling

Bembalge and Panigrahi [20] studied AA6063–SiC composites created through a hybrid manufacturing approach that included stir casting, solution heat treatment, and cryorolling. They examined how different particle sizes—coarse, fine, and nano—affected the wear

behavior of these composites. The results showed that as the particle size decreased, the hardness of the composite increased. The nanocomposite exhibited the highest hardness value (200 HV) relative to composites with coarse and fine SiC particles. Pin-on-disc wear tests were performed under different loads (10–50 N) and sliding velocities (0.5–2 m/s). Both the applied load and sliding velocity were found to affect the specific wear rate of the cryorolled base alloy and the composites. In general, higher loads resulted in lower wear rates, with the minimum wear rate occurring at 30 N and 2 m/s. The cryorolled nanocomposite showed the lowest wear rate among the tested conditions. This improvement was attributed to the smaller particle size, which increased the number of SiC particles in the matrix, thereby reducing the distances between particles. This led to greater hardness and wear resistance. Additionally, the cryorolled microstructure showed more dislocations due to reductions in dynamic recovery and differences in thermal expansion coefficients between the matrix and reinforcement. As a result, the dislocation density was higher than that of the cryorolled base alloy. The fine-grained microstructure associated with this increased dislocation density was found to enhance hardness and wear resistance. Under lower load conditions (10–20 N) and at lower sliding velocities (0.5–1 m/s), abrasive wear features accompanied by adhesive wear characteristics were observed. Variations in groove depth were noted across different testing conditions. The cryorolled composite containing coarse SiC particles exhibited relatively deeper grooves, likely due to the detachment of large and weakly bonded particles from the matrix during wear. Furthermore, oxide wear layers were observed on the worn surfaces, with greater prominence in the cryorolled composites compared to the base alloy. These oxide layers filled microvoids and acted as shields, reducing wear rates by decreasing pin–surface contact. The detached SiC particles may have mixed with the oxide layers, thereby enhancing the wear resistance of cryorolled composites. The microstructure, improved matrix–particle bonding, and oxide wear layer formation contributed to the improved wear resistance of cryorolled composites with fine and nano-sized SiC particles.

8. Role of Reinforcement Volume Fraction in Governing the Tensile Behavior of Al-MMCs

Deb et al. [16] created an AA1050/SiC composite using a hybrid approach, which involved stir casting followed by cryorolling. This approach led to a significant rise in tensile strength, with only a slight change in elongation. The cryorolled composites showed better strength than the stir-cast composites. The addition of nano-sized SiC particles and a higher SiC volume fraction contributed to the improved properties. However, increasing the reinforcement led to a significant drop in ductility. The superior mechanical strength of the composites, compared to the unreinforced base alloy, can be attributed to several factors:

- Grain Refinement: SiC particles pinned the grain boundaries, which refined the grain structure;
- Geometrically Necessary Dislocations: Different thermal expansion coefficients between the matrix and particles created these dislocations, which enhanced mechanical strength;
- Nano-particle Clusters: These clusters acted as barriers to dislocation movement, improving mechanical strength;
- Interaction with Sessile Dislocations: The geometrically necessary dislocations interacted with sessile dislocations during tensile deformation, which further enhanced mechanical strength [5].

At a higher SiC content of 2 wt.%, the emergence of additional nano-sized particle clusters and a greater volume of micropores at the matrix–particle interface were found to adversely affect both strength and ductility. The presence of numerous agglomerates

provided favorable sites for crack initiation, leading to a decline in mechanical strength [6]. Cryorolling was effective in mitigating these effects by breaking up particle clusters and improving the homogeneity of particle distribution in the matrix, while also reducing residual interfacial microporosity from stir casting. The subsequent enhancement in mechanical strength was attributed to dislocation accumulation and grain refinement. Consequently, multiple strengthening mechanisms collectively contributed to the superior mechanical properties of cryorolled composites relative to the base alloy and stir-cast counterparts [21].

9. Influence of Post-Annealing Treatment on the Tensile Properties of Al-MMCs

Deb et al. [19] found that the cryorolling enhances the mechanical strength of both the base alloy and the composite. However, based on the study, an increase in the annealing temperature can lead to a reduction in the mechanical strength due to recovery and recrystallization processes. Beyond 250 °C, elongation remarkably increases for both materials. This trade-off, where mechanical strength drops while elongation rises, is especially clear at 300 °C, resulting in a fully recrystallized microstructure. The dislocation strengthening in the cryorolled material and the significance of grain boundary strengthening at higher temperatures are both evident. Relative to the cryorolled base alloy, the cryorolled composite demonstrated improved mechanical strength, likely due to its reduced grain size. The finer grains are attributed to reinforcement particles located at grain boundaries, which restrict grain growth, consistent with the findings of Deb et al. [19].

10. Role of Reinforcement Particle Size in Governing the Tensile Behavior of Al-MMCs

Bembalge and Panigrahi [18] investigated the aluminum matrix, which contained different sizes of SiC particles: coarse, fine, and nano. It was observed that as the particle size decreases, the mechanical strength increases. However, this led to a reduction in elongation in the stir-cast composite. The mechanical strength improvement was especially clear in cryorolled composites. The nano-sized SiC composite achieved the highest mechanical strength. This improvement resulted from cryorolling, which increased the dislocation density, eliminated micropores in the stir-cast composite, and strengthened the bond between the matrix and particles.

The lower mechanical strength of the stir-cast composites was related to the brittle dendritic microstructure. The SiC particles at these boundaries created stress concentration zones, leading to early failures and reduced mechanical strength. This observation is corroborated by the identification of dendritic globules and characteristic dendritic regions on the fracture surfaces of the stir-cast composites for all SiC variants. However, solution heat treatment followed by cryorolling effectively removed these dendritic structures. The strengthening effect of cryorolling can be attributed to several mechanisms, namely dislocation strengthening, grain boundary strengthening, and Orowan strengthening, the latter resulting from dislocation loop formation around obstructing particles. Furthermore, differences in the thermal expansion coefficients of the matrix and reinforcement particles induce geometrically necessary dislocations, which additionally enhance the mechanical strength of the cryorolled composite.

The fracture surface of failed tensile specimens demonstrates no signs of dendritic regions, only microvoids and dimples that indicate a ductile fracture. In a later study by Bembalge and Panigrahi [22], varying the SiC particle size in the AA6063 matrix and applying cryorolling with post-annealing treatments showed that the mechanical strength increased as the particle size decreased. Post-annealing of the cryorolled products resulted in a progressive decrease in mechanical strength along with a corresponding recovery in

ductility. The trade-off between strength and ductility became particularly evident after annealing at 300 °C, likely due to grain coarsening. Despite this, the AA6063 nanocomposite maintained adequate strength, which can be associated with enhanced matrix–particle interfacial bonding as the particle size decreased.

11. Machine Learning and Digital Twin for Process–Structure–Property Mapping in Al-MMCs

Machine learning (ML) algorithms can be effectively employed to model and predict outcomes in hybrid manufacturing routes, including stir casting and cryorolling. The input features may include stir-casting parameters, such as the melting temperature, stirring speed, stirring time, impeller design, reinforcement size, and volume fraction [23]. The cryorolling parameters, such as overall strain, reduction per pass, rolling speed, and soaking temperature, can be included. In case of post-processing parameters, i.e., post-heat treatment, duration must be included. The target outputs may contain the grain size, mechanical properties, and wear rate [24]. Supervised ML models such as Artificial Neural Networks (ANNs), Random Forests (RFs), Support Vector Regression (SVR), and Gradient Boosting can be trained using experimental datasets reported in the reviewed studies. For example, ML can predict the optimum combination of SiC particle size [25] and cryorolling strain required to achieve ultra-fine grains while avoiding excessive loss of ductility. Feature importance analysis further helps identify dominant strengthening mechanisms, such as grain boundary strengthening versus Orowan strengthening, under different processing regimes [24].

A digital twin (DT) of Al-MMC manufacturing represents a real-time, virtual replica of the physical process, continuously updated using experimental data, sensors, and ML models. The framework for a hybrid route can be routed in the following manner [26]:

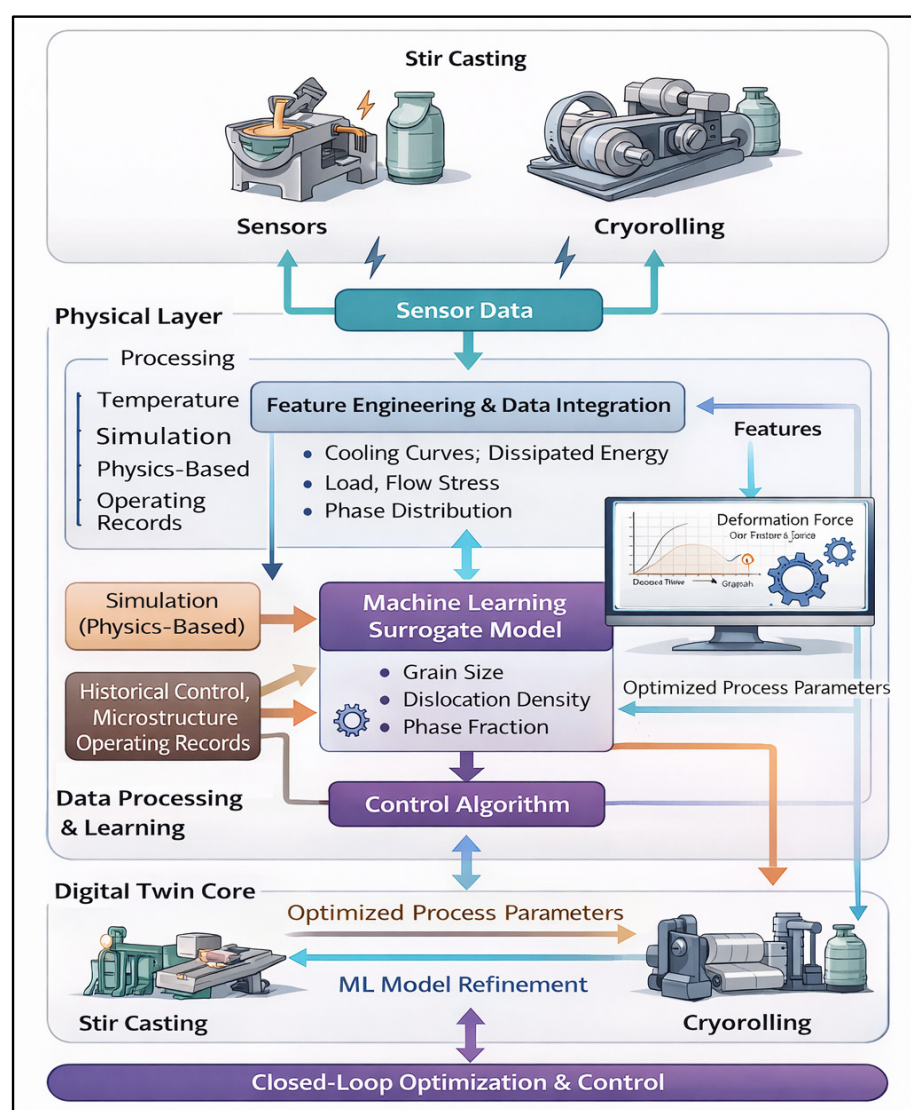
- Process Twin: Including simulating the melt flow, particle distribution, and solidification during stir casting, followed by strain accumulation and thermal evolution during cryorolling.
- Microstructure Twin: That predicts grain refinement, particle clustering, and texture evolution based on the processing history.
- Property Twin: Forecasting the mechanical and tribological performance over the service life.

Recent studies demonstrate the growing maturity of machine learning-enabled digital twins in manufacturing and composite systems. Xu et al. [27] employed hierarchical deep neural networks to construct a digital twin capable of real-time mechanical field prediction in composite structures, validating the ML surrogate modeling accuracy. Zhang et al. [28] proposed a hybrid digital twin framework combining domain knowledge and AI for industrial manufacturing, enabling dynamic process–quality prediction. Perno et al. [29] developed an ML-based digital twin for online prediction of critical process parameters using real plant data. Complementing their work, Sheuly et al. [30] provided a bibliometric overview confirming the rapid adoption of ML and neural network tools within digital twin research, supporting their extension to Al-MMC processing. The consolidated synthesis of machine learning and digital twin technologies for various similar research works is shown in Table 2.

Based on the consolidated synthesis of machine learning and digital twins, the workflow diagram of DT integration for the production of Al-MMCs through stir casting followed by cryorolling is shown in Figure 5.

Table 2. Systematic synthesis of machine learning and digital twin technologies.

Task	Inputs	Model	Validation Metrics	Key Inference
Composite structure DT [27]	Sensing + simulation data	H-DNN	Prediction error	Demonstrated accurate real-time mechanical field predictions
Hybrid ML-DT for machining [28]	Heterogeneous process data	AI pipeline	Industrial validation	Enhanced real-time monitoring & quality pred.
ML-DT param. pred. [29]	Real manufacturing data	ML models	Prediction accuracy	ML-DT improves real-time process parameter pred.
ML-DT bibliometric [30]	Lit. metadata	Scientometric ML	Trends	Validates increasing ML in DT research

**Figure 5.** Digital twin integration for the production of Al-MMCs through stir casting followed by cryorolling.

12. Sustainability and Industrial Readiness of Stir-Cast and Cryorolled Al-MMCs

The integration of stir casting followed by cryorolling shows strong sustainability and industrial preparedness, due to the lower energy consumption and cost-effectiveness of the stir-casting process. Moreover, the process is scalable, and thus it helps in minimizing

material waste. Although cryorolling employs liquid nitrogen, it enables ultra-fine-grained microstructures at reduced deformation loads and without repeated high-temperature cycles, resulting in significant strength enhancement and a longer component service life [31]. The substantial improvements in mechanical and tribological performance reported in the reviewed studies contribute to reduced wear, a lower maintenance frequency, and enhanced durability, aligning with circular economy principles. Importantly, both stir casting and rolling are compatible with existing industrial infrastructure, allowing large-scale sheet production with a high technology readiness level. The reduced process complexity, improved performance-to-weight ratio, and recyclability of cryorolled Al-MMCs make this hybrid approach well-suited for sustainable, industry-ready applications in automotive, aerospace, and structural engineering sectors [31,32].

A quantitative assessment of the sustainability performance is essential to compare hybrid processing routes, such as stir casting followed by cryorolling, with alternative manufacturing methods. A life cycle assessment (LCA) framework offers the most appropriate structured approach to quantify environmental impacts across the entire production chain. The goal of this analysis is to provide a transparent comparison of the environmental performance of Al-MMC sheets produced via stir casting with subsequent cryorolling versus other MMC manufacturing routes (e.g., powder metallurgy, LPDC, green sand casting). The scope follows raw material extraction, primary production, casting, cryorolling, and finishing processes. This scope aligns with the standard practice in manufacturing LCA studies. Table 3 provides the energy demand and carbon footprint for the production of Al-MMCs through stir casting followed by cryorolling.

Table 3. Indicative energy demand and carbon footprint for Al-MMC production via stir casting followed by cryorolling (per kg).

Process	Energy Demand (MJ kg ^{−1})	(kg CO ₂ -eq kg ^{−1})
Primary Al production [32]	200–250	9.7–18.3
Recycled Al production [33]	5–15	0.3–0.8
Reinforcement production [34]	2–6	0.2–0.6
Stir casting [31]	40–80	2–4
Casting yield loss [32]	5–10	0.3–0.8
Cryorolling	5–10	0.3–0.6
Liquid nitrogen	3–8	0.2–0.5
Finishing	3–5	0.2–0.4

Based on the above table, it is suggested that Al-MMCs be prepared using recycled aluminum, which dominates sustainability improvements and reduces CO₂ emissions by ~60–75%, even with cryogenic deformation. Moreover, the LCA for the production of one Al-MMC through stir casting followed by cryorolling is shown schematically in Figure 6. In addition, the sample LCA estimation for Stir-Cast and Cryorolled AA6063–SiC Composite is given in Table 4 with the assumptions of 1 kg (700 g recycled + 300 g primary) of AA6063–4 wt.% SiC composite sheet, cryorolling with a total true strain ≈ 2.5 in 30 passes, and an electricity emission factor of 0.6 kg CO₂ kWh^{−1} [35].

From the LCA reported in Table 4, it is found that though hybrid processing increases the energy input compared to a conventional Al sheet, the enhanced mechanical and wear performance extends the component lifetime, thereby reducing life cycle emissions per service hour, which is a key sustainability advantage for structural applications.

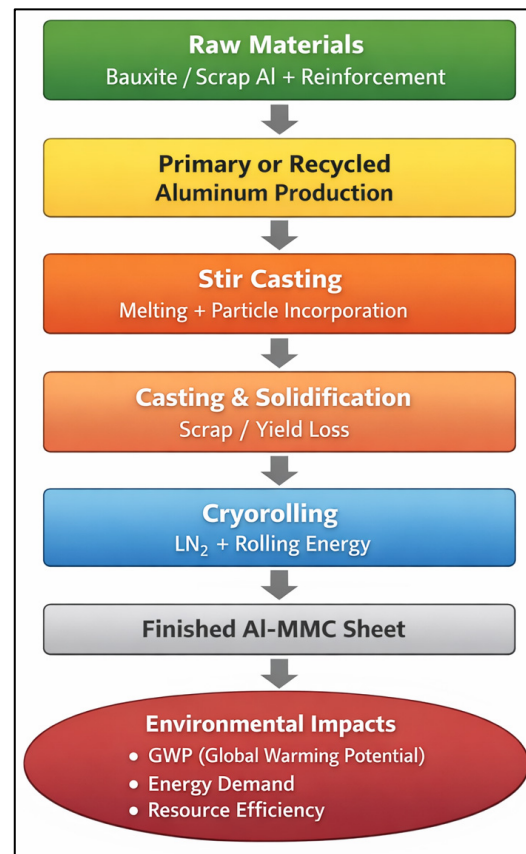


Figure 6. Schematic LCA flow diagram for the production of Al-MMC through stir casting followed by cryorolling.

Table 4. LCA estimation for the production of AA6063—SiC through stir casting followed by cryorolling.

Process	Energy Demand (MJ kg ^{−1})	(kg CO ₂ -eq kg ^{−1})
Aluminum production	$(0.3 \times 220 \text{ MJ}) + (0.7 \times 10 \text{ MJ}) \approx 73$	4.5
Stir casting	60	3.8
Cryorolling	15	
Finishing	5	-
Total	153	8.3

13. Conclusions

This review has provided an overview of producing aluminum metal matrix composites (Al-MMCs) using stir casting and cryorolling, a combined manufacturing approach. It has explored the microstructure, wear behavior, and tensile properties of different Al-MMCs after cryorolling. The study has discussed how the particle size, volume fraction, cryorolling, and post-annealing treatments affected microstructural changes and related properties.

The research found that composites made with stir casting had microvoids at the matrix–particle interface, which led to weaker mechanical strength. Moreover, the clustering of small reinforcement particles created possible sites for crack formation, further reducing the material strength. Cryorolling solved these issues by closing micro-pores and breaking apart clustered particles. This technique improved the distribution of particles in the matrix and strengthened interfacial bonding. Additionally, cryorolling reduced dynamic recovery, which allowed dislocations to accumulate and created necessary dis-

locations due to differences in thermal expansion coefficients. This led to an increase in mechanical strength. The material strength improved as the particle size decreased, and thus smaller particles prevented grain coarsening during annealing. This resulted in cryorolled composites that balanced mechanical strength and ductility. Across the reviewed literature, the dominant strengthening contributions in cryorolled Al-MMCs arise from grain boundary and dislocation strengthening, with additional contributions from Orowan looping, load transfer, and thermal mismatch-induced dislocations. These mechanisms are strongly influenced by cryorolling strain, reinforcement size, and the volume fraction, explaining the consistently observed improvements in strength and wear resistance, particularly for nano-reinforced systems. However, an excessive reinforcement content promotes particle agglomeration and crack initiation, highlighting the need for optimized compositions and controlled deformation schedules.

Beyond structure–property relationships, this review extends the discussion to sustainability and industrial readiness, showing that the hybrid route is compatible with existing casting and rolling infrastructure and can deliver an improved life cycle performance through enhanced durability and recyclability. Indicative life cycle assessments suggest that the use of recycled aluminum significantly reduces the environmental footprint, even when cryogenic deformation is employed. Finally, this review consolidates emerging research on machine learning and digital twin frameworks, illustrating their potential to unify process–structure–property relationships, guide process optimization, and enable intelligent manufacturing of Al-MMCs.

Future research on aluminum metal matrix composites processed via stir casting followed by cryorolling should focus on developing systematic processing–microstructure–property maps and quantitatively separating individual strengthening mechanisms. Process-specific life cycle assessments incorporating recycling and energy sources are required to strengthen sustainability evaluation. In addition, the creation of comprehensive experimental datasets will support the development of machine learning-enabled digital twins for real-time prediction and optimization, enabling scalable and intelligent manufacturing of Al-MMCs.

14. Future Work

Most research has concentrated on Al alloys with ceramic reinforcements, especially SiC particles. Expanding the research to include high-strength materials and composites could significantly increase the use of this combined manufacturing approach. In-depth studies on the effect of different ceramic particles and extending the approach to include metallic reinforcements such as ferrous (Fe), nickel (Ni), stainless steel (SS), and copper (Cu) particles, could help tackle issues like particle breakdown and brittle phase formation. Looking into the production of MMCs based on high-entropy alloys might lead to better mechanical properties. It is expected that further development of Al-MMCs with metallic reinforcements through stir casting followed by cryorolling can help in enhancing the relationship between the structure and mechanical properties, opening up more applications for this manufacturing approach. Despite the strong potential, the application of machine learning and digital twins to stir-cast and cryorolled MMCs remains limited. Key research gaps include a lack of standardized, high-quality datasets linking cryogenic deformation to microstructural evolution, limited integration of physical metallurgy principles into ML models, and the absence of end-to-end DT implementations for MMC manufacturing. Future research should focus on physics-informed ML, hybrid experimental–computational datasets, and scalable DT architectures to transition hybrid MMC manufacturing from empirical optimization to intelligent, autonomous processing. While the reviewed studies established the mechanical and tribological superiority of stir-

cast and cryorolled Al-MMCs, future research should explicitly incorporate sustainability metrics such as energy consumption per unit strength gain, life cycle assessment of hybrid MMC manufacturing, recyclability, and reprocessability of cryorolled composites, and integration with renewable-energy-powered cryogenic systems. The integration of these aspects can further strengthen the case for industrial adoption and align MMC research with global sustainability requirements.

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Abbreviations

The following abbreviations are used in this manuscript:

MMCs	Metal Matrix Composites
AMCs	Aluminum Matrix Composites
CMCs	Ceramic Matrix Composites
PMCs	Polymer Matrix Composites
UFG	Ultra-fine-grained
ECAE	Equal Channel Angular Extrusion
HPT	High-pressure Torsion
FSP	Friction Stir Processing
ARB	Accumulative Roll Bonding
SPD	Severe Plastic Deformation

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