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FABRICATION OF CAST AA5056 ALLOY-BASED COMPOSITES REINFORCED WITH BN, ZrO₂ AND Si₃N₄

Cast aluminum matrix composites (MMCs) produced by stir casting are of considerable interest due to their technological simplicity, relatively low cost, and the possibility of scalable manufacturing of components with balanced mechanical and casting properties. For Al–Mg alloys, particularly AA5056, the elevated magnesium content provides favorable conditions for improved wettability of dispersed particles and enables the implementation of dispersion and structural strengthening mechanisms. This study presents a comparative investigation of the influence of three types of reinforcing phases — BN, ZrO₂+BN, and Si₃N₄ — on the formation of microstructure, porosity, fluidity, and mechanical properties of cast AA5056-based composites produced under identical stir-casting conditions. It is shown that the introduction of 2 wt. % dispersed particles into the melt leads to significantly different effects, governed both by the barrier action of particles on dendrite growth and by possible interfacial interactions. The most pronounced positive effect is observed for boron nitride: significant grain refinement, a more uniform distribution of alloying elements within the microvolume, and the formation of a more homogeneous structure are achieved. This is accompanied by a simultaneous increase in ultimate tensile strength and ductility, indicating an effective combination of strengthening mechanisms without brittle failure. The ZrO₂+BN hybrid system exhibits less pronounced structural changes, with partial retention of dendritic morphology

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Fabrication of cast AA5056 alloy-based composites reinforced with BN, ZrO_2 and Si_3N_4 and particle agglomeration, which limits the efficiency of structural modification. At the same time, this composition demonstrates a compromise between strength, ductility, and fluidity, which is important for cast product manufacturing. The addition of Si_3N_4 results in increased strength due to grain refinement and possible local interfacial reactions; however, it is accompanied by a decrease in ductility due to stress concentration and the probable formation of brittle interaction products, such as interfacial nitride and silicide phases. As a result, the governing relationships between structure formation and property evolution in cast AA5056-based MMCs depending on the nature of the reinforcing phase have been established. They include grain-boundary strengthening and reduced microsegregation for BN, structural heterogeneity for the hybrid system, and possible interfacial reactions for Si_3N_4 . The obtained results can be used for optimization of composition and processing parameters to achieve the required balance between mechanical and casting properties of the materials.

Keywords: AA5056 alloy; metal matrix composite; melt stirring; boron nitride; zirconia; silicon nitride; microstructure; mechanical properties; fluidity; porosity.

INTRODUCTION

Cast aluminum matrix composites (MMCs) are most commonly produced by stir casting and squeeze or squeeze-assisted casting. To increase the particle incorporation efficiency, reduce agglomeration, and improve wetting of the reinforcing phase, a number of studies additionally employ fluxes, powder preheating, ultrasonic treatment, or combined stirring. Casting routes are technologically attractive because they enable production of relatively large blanks at a moderate process cost [1, 2].

Particular attention in the literature has been paid to AA5056-type alloys, in which the elevated magnesium content in the matrix creates prerequisites both for more efficient wetting of some fillers and for the implementation of additional structural and dispersion-strengthening mechanisms. At the same time, published results for Al-Mg systems strongly depend on the matrix composition, particle type and size, introduction method, and solidification conditions. Therefore, direct transfer of conclusions from other systems remains limited [3–5].

Boron nitride, especially hexagonal h-BN, is considered a promising filler due to its low density, high thermal stability, and chemical inertness. In aluminum matrices, BN may act as a barrier to dendrite growth and may localize in interdendritic or intergranular regions, thus affecting the solidification pattern. At the same time, for the specific case of cast AA5056, the efficiency of BN requires separate analysis, as the reactivity of the Al-Mg melt and the actual particle wettability strongly depend on the temperature-time schedule [2, 5–8].

Zirconium oxide (ZrO_2), as a reinforcing component, is characterized by high hardness, thermal stability, and the potential to improve wear resistance and composite strength. A number of studies on Al-Mg systems [2, 9–12] have shown that ZrO_2 can affect solidification and the mechanical response of composites. However, the magnitude of this effect strongly depends on powder dispersion, uniformity of distribution, and the degree of interfacial interaction. For hybrid ZrO_2 +BN systems in an AA5056 matrix, the available literature data remain limited.

Silicon nitride (Si_3N_4) is a rigid and heat-resistant filler that has demonstrated the ability to improve hardness, wear resistance, and strength of aluminum composites in numerous studies [2, 13]. At the same time, its influence in Al-Mg systems is ambiguous because, in addition to the barrier effect of the particles, local interfacial reactions may occur, changing the chemical state of the interface, the morphology of eutectic regions, and the fracture behavior of the material [14–16].

According to the literature [2–13], in cast MMCs based on AA5056-type alloys, the main constituents usually remain the Al-Mg matrix and the introduced BN, ZrO_2 , or Si_3N_4 reinforcing particles. At the same time, under certain temperature-time conditions, thin reaction layers or local secondary phases may form at the interface. Therefore, when interpreting the microstructure, it is reasonable to distinguish between stable initial

phases and probable reaction products, the formation of which depends on the specific processing (Table 1).

Table 1

Stable phases and probable reaction products in cast AA5056-based MMCs containing BN, ZrO₂ and Si₃N₄ particles

Main stable phase	Main stable phase		
	BN	ZrO ₂	Si ₃ N ₄
	Predominantly stable BN [17]	Predominantly stable ZrO ₂ ; under certain conditions partial interaction with Al is possible [11]	Si ₃ N ₄ is a relatively stable phase, but local interaction with liquid Al is possible under certain conditions [20–22]
Probable reaction products	A thin AlN layer under local overheating or prolonged contact [18]	Al ₂ O ₃ at the interface; under certain conditions ZrAl ₃ formation is possible [10, 19]	A thin AlN layer; Si release as a product of local interaction [20–22]
Low-probability phases	Mg ₃ N ₂ under a significant Mg excess; Al borides AlB ₂ and AlB ₁₂ at higher temperatures [8, 18]	Mg-containing oxide products under intense Mg oxidation	A thin AlN layer; Si release as a product of local interaction [20–22]
Comment on interpretation	For BN, inert behavior predominates; reactions are expected only locally.	The effect of ZrO ₂ strongly depends on particle dispersion, distribution, and contact conditions with the melt	For Si ₃ N ₄ , interfacial interaction is the most probable, but it requires direct phase confirmation.

Despite numerous studies on Al–Si, Al–Cu, and Al–Mg systems in general, direct comparative studies specifically for cast AA5056 alloy reinforced with BN, ZrO₂+BN, and Si₃N₄ under identical stir-casting conditions remain scarce. Therefore, the present study aims to comparatively evaluate the influence of BN, ZrO₂+BN, and Si₃N₄ reinforcing particles on the microstructure, porosity, fluidity, and mechanical properties of cast AA5056-based composites, and to establish the regularities of structure formation and property evolution depending on the nature of the reinforcing phase. The practical purpose of the study lies in identifying the most suitable filler for cast products requiring improved mechanical and/or casting characteristics.

MATERIALS AND METHODS

The study dealt with cast aluminum matrix composites based on the AA5056 alloy. The following dispersed additives in the charge of 2 wt.% each were used as reinforcing particles:

- 1) hexagonal boron nitride (BN) with an average particle size of about 5 μm.
- 2) powdered zirconium oxide (ZrO₂) with an average particle sizes up to 50 μm. In addition, the composite contained 0.3 wt.% BN as an auxiliary component intended to facilitate introduction of the powder mixture into the melt.
- 3) powdered silicon nitride (Si₃N₄) with an average particle sizes up to 100 μm.

All additives amount was selected taking into account an estimated particles assimilation by the matrix of about 85%.

A series of experiments was carried out to produce AA5056-based MMCs by stir casting for the following compositions: AA5056+2%BN, AA5056+2%ZrO₂+0.3%BN, and

AA5056+2%Si₃N₄. For a correct comparison, the cast AA5056 alloy without reinforcing particles was used as the reference material.

The chemical composition of the AA5056 alloy used in this study is given in Table 2 [25].

Table 2
Chemical composition of the AA5056 alloy

Element	Al	Mg	Mn	Cr
content, wt. %	95.0	≈5.0	<0.12	<0.12

Melting was carried out in a laboratory resistance furnace using an alundum crucible. To increase the incorporation of the reinforcing particles, the melt was mechanically stirred with a titanium impeller (Fig. 1a) at a speed of 10 s⁻¹. The stirring time was 60 s. After particle introduction,

the melt was held and poured into metal molds to obtain samples for metallographic, mechanical, and casting tests.

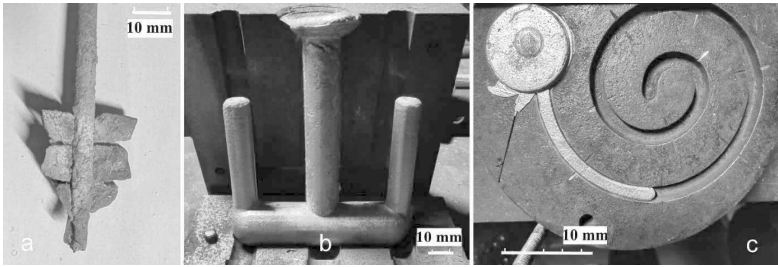


Fig. 1. Elements of the MMC fabrication technology: *a* — titanium impeller; *b* — mold with an experimental aluminum matrix composite sample; *c* — mold for fluidity determination

To improve wetting and incorporation of the reinforcing particles, a fluoride flux was introduced into the melt [26]. The flux was a mixture of KCl, NaCl, and NaF used in a small amount. Application of the flux promoted cleaning of the melt surface and reduced the probability of oxide film formation that hinders introduction of powder particles.

Metallographic specimens were prepared from the experimental samples and, after etching with Keller's reagent [27], were examined by optical metallography in order to assess the composite microstructure. In addition, selected regions were analyzed by scanning electron microscopy and local energy-dispersive spectroscopy (EDS), which made it possible to evaluate elemental distribution between the matrix, interdendritic regions, and local inclusions.

Mechanical properties were studied using an Instron 8802 universal servo-hydraulic testing machine capable of tensile, compression, and bending tests. In the present work, tensile test results are reported, from which the yield strength, ultimate tensile strength, elongation, and reduction in area were determined.

The fluidity of the studied alloys and composites was determined using a standard steel spiral fluidity mold (Fig. 1c). The mold had a spiral cavity of constant cross-section, and fluidity was evaluated from the length of the channel filled with metal. This approach makes it possible to compare the ability of melts to fill the mold under identical casting conditions.

The density of the composites was calculated theoretically and determined experimentally in order to estimate sample porosity. Experimental density was established by hydrostatic weighing based on the mass of the sample in air and in water [28]. The theoretical density was calculated from the equation (1):

$$\rho_{th} = \rho_{Al} \varphi_{Al} + \rho_r \varphi_r \quad (1)$$

where ρ_{th} , ρ_{Al} , and ρ_r are the theoretical density of the MMC, the density of aluminum, and the density of the reinforcing particles, respectively, kg/m³;

φ_{Al} and φ_r are the mass fractions of aluminum and the reinforcing particles, respectively, %.

For the studied samples, porosity was determined according to equation (2):

$$\%porosity = \frac{\rho_{teor} - \rho_{exp}}{\rho_{teor}}, \quad (2)$$

where ρ_{exp} is the experimental density of the MMC, kg/m³.

RESULTS AND DISCUSSION

Microstructural characterization

The microstructure of the initial AA5056 alloy (Fig. 2), produced by permanent-mold casting at a melt temperature of 750 °C, is characterized by a dendritic morphology typical of Al–Mg alloys, with moderately pronounced liquation between the dendrite arms.

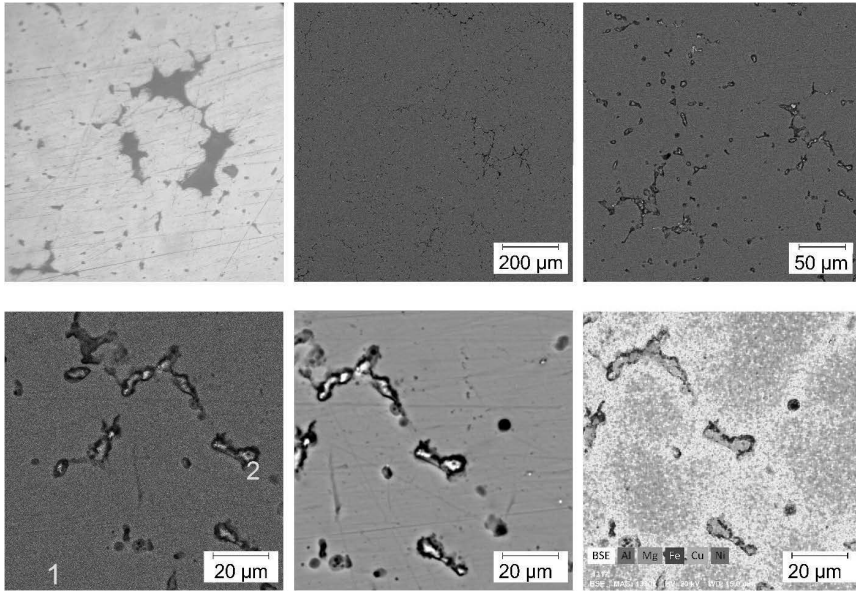


Fig. 2. Microstructure and EDS mapping of the initial AA5056 alloy

The grain size varies within 25–100 μm; larger grains prevail in the central regions of the sample, whereas finer crystals are observed in the near-surface zone because of a higher cooling rate near the mold wall.

Local chemical analysis shows that the magnesium content is lower inside the grains and noticeably higher in the interdendritic regions, which is consistent with segregation during solidification. The presence of trace Fe-containing regions is most reasonably attributed to local intermetallic inclusions rather than to the average composition of the matrix.

The microstructure of the AA5056-composite containing 2 wt.% boron nitride (Fig. 3) is characterized by pronounced grain refinement compared with the initial cast alloy. Introduction of BN intensifies heterogeneous nucleation and/or limits free dendrite growth, which leads to a finer and more uniform structure.

BN particles are distributed relatively uniformly in the matrix and are localized predominantly along grain boundaries and in interdendritic regions, where they restrict coalescence of dendrite arms. The high thermal stability and chemical inertness of BN favor retention of the particles during solidification and reduce the probability of intensive interfacial interaction under the applied processing conditions.

According to local analysis, the magnesium content in different microregions remains close to that expected for the AA5056 alloy, but the elemental distribution becomes more uniform than in the initial cast condition. This structural state is consistent with the simultaneously increased strength and ductility of the composite.

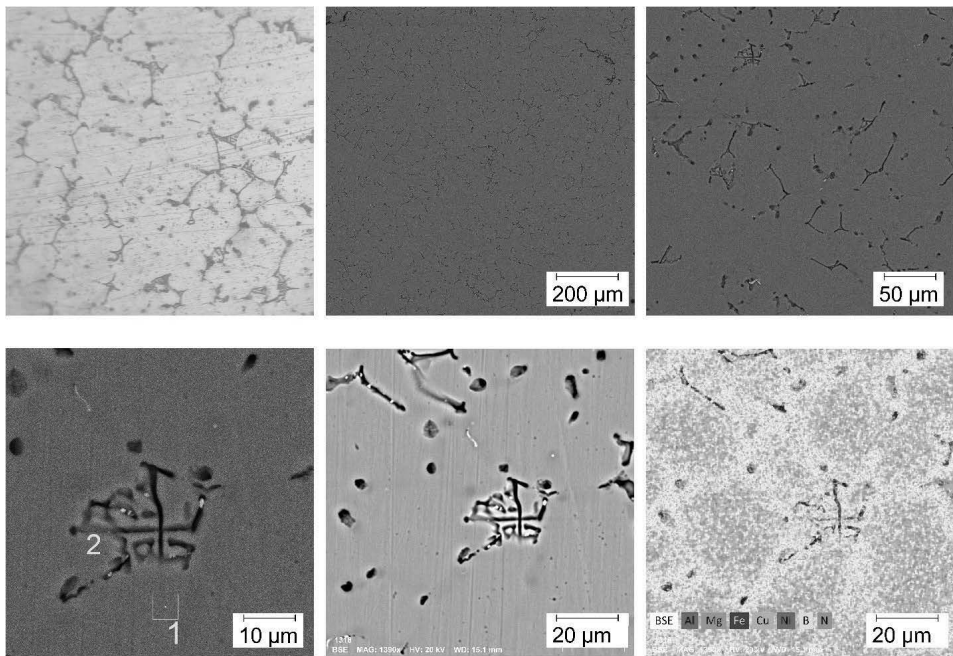


Fig. 3. Microstructure of the AA5056+2%BN composite

The strengthening effect observed for the BN-containing composite can be primarily attributed to grain refinement of the α -Al matrix, which enhances strength according to the Hall-Petch relationship. The introduced BN particles promote heterogeneous nucleation and restrict dendrite growth, resulting in a finer grain structure. The direct contribution of the particles to strengthening via classical dispersion mechanisms is expected to be limited due to their relatively large size ($\sim 5 \mu m$) and spacing. Therefore, the dominant factor controlling the increase in strength is the refined grain structure rather than the intrinsic reinforcing effect of the particles. Additional contributions may arise from a more uniform distribution of alloying elements and the absence of large particle agglomerates or brittle interfacial products, which together promote a more homogeneous stress distribution during deformation.

The AA5056 composite with hybrid reinforcement of 0.3 wt.% BN and 2 wt.% ZrO_2 exhibits microstructural changes that are less pronounced than in the case of BN alone. The α -Al grain size remains relatively large, and the dendritic morphology is retained to a greater extent.

ZrO_2 particles, characterized by high thermodynamic stability, are mostly preserved in their initial state and are distributed non-uniformly in the matrix; local agglomerates are observed in some regions. Such a distribution reduces the efficiency of structural modification and diminishes the barrier effect on dendrite growth.

The dendritic morphology in the composite remains sufficiently pronounced, and the interdendritic regions are characterized by segregation of Mg-enriched phases. The absence of substantial grain refinement and deeper structural redistribution is consistent with a less pronounced strengthening effect compared with the BN-containing material.

Local EDS analysis of selected regions indicates a difference in magnesium content between grains and interdendritic zones. Elevated local Fe contents in individual points should be attributed not to the matrix as a whole, but to analysis of local inclusions or intermetallic particles.

Addition of 2 wt.% silicon nitride results in a more noticeable microstructural modification compared with the hybrid composite (Fig. 5). The α -Al grain size decreases to 15–60 μm , and the dendritic morphology becomes less pronounced.

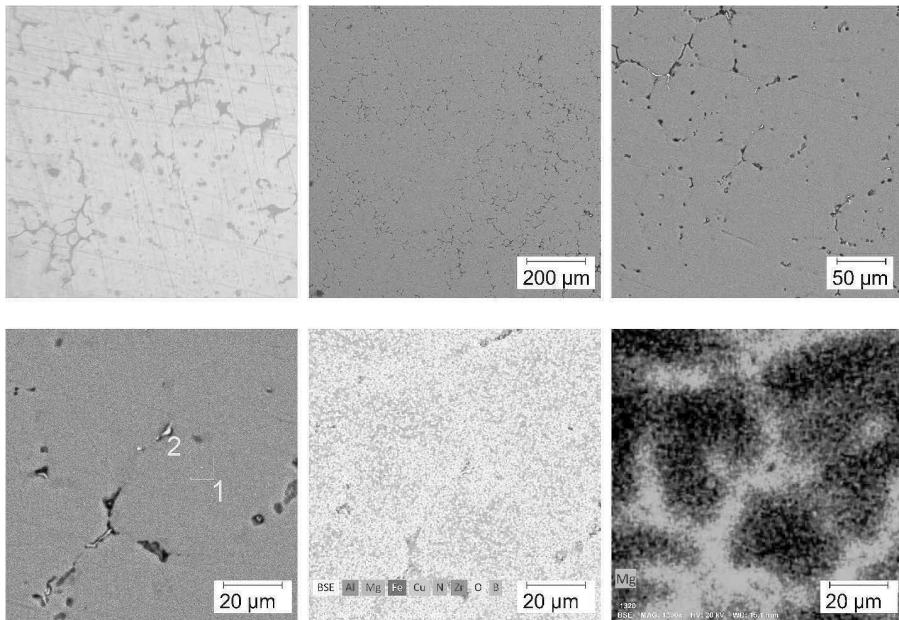


Fig. 4. Microstructure of the AA5056+2%ZrO₂+0.3%BN composite

Probable reasons for this effect are:

- 1) the partial ability of Si₃N₄ to serve as a substrate for heterogeneous nucleation;
- 2) the structural barrier effect of dispersed particles on dendrite growth;
- 3) possible local interfacial reactions that additionally alter the state of the solidifying melt in the vicinity of the particles.

These factors act simultaneously; therefore, the observed effect should not be reduced to a single mechanism. To conclusively confirm the role of interfacial reactions in this system, direct phase analysis would be appropriate.

Thermodynamically probable interaction of liquid Al with Si₃N₄ may be accompanied by formation of thin AlN interfacial layers and release of Si. The released silicon may potentially react with magnesium to form Mg₂Si. However, within the present study these phases are discussed as probable rather than directly confirmed reaction products.

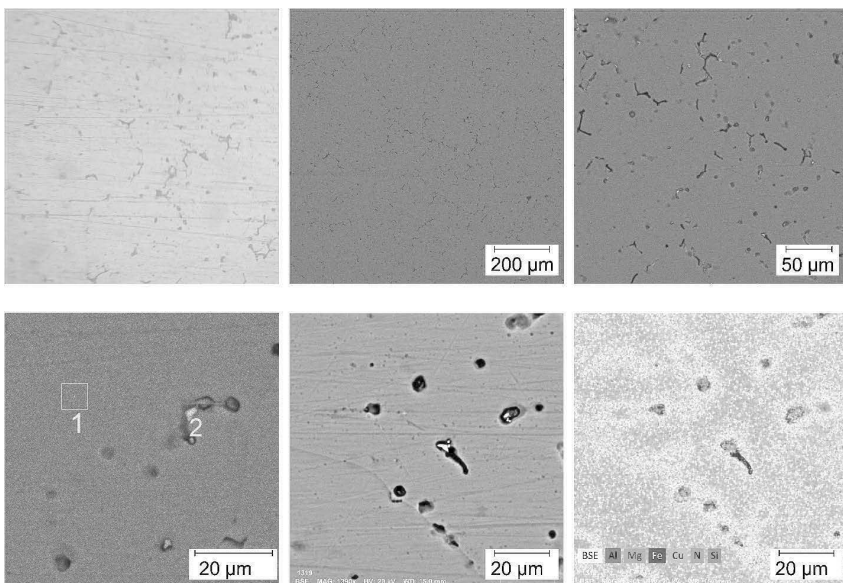


Fig. 5. Microstructure of the AA5056+2%Si₃N₄ composite

The composite microstructure is distinguished by higher uniformity, reduced segregation of eutectic regions, and a relatively homogeneous distribution of Si₃N₄ in the matrix. Such structural rearrangement is consistent with an increase in strength accompanied by some loss of ductility.

Local chemical analysis indicates a difference between the composition of the grains and that of the interdendritic zones. Elevated Fe values at individual points, as in the hybrid composite, should be interpreted as the result of analyzing local Fe-containing particles.

The cast AA5056 alloy in the initial condition is characterized by a set of mechanical parameters typical of an Al–Mg casting material not reinforced with dispersed particles: a moderate yield strength, a relatively low ultimate tensile strength, and limited ductility.

Analysis of Table 3 and Fig. 6 shows that reinforcement of the AA5056 alloy with BN, ZrO₂+BN, and Si₃N₄ increases strength in all cases, whereas the change in ductility differs substantially. The best balance of properties is achieved for the BN-containing composite. The increase in yield strength and ultimate tensile strength in this case is accompanied by a marked increase in elongation, indicating efficient structural refinement without excessive embrittlement of the matrix.

Table 3

Mechanical properties of the obtained MMCs

Parameter	Cast AA5056 alloy [25]	Experimental data for AA5056-based MMCs			
		Initial alloy	2% BN	2% ZrO ₂ +0.3% BN	2% Si ₃ N ₄
Yield strength $\sigma_{0.2}$, MPa	90–120	94.1	104.9	93.1	108.2
Ultimate tensile strength σ_B , MPa	130–160	142.8	186.5	165.4	150.5
Elongation δ , %	2.5–4.0	2.83	5.85	4.72	2.11
Reduction in area ψ , %	3.2–6.0	4.57	7.80	6.47	4.49
Elastic modulus E, GPa	65–75	68.7	71.4	70.2	72.1

The observed mechanical response can be explained in terms of the microstructural constituents of the composites. In the initial AA5056 alloy, the mechanical behavior is governed by the α -Al matrix with pronounced dendritic morphology and microsegregation of Mg in interdendritic regions, which promotes strain localization and limits ductility.

In the BN-reinforced composite, the microstructure is characterized by a refined α -Al grain structure, a more uniform distribution of magnesium, and the presence of chemically inert BN particles without formation of significant brittle interfacial phases. The dominant contribution to strengthening arises from grain refinement of the α -Al phase, while the improved ductility is associated with reduced microsegregation and the absence of brittle constituents that could act as crack initiation sites.

Thus, the favorable combination of strength and ductility is primarily controlled by the modified state of the α -Al matrix rather than by the formation of new strengthening phases.

The hybrid ZrO₂+BN composite demonstrates an intermediate response: strength increases while ductility remains at an acceptable level. This behavior can be attributed to the presence of relatively stable ZrO₂ particles, which contribute to strengthening, combined with their non-uniform distribution and local agglomeration. Such agglomerates act as local stress concentrators, limiting ductility improvement, while the absence of significant brittle interfacial phases prevents its severe degradation.

The Si₃N₄-containing composite exhibits a different response: the strengthening effect

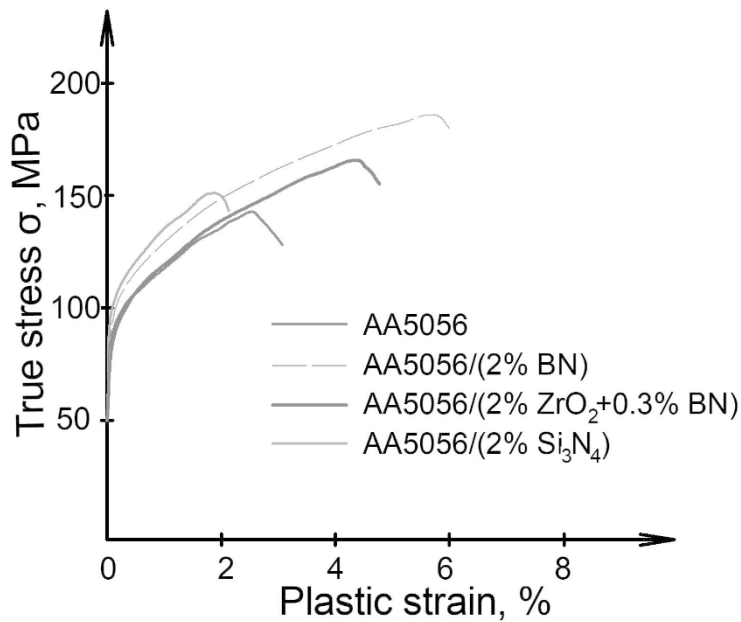


Fig. 6. Stress-strain curves of the experimental samples

is accompanied by a decrease in elongation. This behavior can be associated with the presence of rigid Si_3N_4 particles and possible interfacial reaction products, such as thin AlN layers and locally formed Si-containing phases (e.g., Mg_2Si). These structural constituents can promote stress concentration and act as preferential sites for crack initiation, leading to reduced ductility despite the increase in strength.

Casting properties

The casting properties of AA5056-based MMCs are an important criterion of suitability for real component manufacture, because they determine mold-filling completeness, the uniformity of reinforcing particle distribution, and the tendency to form casting defects.

Based on the chemical composition data, as well as the mass and volume of the experimental samples, porosity values were calculated (Table 4). The comparison shows that introduction of all particle types slightly increases porosity relative to the cast AA5056 alloy without reinforcement.

Table 4

Porosity of the experimental MMCs

MMC sample	AA5056 (cast)	+2% BN	+2% ZrO_2 +0.3% BN	+2% Si_3N_4
Porosity: cylindrical mold (Fig. 1b)	1.5%	2.2%	1.9%	2.3%
Porosity: spiral mold (Fig. 1c)	1.7%	2.5%	2.1%	2.5%

Fluidity in the spiral mold is one of the key casting characteristics of the studied materials. For the experimental samples (Fig. 7), the test results are given in Table 5. It was found that the introduction of reinforcing particles substantially reduces fluidity compared with the initial alloy. The decrease is least pronounced for the ZrO_2 +BN hybrid composition, whereas the greatest losses are observed for the BN- and Si_3N_4 -containing materials.

The obtained porosity values for the cast AA5056 alloy are consistent with literature data for related Al-Mg systems [29]. The observed differences in porosity and fluidity between the studied composites are mainly governed by changes in melt rheology, particle dispersion

Table 5

Fluidity of MMCs in the spiral mold

MMC sample	AA5056 (cast)	+2% BN	+2% ZrO ₂ +0.3% BN	+2% Si ₃ N ₄
Fluidity	428.6 mm —	232.0 mm (-46%)	301.3 mm (-30%)	209.2 mm (-51%)

state, and wettability. The addition of reinforcing particles increases the effective viscosity of the Al–Mg melt, which reduces fluidity and promotes gas entrapment during stirring and solidification. The BN-containing composite shows a moderate decrease in fluidity due to the platelet morphology of BN and its limited wettability, which can locally hinder melt flow. The ZrO₂+BN system exhibits a less pronounced deterioration of casting properties, which is attributed to a more favorable particle distribution and partial improvement of dispersion stability. In contrast, the Si₃N₄-containing composite demonstrates the strongest reduction in fluidity and the highest porosity, which can be associated with the nanoscale nature of particles, their tendency to agglomerate, and increased resistance to melt flow.

In the initial cast condition, the AA5056 alloy is characterized by a weakly pronounced dendritic structure based on the α -Al solid solution, with interdendritic regions enriched in Mg due to microsegregation, and a grain size of 25-100 μ m.

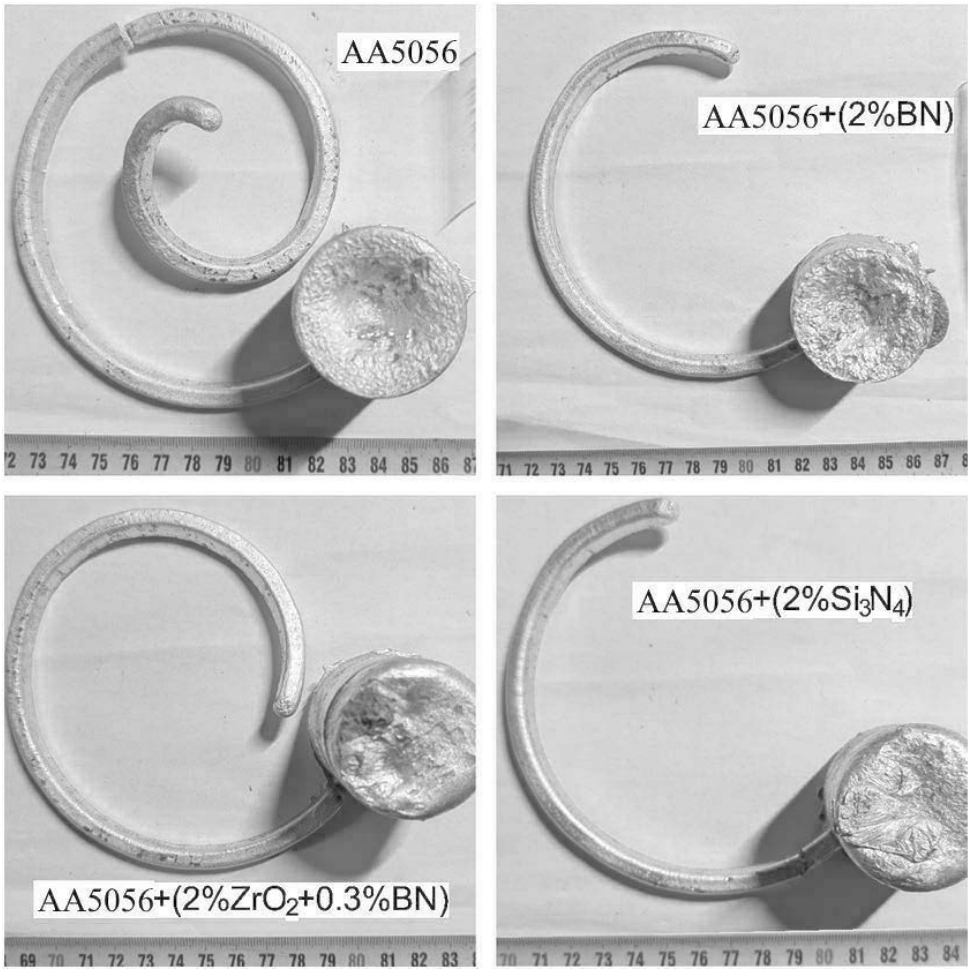


Fig. 7. Samples for determining fluidity in the spiral mold

The introduction of 2 wt. % BN leads to refinement of the α -Al matrix, while BN particles remain as a thermally stable and chemically inert reinforcing phase located predominantly along grain boundaries and interdendritic regions. The observed improvement in strength and ductility is primarily governed by refinement of the α -Al phase and reduced microsegregation of Mg in interdendritic regions, rather than the formation of new strengthening phases. The more uniform microstructure promotes more homogeneous plastic deformation and delays strain localization during tensile loading.

The hybrid AA5056+2%ZrO₂+0.3%BN composite demonstrates a moderate microstructural modification, where the dendritic morphology of the α -Al matrix is largely retained compared with the BN-reinforced material. This behavior is associated with the less effective grain refinement of the α -Al phase and the non-uniform distribution of ZrO₂ particles, partially mitigated by the presence of BN, which improves particle dispersion stability.

At the same time, this composite exhibits a balanced combination of strength and fluidity, which can be attributed to a compromise between partial structural refinement of the α -Al matrix and the absence of extensive interfacial reactions or brittle phase formation.

From a comparative perspective, BN is the most effective reinforcement for improving mechanical properties due to pronounced refinement of the α -Al matrix and reduced microsegregation. The ZrO₂+BN hybrid system provides a balanced but less efficient structural modification due to particle heterogeneity, whereas the Si₃N₄-containing composite is primarily governed by strengthening of the α -Al matrix and possible interfacial interactions, which may simultaneously reduce ductility due to stress concentration effects.

References

- 1 Kumar, D., Angra, S., & Singh, S. (2022). Mechanical properties and wear behaviour of stir cast aluminum metal matrix composite: A review. *International Journal of Engineering*, 35(4), 794–801. <https://doi.org/10.5829/ije.2022.35.04a.19>
- 2 Likhatskiy, R. F., Voron, M. M., Narivskii, A. V., Tverdokhvalov, V. O., Likhatskiy, I. F., & Matviets, E. O. (2025). Aluminum matrix composites based on casting aluminum alloys with oxides and carbides. *Casting Processes*, 159(1), 48–64. <https://doi.org/10.15407/plit2025.01.048>
- 3 Sangghaleh, A., & Halali, M. (2009). Effect of magnesium addition on the wetting of alumina by aluminium. *Applied Surface Science*, 255(19), 8202–8206. <https://doi.org/10.1016/j.apsusc.2009.05.044>
- 4 Saikrupa, C., Chandra Mohan Reddy, G., & Venkatesh, S. (2021). Aluminium metal matrix composites and effect of reinforcements – A Review. *IOP Conference Series: Materials Science and Engineering*, 1057(1), 012098. <https://doi.org/10.1088/1757-899x/1057/1/012098>
- 5 Likhatskiy, R., Voron, M., Narivskiy, A., Tverdokhvalov, V., & Matviets, Y. (2025). Investigation of the fabrication of BN-reinforced pure aluminum composites by casting processes. *New Materials and Technologies in Metallurgy and Mechanical Engineering*, (3), 20–26. <https://doi.org/10.15588/1607-6885-2025-3-3>
- 6 Nemutlu, B., Kahraman, O., Demirel, K. B., Erkul, I., Cicek, M., Sahin, H., Dizdar, K. C., & Dispinar, D. (2023). Processing of boron nitride nanotubes reinforced aluminum matrix composite. *Archives of Foundry Engineering*, 2022(2), 5–10. <https://doi.org/10.24425/afe.2022.140220>
- 7 Abdulkader, N. J., Abass, M. A., Alkhafaji, M. M., & Jassim, G. (2025). Processing and mechanical properties of AA6061 matrix composites reinforced with nano scaled boron nitride. *Revue des composites et des matériaux avancés*, 35(3), 593–600. <https://doi.org/10.18280/rcma.350320>
- 8 Jung, W. G., & Kwon, H. (2004). Fabrication of BN/Al(-Mg) metal matrix composite (MMC) by pressureless infiltration technique. *Materials Science Forum*, 449–452, 301–304. <https://doi.org/10.4028/www.scientific.net/msf.449-452.301>

- 9 Madhusudhan, M., Naveen, G. J., & Mahesha, K. (2017). Mechanical characterization of AA7068-ZrO₂ reinforced metal matrix composites. *Materials Today: Proceedings*, 4(2), 3122–3130. <https://doi.org/10.1016/j.matpr.2017.02.196>
- 10 Prakash, J. U., Jebarose Juliyana, S., Salunkhe, S., Gawade, S. R., Nasr, E. S. A., & Kamrani, A. K. (2023). Mechanical characterization and microstructural analysis of stir-cast aluminum matrix composites (LM5/ZrO₂). *Crystals*, 13(8), 1220. <https://doi.org/10.3390/cryst13081220>
- 11 Rashed, G., Sadawy, M., Kandil, A., Abd Elkarim, A., & Mohrez, W. (2021). Influence of ZrO₂ particles on the tribological properties of AlMg5 alloy. *Journal of Petroleum and Mining Engineering*, 23(1), 95–103. <https://doi.org/10.21608/jpme.2021.68312.1078>
- 12 Rosales-Cadena, I., Falcon-Castrejon, R. A., Guardian-Tapia, R., Roman-Zubillaga, J. L., Gonzaga-Segura, S. R., Falcon-Franco, L. A., Martinez-Landeros, V. H., & Servin, R. (2025). The effect of ZrO₂ addition and thermal treatment on the microstructure and mechanical properties of aluminum metal matrix composites (AMMCs). *Materials*, 18(19), 4507. <https://doi.org/10.3390/ma18194507>
- 13 Podrezov, Y. M., Gogaev, K. O., Voropaev, V. S., Yevych, Y. I., Korzhova, N. P., & Legka, T. M. (2021). The structure and properties of precipitation-strengthened composites produced from a cast alloy in the Al-Si-Mg system. *Powder Metallurgy and Metal Ceramics*, 60(7–8), 496–503. <https://doi.org/10.1007/s11106-021-00261-x>
- 14 Anbuechezhiyan, G., Mohan, B., Senthilkumar, N., & Pugazhenth, R. (2021). Synthesis and characterization of silicon nitride reinforced Al-Mg-Zn alloy composites. *Metals and Materials International*, 27, 3058–3069. <https://doi.org/10.1007/s12540-020-00906-3>
- 15 Öztö, B., & Gürbüz, M. (2021). Investigation of mechanical properties of Si₃N₄ reinforced composites produced from aluminum waste. *European Journal of Science and Technology*, 28, 758–765. <https://doi.org/10.31590/ejosat.1010738>
- 16 Ramesh Kannan, C., Venkatesh, R., Vivekanandan, M., Phani Krishna, J., Manivannan, S., Rajkumar, S., & Vijayan, V. (2022). Synthesis and characterization of mechanical properties of AA8014 + Si₃N₄/ ZrO₂ hybrid composites by stir casting process. *Advances in Materials Science and Engineering*, 2022, 1–11. <https://doi.org/10.1155/2022/9150442>
- 17 Arya, S. M., & Griffiths, W. D. (2023). Aluminum nitride in Al-Si-Mg alloy. *Metallurgical and Materials Transactions B*. <https://doi.org/10.1007/s11663-023-02810-8>
- 18 Moustafa, E. B., Djouider, F., Alhawsawi, A., Elmoujarkach, E., Banoqitah, E., & Mohamed, S. S. (2023). A comprehensive investigation of BN and VC reinforcements on the properties of FSP AA6061 composites. *Lubricants*, 11(12), 507. <https://doi.org/10.3390/lubricants11120507>
- 19 Juliyana, S. J., Prakash, J. U., Salunkhe, S., Hussein, H. M. A., & Gawade, S. R. (2022). Mechanical characterization and microstructural analysis of hybrid composites (LM5/ZrO₂/Gr). *Crystals*, 12(9), 1207. <https://doi.org/10.3390/cryst12091207>
- 20 Raghavendra Rao, P. S., & Mohan, C. B. (2020). Study on mechanical performance of silicon nitride reinforced aluminium metal matrix composites. *Materials Today: Proceedings*, 33, 5534–5538. <https://doi.org/10.1016/j.matpr.2020.03.495>
- 21 Chahuan, N., Singh, S., Thethi, H. P., Ch, S., A, S. J., & Ahmed, R. (2024). Enhancing aluminum-based composite manufacturing: harnessing Si₃N₄ reinforcement via stir casting technique. *E3S Web of Conferences*, 507, 01038. <https://doi.org/10.1051/e3sconf/202450701038>
- 22 Yürektürk, Y., Şenyurt, B., Çeltik, C., Küçükelyas, B., & Akçamlı, N. (2025). Si₃N₄ reinforced Al-Si-Mg matrix composites: powder metallurgy fabrication, PEO coating and characterization. *Applied Surface Science*, 162622. <https://doi.org/10.1016/j.apsusc.2025.162622>

- 23 Zhang, C. F., Cao, W., Fan, T. X., & Zhang, D. (2007). Prediction of the effect of alloying elements on in-situ reaction in synthesizing (AlN+Mg₂Si)/Mg composites. *Key Engineering Materials*, 351, 156–160. <https://doi.org/10.4028/www.scientific.net/kem.351.156>
- 24 Zhu, X., Yang, H., Dong, X., & Ji, S. (2018). The effects of varying Mg and Si levels on the microstructural inhomogeneity and eutectic Mg₂Si morphology in die-cast Al–Mg–Si alloys. *Journal of Materials Science*, 54(7), 5773–5787. <https://doi.org/10.1007/s10853-018-03198-6>
- 25 Okayasu, M., & Takeuchi, S. (2017). Mechanical properties of cast Al–Mg₅ alloy produced by heated mold continuous casting. *International Journal of Metalcasting*, 12(2), 298–306. <https://doi.org/10.1007/s40962-017-0163-6>
- 26 Kataria, M., & Mangal, S. K. (2018). Characterization of aluminium metal matrix composite fabricated by gas injection bottom pouring vacuum multi-stir casting process. *Metallic materials*, 56(4), 231–243. https://doi.org/10.4149/km_2018_4_231
- 27 Mohammadtaheri, M. (2012). A new metallographic technique for revealing grain boundaries in aluminum alloys. *Metallography, microstructure, and analysis*, 1(5), 224–226. <https://doi.org/10.1007/s13632-012-0033-9>
- 28 Kishore, R., Karthick, G., Vijayakumar, M. D., & Dhinakaran, V. (2019). Analysis of mechanical behaviour of natural filler and fiber based composite materials. *International journal of recent technology and engineering*, 8(1S2), 117–124.
- 29 Zare, M. A., Taghiabadi, R., & Ghoncheh, M. H. (2021). Effect of cooling rate on microstructure and mechanical properties of AA5056 Al–Mg alloy. *International Journal of Metalcasting*. <https://doi.org/10.1007/s40962-021-00704-6>

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ВИГОТОВЛЕННЯ ЛИТИХ КОМПОЗИТИВ НА ОСНОВІ СПЛАВУ AA5056, АРМОВАНИХ BN, ZrO₂ і Si₃N₄

Металеві композиційні матеріали з алюмінієвою матрицею (МКМ), отримані методами лиття з перемішуванням, становлять значний інтерес завдяки поєднанню технологічної простоти, відносно низької вартості та можливості масштабованого виробництва виробів зі

збалансованими механічними та ливарними характеристиками. Для сплавів системи Al–Mg, зокрема AA5056, підвищений вміст магнію створює сприятливі умови для змочування дисперсних частинок та реалізації механізмів дисперсійного і структурного зміцнення. У роботі проведено порівняльне дослідження впливу трьох типів армувальних фаз — BN, ZrO_2 +BN та Si_3N_4 — на формування мікроструктури, пористість, текучість і механічні властивості литих композитів на основі AA5056, отриманих за однакових умов лиття з перемішуванням. Показано, що введення 2 мас.% дисперсних частинок у розплав призводить до суттєво різних ефектів, зумовлених як бар'єрною дією частинок на ріст дендритів, так і можливими міжфазними взаємодіями. Найбільш виражений позитивний ефект встановлено для нітриду бору: спостерігається істотне подрібнення зерна, вирівнювання розподілу легувальних елементів у мікрооб'ємі та формування більш однорідної структури. Це супроводжується одночасним підвищенням межі міцності при розтягу та пластичності, що свідчить про ефективне поєднання механізмів зміцнення без крихкого руйнування. Для гібридної системи ZrO_2 +BN характерні менш виражені структурні зміни зі збереженням дендритної морфології та частковою агломерацією частинок, що обмежує ефективність модифікування. Водночас така композиція демонструє компроміс між міцністю, пластичністю та текучістю, важливо для виготовлення литих виробів. Додавання Si_3N_4 забезпечує підвищення міцності за рахунок подрібнення зерна та можливих локальних міжфазних реакцій, однак супроводжується зниженням пластичності внаслідок концентрації напружень та ймовірного утворення крихких продуктів взаємодії, таких як інтерфейсні нітридні та кремнієві фази. У результаті встановлено закономірності формування структури та властивостей литих МКМ на основі AA5056 залежно від природи армувальної фази. Вони полягають у переважанні міжзеренного зміцнення та зниженні мікросегрегації для BN, структурній неоднорідності для гібридної системи та можливих міжфазних реакціях для Si_3N_4 . Отримані результати можуть бути використані для оптимізації складу і технологічних параметрів з метою досягнення необхідного балансу між механічними та ливарними характеристиками матеріалів.

Ключові слова: сплав AA5056; металоматричні композити; перемішування розплаву; нітрид бору; діоксид цирконію; нітрид кремнію; мікроструктура; механічні властивості; рідкоплинність; пористість.