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INVESTIGATION OF THE FABRICATION OF BN-REINFORCED PURE ALUMINUM COMPOSITES BY CASTING PROCESSES

***Purpose**. The main objective of this research was to evaluate the feasibility of producing aluminum matrix composites (AMC) based on pure aluminum reinforced with boron nitride using casting technologies, in particular the stir casting method. This approach was chosen due to its technological simplicity, relatively low cost, and potential scalability for industrial applications.*

***Research methods**. To analyze the distribution and morphology of the reinforcing particles, microstructural metallographic analysis using optical microscopy was applied. The chemical composition of the composites was determined by X-ray fluorescence analysis and spark optical emission spectrometry. These methods provided reliable data on the content and incorporation of boron nitride particles into the aluminum matrix, as well as the influence of additional alloying elements (Ni, Sn, Zr) on the composite structure.*

***Results**. Experimental AMC samples containing 1–3 wt.% BN were produced by stir casting, including variants with fluxes and alloying elements under different melting conditions. The composite structures contained BN particles evenly distributed in the matrix; however, their actual content was only 7–15 % of the amount initially introduced in the charge. It was found that the efficiency of BN incorporation strongly depends on the melt composition (amount of reinforcing particles, presence of fluxes and microalloying elements) and on the melting parameters (superheating temperature, stirring time). The porosity of the obtained composites was also studied: the addition of BN significantly increased porosity, whereas the presence of Sn reduced it due to eutectic formation.*

***Scientific novelty**. New data were obtained on the feasibility of producing AMCs based on pure aluminum with BN reinforcement by stir casting with the use of fluxes and microalloying additives, which improve BN incorporation.*

***Practical value**. The results complement existing knowledge on AMC fabrication and explain the lack of studies using pure aluminum as the matrix. The findings may also be applied to optimize casting technologies for manufacturing aluminum matrix composites.*

***Key words:** aluminum matrix composites, stir casting, aluminum, boron nitride, microstructure.*

Introduction

Aluminum matrix composites (AMCs) based on pure aluminum are attracting increasing interest in materials science due to their unique combination of properties: low density, high electrical conductivity, and corrosion resistance, complemented by the strength, wear resistance, and thermal stability of the reinforcing phases. Despite the widespread use of powder metallurgy technologies in AMC production, one of the most economically feasible and technologically simple methods for obtaining such composites is stir casting, which ensures low cost and suitability for mass production [1].

However, the implementation of this method in case of pure aluminum (Al ≥ 99.7 %) encounters a number of significant challenges, the main one being the insufficient wettability of ceramic, carbon, and other particles by the metallic matrix. The low interfacial energy between the reinforcement particles (e.g., SiC, Al_2O_3, TiB2, graphene) and the aluminum melt hinders their uniform distribution within the matrix and leads to aggregation, pore formation, or defective bonding at the phase interface [2, 3]. As a result, the obtained composite may exhibit a non-uniform microstructure, reduced mechanical strength, and lower wear resistance.

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The main factors influencing the incorporation and distribution of reinforcing particles include wettability, particle shape and size, rheological properties of the melt, stirring rate, density of the reinforcing material, temperature regime, and others [4–7].

To ensure better wettability of reinforcing particles in the metallic matrix and their uniform distribution in the melt volume, fluxes and modifying additives are widely used. These components alter the surface energy of the system, contributing to the reduction of interfacial tension and minimizing the probability of particle agglomeration. Fluxes play an important role in improving wettability by promoting effective wetting of the particle surface with the melt and removing oxide films that hinder the formation of a strong matrix-particle interface. In the production of aluminum matrix composites (AMCs), chloride-fluoride fluxes have proven their efficiency, as they actively clean the melt surface from aluminum oxides, thereby facilitating the incorporation of reinforcing particles into the melt and ensuring their uniform inclusion in the matrix [8].

The use of hexagonal boron nitride (BN) as the primary reinforcing phase in aluminum-based composites is attracting increasing attention due to its unique combination of structural and functional efficiency [1, 9, 10]. BN has a low density (2200 kg/m^3), a layered hexagonal crystal structure similar to graphite, which provides a low coefficient of friction and high thermal stability (~1000 °C). In the context of stir casting, these properties make BN a promising alternative to traditional ceramic fillers (SiC, Al_2O_3), especially for systems operating under intensive friction or thermal loading [11].

Despite these advantages, the use of BN for AMC fabrication by stir casting is associated with several technological challenges, the most critical being the poor wettability of BN surfaces by molten aluminum, which arises from its chemical inertness and energetically stable surface structure.

Existing studies on the use of BN in AMC fabrication by casting technologies have demonstrated significant improvements in the mechanical and tribological properties of the composites. However, aluminum alloys such as AA3003 [12] and AA7075 [13] have been used as matrix materials. Investigations of similar AMCs based on pure aluminum may allow a better evaluation of the influence of individual melting conditions on the reinforcement efficiency of boron nitride.

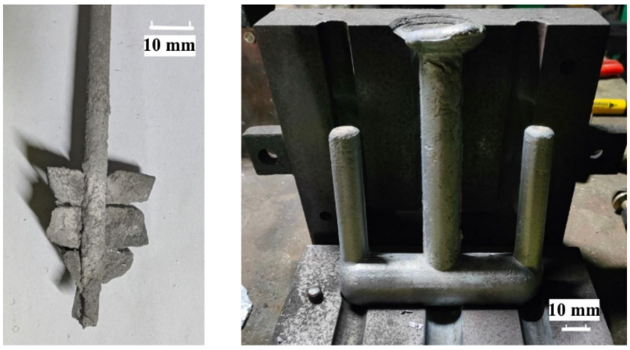
Purpose

The aim of this study is to produce aluminum matrix composites based on pure aluminum with boron nitride by melt stirring followed by casting, and to evaluate the incorporation of reinforcing particles into the matrix as well as the factors affecting this process.

Materials and methods

The material of study was aluminum matrix composites based on high-purity aluminum grade A95 (≥ 99.7 % Al, analogous to AA1350). Hexagonal boron nitride with an average particle size of ~5 μm was used as the reinforcing phase. The BN content in the charge ranged from 1 to 3 wt.% under different conditions of AMC fabrication (Table 1).

Melting was carried out in a laboratory resistance furnace using an alumina crucible. To improve particle incorporation, the melt was mechanically stirred with a titanium impeller (Fig. 1*a*) at a rate of 10 s^{-1}. Stirring time prior to casting varied depending on the experiment. Reinforcing particles were preheated to 200 °C. The casting temperature was 750–850 °C. The melt was poured into thick-walled steel molds to produce cylindrical samples with diameters of 10 and 15 mm. Cooling occurred under normal air conditions directly in the mold (Fig. 1*b*).



a *b*

Figure 1. Features of the technology for producing AMCs: *a* – titanium stirrer; *b* – mold with an experimental aluminum matrix composite sample

Some experimental melts included fluoride fluxes [8], as indicated in Table 1. The flux consisted of a mixture of KCl, NaCl, and NaF in an amount equivalent to the mass of BN particles.

Table 1 – Chemical composition of experimental samples

AMC	Element content in the charge, wt.%				
	Al	BN	Sn	Ni	Zr
Al-BN	97,7	2,3^1	-	-	-
	98,2	1,8	-	-	-
	97,7	2,3	-	-	-
	97,0	3,0	-	-	-
Al-(Sn+BN)	99,0	0,5	0,5	-	-
	98,0	1,0	1,0	-	-
Al-(Ni+BN)	97,2	1,8	-	1,0	-
	96,7	2,3	-	1,0	-
	96,0	3,0	-	1,0	-
Al-(Ni+Zr+BN)	97,5	1,5	-	0,5	0,5
	97,0	2,0	-	0,5	0,5

Note. 1. In this AMC no flux was used.

Additional melts were conducted with the addition of tin (Sn) to improve BN incorporation (Table 1). According to the Al-Sn phase diagram, under normal conditions, Sn may exist in solid solution in small amounts [14]. Sn can act as a surface energy modifier, thereby enhancing BN

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wettability by molten aluminum [15]. Tin also improves plasticity and wear resistance of the composite [16], and in synergy with BN, this may yield improved performance. The drawback of Sn is reduced thermal stability [14, 17]. At the microstructural level, Sn may localize at grain boundaries or BN-matrix interfaces, forming interlayers that affect grain growth, hinder BN coalescence, and reduce agglomeration [18].

Nickel additions exert a fundamentally different effect. Ni exhibits high solubility in liquid Al and strong reactivity, forming intermetallic phases, improving interfacial adhesion, generating eutectics, and enhancing thermal stability. At the casting temperature (750-800 °C), Ni actively interacts with Al, forming Al_3Ni, which may distribute at grain boundaries or around BN particles [19, 20]. The formation of reaction interlayers such as Ni-BN or Al-Ni-BN at the matrix-particle interface can further improve adhesion. Corresponding data on the chemical composition of Al-Ni-BN composites are given in Table 1.

The addition of zirconium to Al-Ni-BN systems further modifies the microstructure. During solidification, stable Al_3Zr intermetallics form, refining grains and strengthening the matrix. Due to Zr’s high affinity for nitrogen and boron, interfacial reactions may produce ZrN or ZrB_2, enhancing BN-matrix bonding [21]. The composition of Al-(Ni+Zr+BN) composites is shown in Table 1.

Metallographic specimens were prepared from the samples and etched with Keller’s reagent (aqueous solution of HNO_3, HCl, and HF) [22] for microstructural analysis under an optical microscope. Chemical composition was analyzed using an Expert 3L X-ray fluorescence spectrometer. The BN content was determined using a SPECTROMAXx spark optical emission spectrometer.

Composite density was both theoretically calculated and experimentally measured to evaluate porosity. Experimental density was determined by mass measurement in air and water according to ASTM C135-2003 [23]. Theoretical density was calculated by the rule of mixtures (Eq. 1).

$$\rho_{th} = \rho_{Al}\varphi_{Al} + \rho_x\varphi_x \,, \tag{1}$$

where ρ_{th}, ρ_{Al}, ρ_x are the theoretical densities of the AMC, aluminum, and reinforcing particles, respectively, kg/m^3;

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

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

$$\%porosity = \frac{\rho_{th}-\rho_{exp}}{\rho_{th}} \,, \tag{2}$$

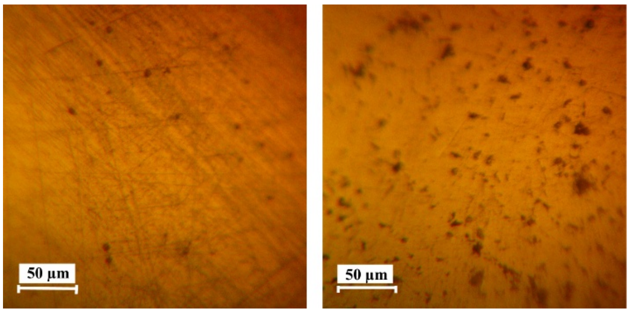
where ρ_{exp} is the experimental density of the AMC, kg/m^3.

Results

Metallographic analysis revealed that the macrostructures contained only minor inclusions of BN particles, which became visible only after prolonged etching. In samples with 2.3 wt.% BN produced without flux, optical microscopy did not reveal BN inclusions.

Figure 2 presents a comparison of the microstructures of composites with 2.3 wt.% BN produced without and with flux. Chemical analysis likewise did not detect reinforcing BN particles in the sample cast without flux. In the other sample, the BN content was only 0.15 wt.%. This indicates poor wettability of boron nitride by aluminum, causing BN to agglomerate and float on the melt surface.

For AMC samples with BN and flux, a series of melting runs was conducted to establish the dependence of particle incorporation on the duration of mechanical stirring and on the melt temperature prior to pouring (Fig. 3). The obtained data indicate that the stirring duration may range from 30 to 90 s, as this parameter had only a minor effect on the BN content measured by chemical analysis. All melts were mechanically stirred not only before pouring but also during melting; otherwise, BN would float and be absent from the composite. The effect of melt superheating can be assessed more precisely: the optimal pouring temperature is 800–820 °C, above which the BN content changes negligibly. For subsequent runs, the following parameters were used: mechanical stirring for 60 s at a pouring temperature of ~ 800 °C.



a *b*

Figure 2. Microstructure of Al-2.3 wt.% BN samples:
a – without flux; *b* – with flux

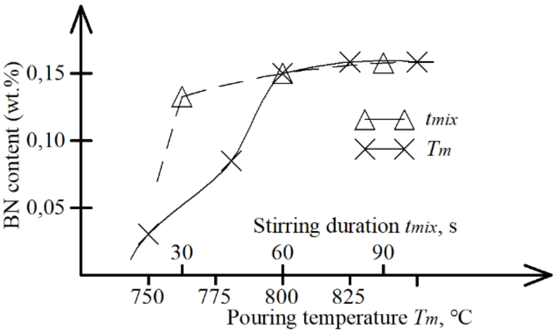


Figure 3. Dependence of BN content in AMCs on melting parameters at 2.3 wt.% BN in the charge

To assess the effect of the amount of BN reinforcing particles, several experimental melts were carried out with a BN mass fraction in the charge from 1.5 to 4 wt.%. The results of chemical analysis (Fig. 4a) indicate inefficient reinforcement with BN above 2.5 wt.%, which is explained by the poor wettability of BN by pure aluminum and more pronounced reverse sedimentation.

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Tin additions to BN-containing composites improve the wettability of the reinforcing particles and increase their retained amount in the samples (Fig. 4*b*). However, the incorporated amount is only about 10 % of the BN mass charged. Moreover, increasing the joint content of Sn and BN to 1 wt.% worsens particle incorporation. The microstructure of the Sn-containing composite exhibits eutectic regions and dark BN inclusions within a fine-grained aluminum matrix (Fig. 5*a*).

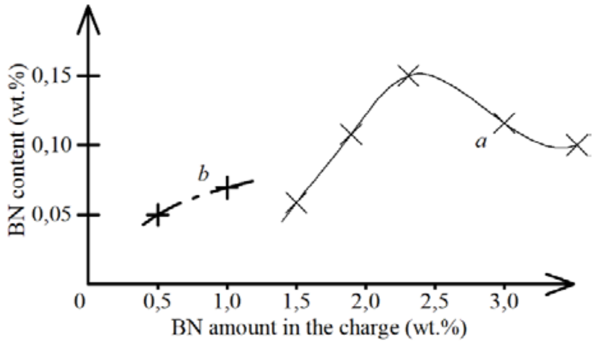
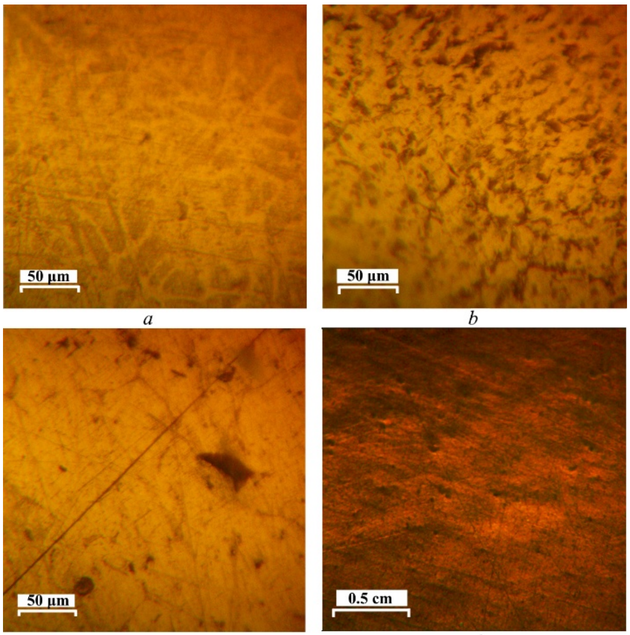


Figure 4. Dependence of BN content in AMCs on its amount in the charge for composites: *a* – Al-BN; *b* – Al-(*x*%Sn+*x*%BN)

As expected, samples containing nickel showed better BN incorporation. The microstructure of the alloy with 2.3 wt.% BN and 1 wt.% Ni indicates the presence of intermetallic phases (Fig. 5b). According to chemical analysis, the sample contains reinforcing BN particles up to 0.3 wt.%.

Replacing half of the nickel in the charge with zirconium led to an even larger amount of intermetallic phases. The microstructures (Figs. 5c, 5d) show dark inclusions up to 20 µm that may be clusters of Al_3Ni, Al_3Zr intermetallics and boron nitride.



a *b*

c *d*

Figure 5. Microstructures of AMC samples (wt.%):
a – Al-(0,5Sn+0,5BN); *b* – Al-(1,0Ni+2,3BN);
c, d – Al-(0,5Ni+0,5Zr+1,5BN)

Composites with nickel (including those with zirconium) exhibit better BN incorporation (Fig. 6). At the same time, the dependence of BN incorporation on its amount in the charge is similar to that in AMCs without Ni and Zr (Fig. 4*a*).

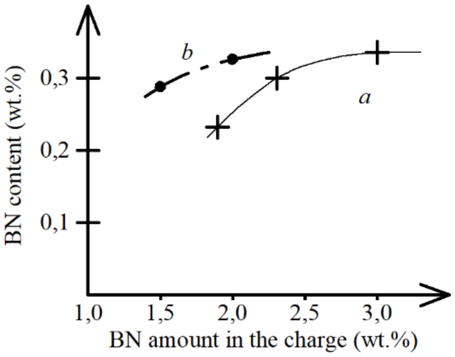


Figure 6. Dependence of BN content in AMCs on its amount in the charge for composites: *a* – Al-(1%Ni+BN); *b* – Al-(0,5%Ni+0,5%Zr+BN)

A summary of BN incorporation in the obtained composites is presented in Fig. 7. After measuring the sample masses and performing the corresponding calculations, the porosity of each composite was determined. The porosity of the aluminum matrix composites is shown graphically in Fig. 7.

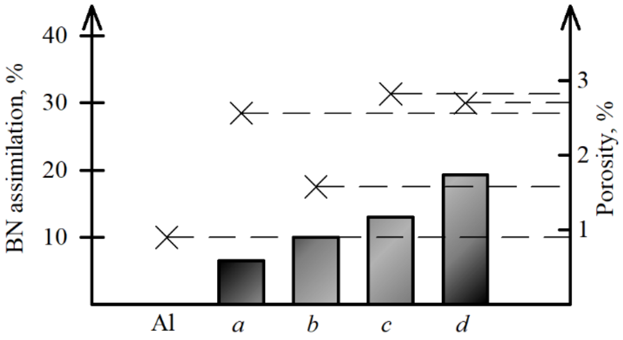


Figure 7. Assimilation of BN and porosity in Al-matrix composites: *a* – Al-2,3%BN; *b* – Al-(0,5%Sn+0,5%BN); *c* – Al-(1%Ni+2,3%BN); *d* – Al-(0,5%Ni+0,5%Zr+1,5%BN)

The porosity values of the AMCs were significantly higher than for pure aluminum, due to poor wettability and gas removal during melting. The formation of intermetallics in Ni- and Zr-containing composites hinders gas evolution from the melt; therefore, effective melt degassing should be employed for such AMCs. The presence of Sn reduces the concentration of gas voids and improves particle-matrix bonding, which favorably affects the porosity of these composites.

Conclusions

In this study, the feasibility of producing aluminum matrix composites (AMCs) based on pure aluminum with the addition of boron nitride by melt stirring and the use of agents to improve its incorporation was investigated. Tin, nickel, and zirconium were also introduced into the composites. Based on the obtained results, the following conclusions were drawn:

- The wettability of BN by aluminum in the absence of magnesium or other metals capable of significantly reducing the melt surface tension is very poor. Sn improves wettability due to eutectic formation in the melt, while Ni and Zr enhance it through the formation of intermetallics and the strong affinity of Ni for BN. At best, during stir casting, about 19% of the charged BN was incorporated.
- For stir casting, the addition of fluxes or modifiers is essential, as is melt stirring for at least 60 s before pouring and superheating the melt to 800–830 °C.
- The presence of BN leads to a sharp increase in composite porosity. The lowest porosity was observed in samples containing Sn, whereas the presence of Ni and Zr intermetallics further increased porosity.
- Increasing the BN content in the charge to 3 wt.% or higher did not improve, and in some cases even reduced, the BN content in the composite. This was caused by severe particle agglomeration and flotation to the melt surface during melting. The optimal BN content was 1–2.5 wt.% depending on the alloying elements present. However, with the addition of magnesium or other modifiers, larger amounts of BN can be effectively incorporated due to the significantly improved wettability of BN by aluminum.

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ДОСЛІДЖЕННЯ ОДЕРЖАННЯ КОМПОЗИТІВ З НІТРИДОМ БОРУ НА ОСНОВІ ЧИСТОГО АЛЮМІНІЮ ЛИВАРНИМИ ТЕХНОЛОГІЯМИ

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Мета роботи. *Основною метою дослідження було оцінити можливість одержання алюмоматричних композитів (АМК) на основі чистого алюмінію з армуванням нітридом бору за допомогою ливарних технологій, зокрема методу лиття з перемішуванням. Такий підхід обрано завдяки його технологічній простоті, відносно низькій вартості та потенційній масштабованості до промислових умов.*

Методи дослідження. *Для аналізу розподілу та морфології армуючих частинок застосовано мікроструктурний металографічний аналіз за допомогою оптичної мікроскопії. Хімічний склад композитів визначали методами рентгенофлуоресцентного аналізу та іскрової оптично-емісійної спектрометрії. Це дозволило отримати достовірні дані щодо вмісту та засвоєння частинок нітриду бору в алюмінієвій матриці, а також оцінити вплив додаткових легуючих елементів (Ni, Sn, Zr) на структуру композиту.*

Отримані результати. *Експериментальні зразки АМК з вмістом 1–3 % (мас.) BN були отримані методом лиття з перемішуванням, у тому числі із застосуванням флюсів і легуючих елементів за різних умов плавки. У структурах композитів виявлено частинки BN, рівномірно розподілені в матриці, проте їх фактичний вміст становив лише 7-15% від кількості, внесеної у шихту. Встановлено, що ефективність засвоєння BN суттєво залежить від складу розплаву (вмісту армуючих частинок, наявності флюсів і мікролегуючих елементів), а також від технологічних параметрів плавки (температура перегріву, тривалість перемішування). Досліджено пористість отриманих композитів: введення BN значно її збільшує, тоді як наявність Sn знижує пористість завдяки утворенню евтектики.*

Наукова новизна. *Одержано нові дані щодо можливості виплавки алюмоматричних композитів на основі чистого алюмінію з нітридом бору технологією перемішування розплаву з використанням флюсу та мікролегуючих добавок, які підвищують засвоєння нітриду бору.*

Практична цінність. *Результати роботи доповнюють наявні відомості про виплавку алюмоматричних*

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композитів та пояснюють відсутність досліджень саме з чистим алюмінієм як матрицею. Також отримані дані можуть бути використані для оптимізації ливарних технологій виготовлення таких композитів.

Ключові слова: *алюмоматричні композити, лиття з перемішуванням, алюміній, нітрид бору, структура.*

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