Research Article

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Evaluation of the Mechanical Properties of Aluminium Hybrid Nano Composites Using Ultrasonic-Assisted Stir Casting Method and Reinforced with Nano-scale SiC and MoS_2 Particles

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ABSTRACT

The purpose of this research is to investigate the effects of adding large quantities of reinforcing agents specifically, 3% MoS_2 along with different SiC concentrations 5%, 10%, and 15% to LM25 aluminium alloys. The goal of producing these composites was to improve the material characteristics of hybrid metal matrix composites (HMMCs) by the use of ultrasonic-assisted stir casting. The study looks at the possible benefits of using particulate materials to improve the mechanical properties of metallic composites, such as silicon carbide (SiC) and molybdenum disulphide (MoS_2). The research assesses the impact of SiC and MoS_2 Nano scale additions on the mechanical and structural characteristics of LM25 composites by experimental analysis. The results of mechanical property testing show significant improvements, especially when 15% of Nano-scale SiC is included. This is mainly because the Nano-scale SiC is evenly distributed throughout the host metal.

Keywords: Metal matrix composite; Ultrasonic stir casting; Nano SiC reinforcements; Tensile strength; Nano composite.

1. INTRODUCTION

Metal is used as a matrix material and may be reinforced with ceramic, metal, or organic compounds to create metal matrix composites. Metal can't me*et al*l of the requirements for every application, thus in order to get around this, the metal's qualities need to be improved, which is why other materials are reinforced with metal. With the aid of AL MMCs, it becomes simple to meet the requirements of several applications, including those in the automotive, aerospace, and other sectors. To improve the characteristics of base alloys, materials such as SiC, Al2O3, boron carbide, zircon, fly ash, etc. are employed as reinforcement. Reinforcement comes in three different forms: particles, discontinuous fibres, and continuous fibres. Sulaiman *et al.* (2017) this work examined how different weight percentages of strontium affect the mechanical and microstructural characteristics of Al-12Si (LM6) alloy and Al-SiC composites. The effect of strontium as a modifier on the microstructure was investigated using an electron microscope equipped with an EDS scanning system. Using the vortex process, the Al-SiC composite was created using 10 weight percent silicon carbide and various Al-10Sr fractions (0.02, 0.5 weight percent). The inclusion of SiC and Sr enhanced the ultimate tensile strength, but any increases in tensile characteristics were limited by the weak contact between the particles and the matrix. Mohan *et al*. (2015) because of its increased strength and stiffness, silicon carbide reinforced aluminium matrix composites are extensively used in the automotive and aerospace sectors. Many studies have been conducted on the production of AMCs using the stir casting method with different weight percent of SiC. Studies show that as the SiC content increases, so do the yield strength and modulus of elasticity of Al/SiC composites. However, the inclusion of SiC particles causes a shift in fracture behavior from ductile to brittle, as shown by SEM fractographs, indicating a trade-off between strength and fracture toughness.

Singh *et al.* (2020) the mechanical and microstructural features of aluminium silicon carbide composites made by powder metallurgy and stir casting techniques have been extensively studied. Research indicates that the effective transmission of stress and strengthening of dislocations are the reasons why adding more SiC to Al/SiC composites increases their hardness. Analyses using SEM show how SiC particles are distributed and affect the composites. Furthermore, the SiC concentration has a major impact on the densification behavior, which in turn affects the composites' overall density and mechanical performance. Ashebir *et al.* (2022) Compared to single-reinforcement composites, hybrid aluminium matrix composites, which combine many reinforcing elements, have better qualities. This study of the literature looks at several synthesis techniques, such as powder metallurgy and stirs casting, and assesses the effects of reinforcements on mechanical and metallurgical characteristics, including graphite, silicon carbide, and aluminium oxide. Thorough explanations of testing (hardness, tensile, compressive, and tribological) and characterizations (X-ray diffraction, optical microscopy) demonstrate the thorough comprehension of HAMCs' physic mechanical characteristics and production methods. Nirala *et al.* (2023) the increased mechanical characteristics of aluminium Nano composites supplemented with B_4C, SiC, and CNT particles are attracting growing attention in research. SEM and XRD tests validate that the reinforcing distribution is uniform throughout the fabrication process of squeeze stir casting. The production of intermetallic compounds and dislocation structures, which increase composite strength, is shown by TEM examinations. Comparative analyses show that B_4C-reinforced composites outperform SiC-reinforced composites in terms of hardness, Young's modulus, and wear resistance, underscoring the important influence of reinforcing type on the performance of the Nano composites. Sharifi, E *et al.* (2011) due of their improved mechanical characteristics, Al–B_4C Nano composites have been the subject of much investigation in both their synthesis and characterization. When pure Al powder and B_4C nanoparticles are combined by ball milling and hot pressing, bulk samples with different B_4C contents are obtained. Research shows that when compared to pure aluminium, composites with a greater B_4C content especially at 15% weight percentage have far better wear resistance, compressive strength, and hardness. The creation of a mechanical mixed layer on the composite surface, which improves wear performance, is the main wear mechanism seen.

Arif *et al.* (2019) a great deal of research has been done on the wear behavior of hybrid Al-SiC Nano composites, which combine micro-SiC with different concentrations of Nano-silicon carbide. Studies show that wear resistance is highly dependent on the addition of nano-SiC, sliding distance, and applied stress; 5 weight percent of nano-SiC is shown to provide the best results. Wear debris and worn surfaces analyzed by SEM and EDS demonstrate the effect of nano-SiC reinforcement. High accuracy is shown by regression models used to forecast tribological behaviour, demonstrating their usefulness in forecasting wear characteristics under certain circumstances. Vinayaka. N *et al.* (2023) because of their exceptional mechanical qualities, aluminium metal matrix composites, particularly those reinforced with Nano scale particles, are essential in the automotive, aerospace, and defense industries. Research on stir-cast aluminium alloy AA8011 reinforced with 15% nano boron carbide particles has showed notable improvements in tribological behaviour. Scanning electron microscopy analysis of studied with different sliding velocities, wear temperatures, and applied loads reveals improved performance. The efficiency of these composites in obtaining desired tribological features was further validated by multi objective optimisation with the grey relational approach. Ma M *et al.* (2015) The remarkable hardness, high-temperature oxidation resistance, and low wear rates of nano-multilayered films, which were distinguished by their nanoscale layer arrangement, make them perfect for surface protection in a variety of applications. Their kinds, preparation techniques, microstructures, mechanical characteristics, and corrosion resistance have all been the subject of recent study. Research has elucidated the processes behind their exceptional toughness and hardness, offering insights into their extraordinary performance. Future studies will focus on designing films with better toughening and strengthening qualities in an effort to further improve these qualities.

Cheng *et al.* (2023) The use of nano-multilayered films, comprising of layers organized at the Nano scale, is widespread in surface protection because of their low wear rates, high temperature oxidation resistance, and hardness. Their varieties, preparation techniques, microstructures, mechanical characteristics, and corrosion resistance have all been studied recently. The processes behind their extreme toughness and hardness have been clarified by in-depth examinations. In the future, scientists want to create nano-multilayered films with improved toughness and strengthening capabilities, which will increase their use in the electrical and engineering sectors. Nagavelly *et al.* (2024) the creation of lightweight materials, such as aluminium alloys, was essential to reduced CO_2 emissions and improved fuel economy. Metal matrix composites with improved mechanical and tribological characteristics were created when aluminium 7075 alloy was reinforced with different types of nanoparticles. Studies showed that stir casting ceramic nanoparticles greatly enhanced these characteristics, which makes them ideal for use in aeronautical applications. In order to fully realized the promise of these sophisticated composites, this study also discussed the difficulties that exist now and suggested future research avenues. Kumar *et al.* (2020) Many studies have been conducted on the high-temperature wear behaviour of Al2219-based composites, such as Al2219+2%n-B_4C (mono) and Al2219+2%n-B_4C+2%MoS_2 (hybrid). These composites were prepared by stir casting, and wear experiments showed that temperature, load, and sliding velocity had a major impact on wear rates. Owing to the production of oxide layers and the lubricating properties of MoS_2, the Al2219/2%n-B_4C/2%MoS_2 hybrid composite exhibits decreased wear at higher temperatures, while the specific wear rate of Al2219 and Al2219/2%n-B_4C rises with temperature. At higher temperatures, SEM analysis verified that the hybrid composite has shallower and narrower wear tracks. Wu *et al*. (2022) this work used an in-situ reaction between KBF4 and $K2ZrF_6$ fluoride powders to create ZrB_2/Al7085 Nano composites, which were then heated and subjected to heat treatment and hot deformation. ZrB_2 nanoparticles and second phases were redistributed during hot rolling, which enhanced the microstructure. ZrB2 particles and α-Al interfaced semi-coherently, according to TEM examination. By minimizing anisotropy, reducing residual stress, and refining grain size, ZrB_2 particles improved the mechanical properties. To increase the strength of the composite, the strengthening methods comprised load transfer, Orowan strengthening, thermal expansion coefficient, and grain refining. Gao *et al*. (2023) One efficient way to improve the ductility and strength of metals and alloys is by the incorporation of scattered nanoparticles. The mechanical characteristics of ZrB_2/AA7085 nano composites, which were created by in-situ melt processes, have significantly improved, according to recent research. With an average size of 95 nm, the ZrB_2 nanoparticles aid in dynamic recrystallization and alter precipitation behaviour, resulting in enhanced particle dispersion and refined α-Al grains. The ultimate tensile strength and elongation both significantly improve as a consequence, underscoring the promise of nanoparticle reinforcement in the development of high-performance nano composites. Fang *et al*. (2020) investigated the in situ reinforced AA6016 matrix composite with ZrB_2 and Al_2O_3 nanoparticles demonstrated that temperature and strain rate have a major impact on the behaviour of hot deformation, with flow stress quickly rising with true strain and falling with temperature. The behaviour of the material is well described by the constitutive model based on the Arrhenius equation. Two stable deformation zones were found by processing maps: Domain B (410–430 °C/0.37–1 s−1), which is characterized by dynamic recrystallization, and Domain A (300–360 °C/0.08–0.01 s−1), which was regulated by dynamic recovery. According to microstructural study, these nanoparticles improved the nucleation of recrystallization at high temperatures, which makes Domain B the ideal hot processing window. Zhao *et al*. (2018) Study conducted on in situ 2 vol. % nano ZrB_2/AA6111 composites have showed that flow stress reduces with increasing temperature and decreasing strain rates, with notable post-stability variation in the flow curves. Constitutive modeling based on predicted material constants accurately characterizes the behaviour of the composite. Processing maps revealed the best hot deformation domains, with Domain B (430 °C–460 °C/0.13–1.1 s−1) being the most advantageous because particle clusters promote dynamic recrystallization. By lowering recrystallization grain size, these clusters improve high-temperature performance by enhancing DRX while restricting grain growth. Kai *et al*. (2015) the analysis of the hot deformation behaviour of an in situ 5 weight percent nano ZrB_2/2024Al composite revealed that temperature and strain rate had a substantial impact on flow stress. Notably, the presence of nanoparticles at higher temperatures and strain rates resulted in noticeable strain hardening. Microstructural data collaborate the kinetic equation's identification of dynamic recrystallization as the main deformation process. Two primary domains were found by processing maps: domain 1 (380–410°C/0.018–0.032 s−1) and domain 2 (440–460 °C/0.075–0.56 s−1). Domain 2 was best suited for hot processing because of its finely equiaxed grain structure and better power dissipation efficiency. The results highlighted domain 2 as the ideal window for effective and secure hot deformation. Tao *et al*. (2022) Due to particle-matrix separation, particle-reinforced aluminium matrix composites often have poor forming stability; however, in situ PRAMCs, such as ZrB_2-reinforced AA6111, showed better interface bonding and mechanical characteristics. Grain size was greatly refined in AA6111 composites by increasing the ZrB_2 content, which also increased the geometrically required dislocation density and encourages continuous dynamic recrystallization Tensile characteristics are improved by this refinement and increased dislocation density; the 2 vol% ZrB_2/AA6111 composite achieves noteworthy ultimate tensile strength, yield strength, and elongation. Qian *et al*. (2023) In situ ZrB_2 nanoparticle-reinforced AA6111 composites exhibit significantly improved high-temperature creep resistance compared to the base alloy, with a threshold stress of 28 MPa at 573 K versus 15MPa for the matrix. ZrB_2 particles enhance creep properties by impeding dislocation motion and pinning grain boundaries, maintaining their size stability during deformation. The creep mechanism for both the composite and the matrix alloy is dominated by high-temperature dislocation climb, as indicated by a stress exponent of 5. Yang *et al*. (2016) used a direct melt reaction with halide salts, ZrB_2/6061Al hierarchical nano composites were created, yielding a two-level composite structure. In comparison to the unreinforced matrix, the composite's mechanical characteristics were significantly improved by this special microstructure, resulting in increases in hardness, strength, and ductility. The ZrB_2/6061Al composite with a volume percentage of two shown significant improvements in yield strength and elongation. This was mainly because to quench strengthening and the presence of toughened clusters that enabled plastic deformation.

2. MATERIALS AND METHODS

2.1 Selection of Matrix and Reinforcement Materials

Aluminium (purity 98%) was used as the matrix material in this study, while SiC (5%, 10%, and 15%) and molybdenum (IV) sulphide (MoS_2)-3% were used as reinforcing materials to create aluminium hybrid metal matrix composites using ultrasonic aided stir casting operations. The particle sizes of the SiC and MoS_2 particles were assessed using the Zetasizer particle size analyzer. During the manufacturing process, MoS_2 powder with a particle size of 2 µm is employed, and SiC particles with a purity of 40–50 nm is used. The size and surface appearance of the composite with SiC nanoparticles serving as reinforcement are shown in Fig 1.

Table 1. LM25 aluminium alloy chemical composition

Chemical composition	Ti	Sn	Pb	Zn	Ni	Mn	Fe	Si	Mg	Cu
LM25	0.2	0.1	0	0.1	0.1	0.3	0.5	6.5-7.5	0.2-0.6	0.1

Table 2. Mechanical properties of pure LM25 and LM25-MoS_2-SiC composites

Samples composition	LM25-MoS_2-SiC/Nano composites			
	Ultimate Tensile Strength (MPa)	Yield strength (MPa)	% of elongation	Hardness (BHN)
Pure LM25	205.60±0.5	132.24 ±2.5	11.23±0.5	70.26
LM25-3% MoS_2	242.25±0.7	165.29±0.6	10.56±0.6	87.28
LM25-3% MoS_2-5% SiC	251.58±2.0	182.34±1.5	8.25±1.3	90.43
LM25-3% MoS_2-10% SiC	261.79±2.2	194.21±2.2	6.54±1.5	94.16
LM25-3% MoS_2-15% SiC	280.71±2.3	220.56±0.8	3.3±2.1	103.16

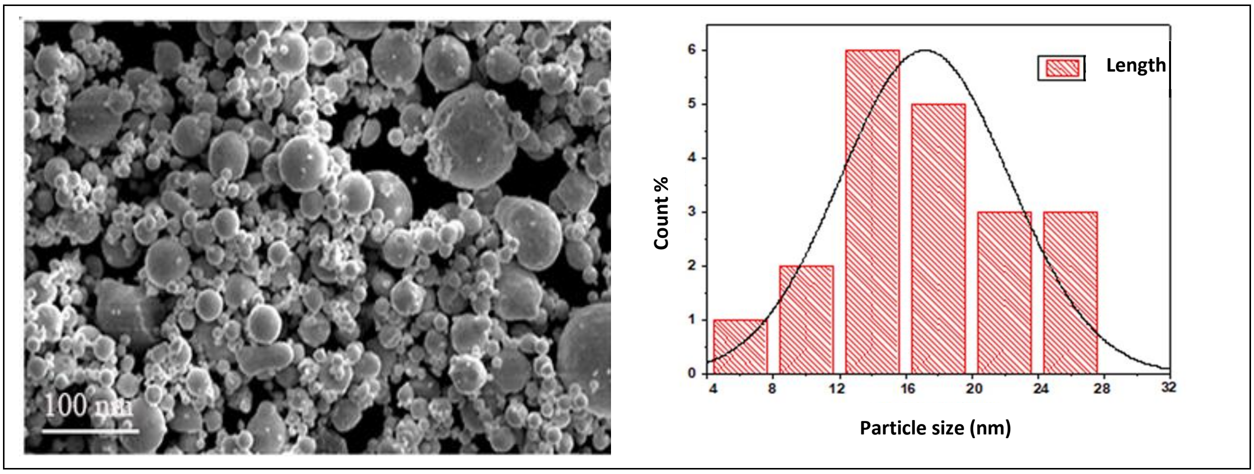

Fig. 1: (a) Microstructure of SiC particle (b) SiC nanoparticle size (20-21nm)

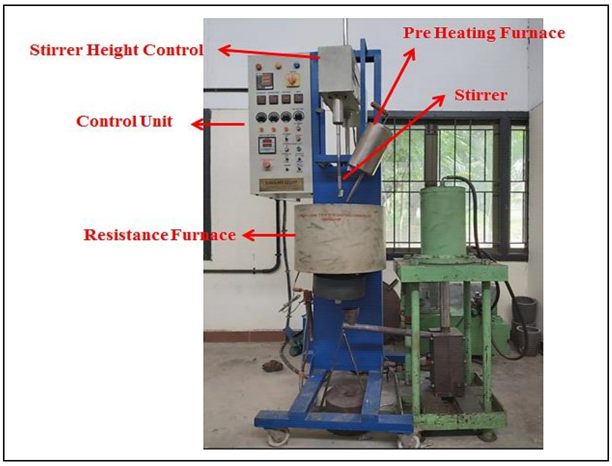

Fig. 2: Experimental setup of ultrasonic assisted stir casting process

2.2 Hybrid Composite Slurry Formation by Stirring Operation

Al-LM25 was heated and filled with all possible combinations of composite samples into a graphite crucible furnace that measured 150 x 150 mm in height and diameter. The addition of a fixed 5-wt% of MoS_2 for reinforcement to the molten metal was accomplished by using an external device running at 900 °C. To get a uniform dispersion of the reinforcing particles inside the aluminium melt, a standardized mixing procedure was used, which included a 10-minute duration and 460 rotations per minute. To reduce the amount of gas trapped within the aluminium, a tablet containing hexachloroethane (C_2Cl_6) was added to the mixture in order to degas it. Then, the SiC nanoparticles were added to the molten aluminium after being heated to 2000 °C for 30 minutes. An automatic mixer was then used to thoroughly mix this mixture for a further 20 minutes at a speed of 350 to 400 rpm. Magnesium (Mg) powder was mixed into the melt during the mixing phase to enhance the wetting connection between the reinforcements and the matrix. An argon (Ar) gas shield was used throughout the stir-casting process to stop the reinforcements and matrix from oxidizing.

2.4 Mechanical Testings

Using the Archimedes principle, the density was calculated both theoretically and empirically. According to ASTM E384-16, the purpose of the hardness test was to determine how the nano-scale SiC/MoS_2 reinforcement affected the hardness characteristics of the LM25 aluminium matrix. With a dwell period of three seconds and a load of 25 N, the hardness profile was measured. The assessment energy was sustained for 10-15 seconds and exposed to a range of applied loads, from 1 to 120 kgf. The initial energy application interval was specified as 2-8 seconds. The study was conducted under ambient settings, and the data that was collected was the average of each specimen's five consecutive impressions. Using the ASTM E8 standard as a guide, the tensile strength was calculated parallel to the extrusion direction. A universal testing machine (UTM) was used to perform a tensile test at room temperature and a cross-head speed of one mm per minute.

3. RESULTS AND DISCUSSION

3.1 Density Measurement

The calculated density values for novel hybrid Nano composites, consisting of varying ratios of nano-sized silicon carbide and molybdenum disulphide within a monolithic aluminum alloy matrix, show that the experimental densities are consistently lower than the theoretical values. The alloying elements' proportions by weight were converted to their respective volume fractions to determine the theoretical density using the rule of mixtures. The experimental density ($e_{xperimental}$) is calculated using the formula:

$$\rho_{Experimental} = \left[\frac{m_{air}}{m_{air-}m_{water}}\right] x\rho_{water} \quad \text{......... (1)}$$

Density of water (0.998 g/cm^3 at 20 °C).

$$\rho_{Theoretical} = \rho_{Al\ alloy} + W_{Al\ alloy} + \rho_{SiC} * W_{SiC} + \rho_{MoS_2} - W_{MoS_2} \quad \text{......... (2)}$$

Where the weight fraction and density are W and ρ

$$\%porosity = \left(1 - \frac{\rho_{Experimental}}{\rho_{Theoretical}}\right) x100$$

The 3 wt% of MoS_2 reinforced on LM_{25} aluminium composite density 2.74 g/cm^3 is 5.3% higher than pre-aluminium alloy. Pure LM25 alloy demonstrated the smallest density value due to differences in the densities of the reinforcing material and the matrix, as shown in Figure 3. As previously indicated, the density of the 3 wt%MoS_2-5wt% SiC particles amounts to 2.589 g/cm^3, a value that increases above the density of Aluminium LM_{25} matrix alloy. Metal matrix composite can be linked to the inclusion of ceramic particles, which are less dense. Therefore, the sample with the reduced density is predicted to be the more delicate. When SiC particles are added to the Al matrix, the porosity levels in hybrid composites different from those in previous aluminium alloys—are successfully decreased. It leads to an increase in the density of the composite material.

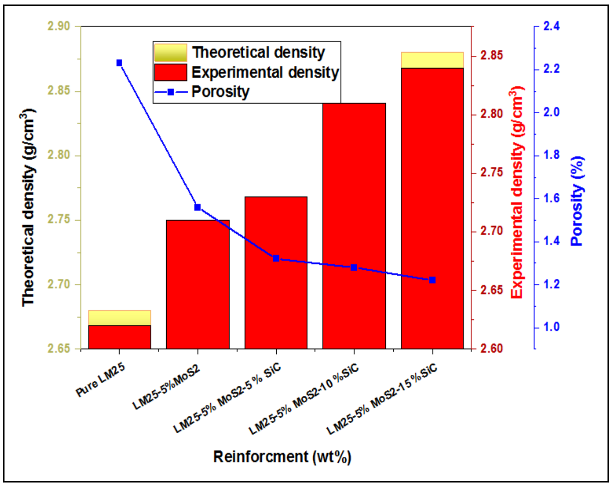

Fig. 3: Density prediction for prepared composites

3.3 Effect of SiC Nanoparticles on Tensile Strength of LM25 Hybrid Composites

Ultimate Tensile Strength Yield Strength and Elongation (E) for the newly developed hybrid metal matrix composites. These tensile properties were measured at ambient temperature with the aid of a universal testing machine. To ensure accuracy, the tensile strength readings for the composite specimens were averaged from three individual tests. The composite comprising LM25 alloy, augmented with 3wt% MoS_2 and 15wt% SiC nanoparticles, exhibited a maximum tensile strength of 280.71 MPa. This represents a significant increase in strength 36.23% in UTS and 40.93% in YS compared to the unaltered base alloy. When LM25 alloy was combined with 3% MoS_2, without SiC, it demonstrated a tensile strength of 251.2 MPa and a YS of 165.29 MPa. The inclusion of up to 15 wt% SiC nanoparticles has been proven to substantially enhance the mechanical characteristics of Al-SiC Nano composites. Further, the homogeneous dispersion of SiC nanoparticles throughout the aluminum matrix strengthens the inter-particle bonding, The Nano composites of hardness increasing trend were observed with increases of SiC volume fraction from 5wt% to 15wt

%. The inclusion of 15 vol. % nano- SiC_P resulted in the attainment of the highest hardness of pure LM25.

4. CONCLUSION

Through the use of ultrasonic-assisted stir casting, the aluminium composite was fabricated using nano SiC particles and MoS_2. The main goal of the study was to determine how changing the weight percentages of SiC would affect the composite's mechanical properties, tensile strength, and hardness. Several findings were drawn from the study's data collection. After adding 15wt% SiC and 3wt% MoS_2 particles, the synthesized composite's hardness and ultimate tensile strength (UTS) significantly increased respectively. This improvement was seen when compared to LM25 aluminium that was pure. By adding additional stiff reinforcement particles, the hybrid composite's BHN, US, and YS may be improved by increasing the weight % of SiC and MoS_2. The LM25 composite reached a pinnacle tensile strength of 280.71 MPa after being strengthened with 3 wt. % MoS_2 and 15 wt. % SiC nanoparticles. This represents an increase of UTS and YS over the original matrix alloy. The volume percentage of SiC in the Nano composites arise from 5wt% to 15wt%, and a trend of increasing hardness was seen. The hardest BHN (103.16 BHN) was obtained by including 15% of nano-SiC; this was an improvement over the hardness of pure LM25 (70.26 BHN).

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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