

Effect of Premixing Process on the Uniform Distribution of Nano hBN and Carbon Fiber Reinforcements in AA7050 Matrix

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Original scientific paper

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Abstract:

In Aluminium metal matrix composites, achieving a homogeneous dispersion of reinforcements remains a significant challenge, especially when mixing fibrous and nanoscale reinforcements. The effect of the premixing procedure on the homogeneous dispersion of carbon fiber (CF) and nano hexagonal boron nitride (hBN) reinforcements in AA7050 matrix is studied in this work. Before composites are prepared, a multi-stage process for premixing is used, which consists of ultra-sonication, magnetic stirring, and mechanical mixing in order to minimize particle clustering. This also improves the wetting between the reinforcement and the matrix. Field emission scanning electron microscope (FESEM) was used to characterize the premixed powders to assess agglomeration behaviour, interfacial integrity, and dispersion uniformity. Due to the premixing process, better densification of nearly 95.2% and enhancement of 33.3% of micro-hardness are reported for 0.25 wt.% CF and 0.5 wt.% hBN addition. The results reveal that after the premixing process, particle dispersion was improved, leading to high-quality composites in the subsequent sintering process. The premixing process offers a better way to disperse the nano reinforcement particles in the production of aluminium metal matrix nanocomposites, which directly influences the properties of the composites.

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1. INTRODUCTION

The relevance of aluminium metal matrix composites (AlMMCs) is very high due to their unique properties, such as a high strength-to-weight ratio and high corrosion resistance, compared to conventional materials. Several research works are ongoing to reinforce different types of materials in aluminium (Al) alloys, which can be ideal for various aerospace and automotive applications [1-3]. The usage of Al alloys (AA) is restricted in some areas due to their property degradation resulting from their prolonged usage

and high-temperature stability issues. For high temperature applications, heat treatable alloys such as 2xxx, 6xxx, and 7xxx alloys are commonly used, but most of the works are restricted to AA2024, AA6061, AA2219, AA7075, etc., and limited research works were focused on the usage of AA7050 [4,5]. Some drawbacks of the AA7050 include low hardness under dry sliding conditions, poor wear resistance at high loads, etc. [6,7]. These drawbacks restrict the usage of AA7050 in most engineering applications. In this regard, this research focuses on improving the mechanical and tribological properties of the AA7050. Zinc is the

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major alloying element in the AA7050, having 5.7 weight percentages (wt.%), along with copper 2.19 wt.%, Magnesium 1.99 wt.%.

Reinforcement selection is one of the main challenges in the manufacturing of composites. Reinforcement addition in the matrix enhances the property upgradation of Al alloys; especially, we can tailor the properties depending on the end application. To date, much work has been done by reinforcing a single type of reinforcement in the Al matrix. In most cases, reinforcement of single particles enhances one property at the expense of the others. SiC is added into the AA7075 matrix, and the mechanical and tribological properties were studied. The results show that mechanical properties have improved at the expense of tribological properties [8].

In this regard, the importance of hybrid composites is recognized, in which two or more reinforcements are added to the matrix to simultaneously improve both mechanical and tribological properties. Choosing the right combination of reinforcements in the hybrid composites is the most challenging part [9-11]. Nano-sized reinforcement particles are shown to have superior properties compared to micron-sized particles, but some studies claim that using nano particles at levels above 2 wt.% in the matrix resulted in severe agglomeration and property degradation [12-15]. Nano and micro-sized TiB₂ particles were reinforced into A356, and the nanocomposites showed 27% improvement in toughness and 43% in tensile strength at 1.5 wt.% TiB₂ nano particle addition [16]. Fiber reinforcements were not commonly used in Al alloys due to their manufacturing difficulty, fiber pull-outs, interfacial reactions, etc. In some cases, coatings were applied to the fiber to improve its interfacial bonding with the matrix [17]. Considering the research works on the Al alloys by reinforcing different types of reinforcement materials, a few works were reported in the Al composites, which reinforce nano hexagonal boron nitride (hBN) and carbon fiber (CF) into the AA7050 matrix. In this regard, our research is focusing on reinforcing nano hBN and carbon fiber into the AA7050 matrix.

The manufacturing of nanocomposites is one of the main challenges faced by researchers; agglomeration formation and wettability issues are two of the main drawbacks while manufacturing composites through the casting method. To overcome the issues, the powder metallurgy method is suggested, which mitigates

agglomeration and wettability issues to some extent, especially in the case of Al composites [18]. Some of the advantages of following powder metallurgy include near-net-shaped products, better microstructural control, and low structural damage, etc. The conventional sintering process is chosen due to its higher densification and enhancement in the properties [19].

Premixing of the reinforcement and matrix particles has shown better results by improving the uniform dispersion of the composites in the matrix, which is one of the main challenges in the manufacturing of the nanocomposites [20]. This step also facilitates more effective interfacial interactions between particles, thereby improving load transfer efficiency. Premixing is followed by consolidation and sintering. During premixing, agglomerations break up, enhancing the uniform dispersion of particles in the matrix and helping achieve high-performance nanocomposites.

Carbon Nano Tube (CNT)s were added into the Al matrix, and the influence of sonication was studied. Sonication enhances CNT dispersion in the matrix and prevents structural damage. It also suggests that high-energy ball milling (HEBM) followed by sonication improves the homogeneity of particles [21]. The premixing process also improves the ball milling efficiency, which directly correlates with the matrix-reinforcement interface, load-carrying capacity, and the composite performance. The effective premixing process improves the properties of the composites by reducing agglomeration and providing consistency in the composite material [22]. The influence of multi-walled CNTs (MWCNTs) in AA2219 is studied at two conditions, by direct ball milling and premixing followed by ball milling. The results show that premixing followed by ball milling shows better dispersion of the particles in the metal matrix composites. The premixing process includes ultra-sonication, magnetic stirring, and mechanical stirring [23]. Nano hBN particles were dispersed into AA7050 through the premixing process, including ultra-sonication, magnetic and mechanical stirring, and show better uniform distribution of nano particles in the matrix [24,25].

This work focuses on the influence of premixing processes such as ultra-sonication, magnetic stirring, and mechanical stirring in achieving the uniform dispersion of the nano hBN and carbon fiber reinforcement in the AA7050 matrix. The novelty of this work lies in the determination of premixing process parameters tailored for bi-modal reinforcement on the Al matrix, dispersion of

particles in the matrix, and creation of a direct relation between the premixing effectiveness and homogeneity of the final PM composite.

2. MATERIALS AND METHODS

AA7050 is taken as the base matrix for the study, having a particle size of 5 μm. Nano hexagonal boron nitride (average size of 70 nm) and carbon fiber (diameters ranging from 6–7 μm) have been chosen as the reinforcements. FESEM images of the as-received matrix and reinforcement particles are shown in Fig. 1. The FESEM images were taken from the FESEM Laboratory, Department of Physics,

CUSAT. Fig. 1(a) shows the FESEM of AA 7050, having a spherical shape, which implies good flowability and packing features during compacting. The hBN FESEM is shown in Fig. 1(b), which reveals that the nanoparticles were agglomerated into large bundles due to their strong Van der Waals forces and the covalent bond between the boron and nitrogen atoms. The image clearly shows the need for premixing in order to break the bundles. The carbon fiber shows, Fig. 1(c), a clean surface, which indicates that the fibers were free from defects and impurities. Such morphological features of all three constituents are crucial, as they directly influence the homogeneity and interfacial bonding in the final composite.

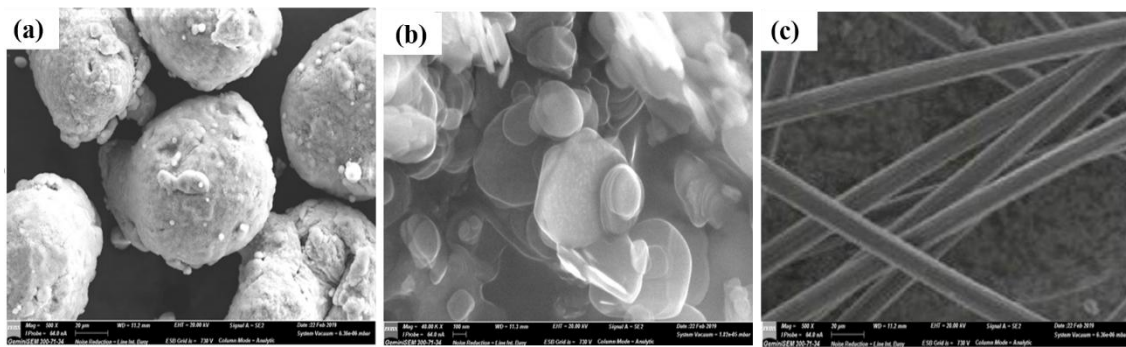


Fig. 1. FESEM images as-received (a) AA7050 (b) nano hBN (c) Carbon fiber

The carbon fiber weight percentage in this study is fixed at 0.25 wt.% based on preliminary experiments on the same matrix, as higher concentrations have shown large clustering. The weight percentage of nano hBN was varied from 0, 0.25, 0.5, 0.75, 1, 1.5, and 2 wt.%, and accordingly, different combinations of the hybrid composite were prepared, as summarised in Table 1.

Table 1. Hybrid composite sample combinations in weight percentages

Sample	AA 7050 (wt. %)	Carbon fiber (CF) (wt. %)	hBN (wt. %)
AA	100	0	0
AA0	99.75	0.25	0
AA25	99.5	0.25	0.25
AA50	99.25	0.25	0.5
AA75	99	0.25	0.75
AA100	98.75	0.25	1
AA150	98.25	0.25	1.5
AA200	97.75	0.25	2

The premixing of the particles includes ultrasonication, magnetic stirring, and mechanical

stirring. The schematic representation of the premixing process is shown in Fig. 2. Firstly, nano hexagonal boron nitride (hBN) particles were ultrasonicated in an ethanol solution for 30 minutes at ambient temperature. In this step, due to the 5-second pulsed ON/ OFF high-frequency (above 20 Hz) acoustic waves, the agglomerated hBN starts to break down to form a homogenous suspension by reducing the effect of the Van der Waals force. After 30 minutes, carbon fibers were added to the suspension, and it was subjected to 15 minutes of sonication; in this step, the initial interaction of the two reinforcement phases started without compromising the structure and aspect ratio of the fibers. Sonication is followed by 15 minutes of magnetic stirring at a speed of 500 rpm. During magnetic stirring, hBN particles were uniformly dispersed over the fiber surface, thus creating a bimodal reinforcement phase.

Subsequently, once the bimodal reinforcement phase is formed, the base matrix AA 7050 is added to the suspension, and magnetic stirring is continued for another 15 minutes. The base matrix was added slowly to avoid agglomeration during the initial mixing and to increase the interfacial contact area. Magnetic stirring is followed by mechanical

stirring at a controlled speed of 300 rpm for 30 minutes for additional uniform dispersion of the particles. The final stage of mechanical stirring ensures the enhancement of interfacial contact between the particles, breaks down any agglomeration present, and improves the wettability of the reinforcement particles with the

matrix. After mechanical stirring, the ethanol-hBN-CF-AA7050 suspension is dried in an oven at 80 °C for 30 minutes, until all the ethanol is evaporated. This step-wise premixing process improves the uniform dispersion of the reinforcement particles in the matrix without structural damage and minimizes defects.

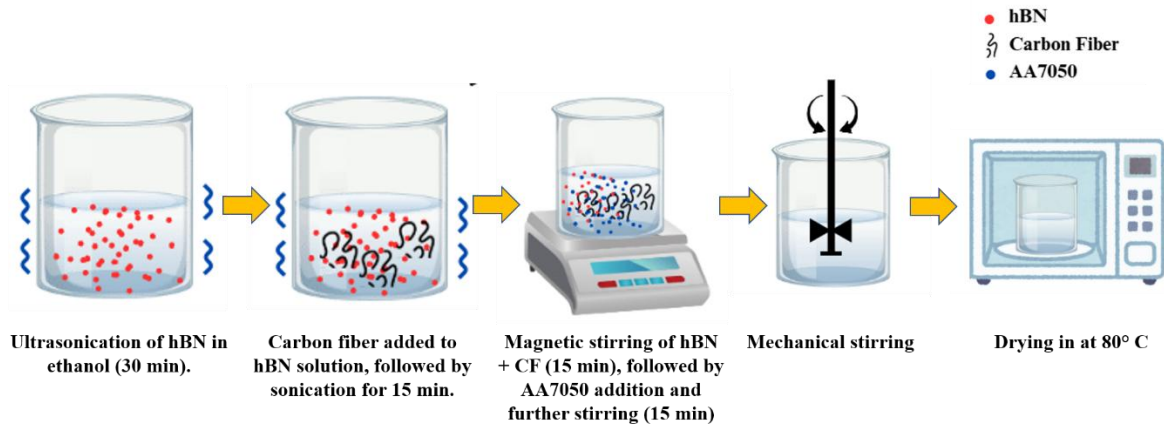


Fig. 2. Schematic representation of powder preparation using premixing techniques

3. RESULTS AND DISCUSSION

The FESEM images of the samples after premixing are shown in Fig. 3, all captured at the same magnification. FESEM characterization helps identify the homogeneity of the reinforcement particles in the matrix. Fig. 3(a) shows the premixed

AA7050 without reinforcements, where no significant morphology changes occurred. Fig. 3(b) indicates that the addition of 0.25 wt.% carbon fiber, since it is a fibrous reinforcement, has a limited influence on the AA7050 surface during the premixing.

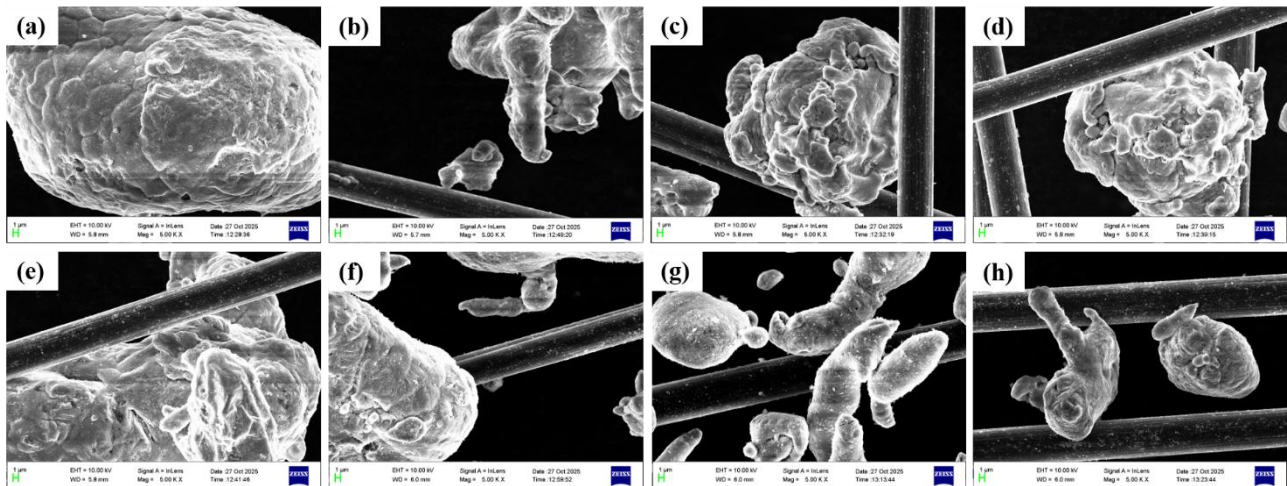


Fig. 3. FESEM of the premixed samples at different concentrations (a)AA (b) AA0 (c) AA25 (d) AA50 (e) AA75 (f) AA100 (g) AA150 (h) AA200

Fig. 3(c) shows the effects of the addition of 0.25 wt.% hBN nanoparticles, and the images show the hBN particles on the AA7050 and carbon fibers as fine particles that were uniformly distributed in the matrix. Fig. 3(d) shows the effect of increasing the hBN concentration to 0.5 wt.%, and the image clearly shows more evenly dispersed nanoparticles

compared to the previous case, indicating that the combination improved powder homogeneity. From Fig. 3(c) and (d), at the lower hBN concentrations (0.25–0.5 wt.%), the hBN nanoparticles were evenly distributed on the AA7050 and carbon fibers.

Fig. 3(e) shows the premixed sample with 0.75 wt.% hBN. At this concentration, some

nanoparticles start to show small clusters, adjacent to both alloy and fiber surfaces, showing that some clustering starts to occur, and this increases with further reinforcement. Fig. 3(f) shows further clustering with 1 wt.% hBN addition, as clusters of particles can be seen across the matrix. Fig. 3(g-h) shows the images with 1.5 wt.% and 2 wt.% hBN addition. As can be seen in the higher reinforcement levels, the nanoparticles started to lose their uniformity and aggregate into bundles, appearing similar to the agglomerated structure of the as-received hBN powder. The presence of these agglomerations at higher hBN concentration levels significantly decreases the surface area available for bonding, and these points act as stress concentration zones and hinder the uniform densification during the sintering process, directly affecting the properties of the composites.

Upon analyzing the FESEM images, the best combination of the reinforcement particles with uniform dispersion is visible at 0.25 wt.% CF + 0.5 wt.% hBN. Uniform dispersion of the particles at 0.25 wt.% CF + 0.5 wt.% hBN indicates a possible way for better enhancement in the property. The observations reveal that premixing facilitated a reasonably uniform distribution of matrix and reinforcement particles at lower concentrations, while clustering tendencies reappeared at higher reinforcement levels.

The FESEM images of premixed AA7050 +0.25 wt.% CF +0.5 wt.% hBN at different magnifications is shown in Fig. 4; these images clearly demonstrate the efficiency of the premixing process to get effective dispersion of nano hBN particles across the alloy and carbon fiber surfaces. At Fig. 4(a), the distribution of 0.5 wt.% hBN in the AA7050 and 0.25 wt.% CF is clearly noticeable, at 5KX magnification. The nanoparticles are uniformly distributed without agglomeration or sticking. The magnified view at 10KX (Fig. 4(b)) is even clearer, revealing better dispersion without particulate agglomeration. At 20KX (Fig. 4(c)), the distribution of hBN particles on the carbon fiber surface is further evident and free of sticking, which enhances effective reinforcement at the fiber matrix interface. Lastly, the high-resolution image at 50KX (Fig. 4(d)) further demonstrates a finer distribution of hBN particles, in contrast to the as-received hBN powders, which revealed potential particle agglomeration.

Fig. 5 shows the FESEM images of the AA7050 + 0.25 wt.% CF + 2 wt.% hBN composite after premixing, taken at magnifications between 5KX and 50KX. These images clearly mention the effect of increased hBN concentration on the matrix's

dispersion behaviour. The 2 wt.% hBN concentration is clearly visible on the AA7050 and carbon fiber surfaces at 5KX magnification (Fig. 5(a)). Regardless, nanoparticles appearing bound in groups indicate a non-uniform distribution and the beginning of clustering. The enlarged view at 10KX magnification (Fig. 5(b)) provides clearer evidence of this non-homogeneity, with distinct clusters of hBN particles forming rather than dispersing evenly.

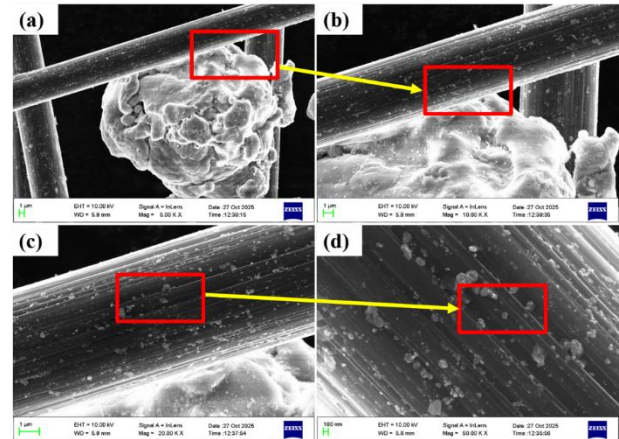


Fig. 4. FESEM images of AA7050 + 0.25 wt.% CF + 0.5 wt.% hBN composite after premixing, captured at different magnifications

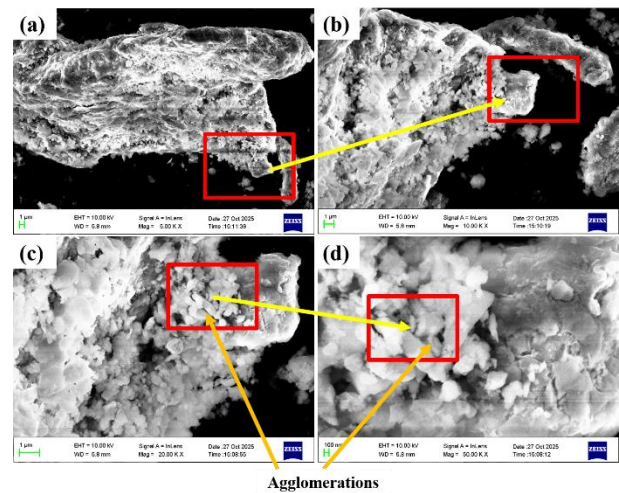


Fig. 5. FESEM images of AA7050 + 0.25 wt.% CF + 2 wt.% hBN composite after premixing, captured at different magnifications

At 20KX magnification (Fig. 5(c)), the clustering becomes more pronounced, with large bundles of nanoparticles observed across the matrix and fiber surfaces, confirming poor dispersion at this reinforcement level. Fig. 5(d) shows the 50KX magnification of the sample, revealing severe agglomeration of the nano hBN particles on the AA 7050 and CF surfaces, similar to the as-received image of the hBN (Fig. 1(b)). The observations

reveal that at higher concentrations (≥ 0.75 wt.%), nanoparticles were not uniformly distributed within the matrix phase even after premixing, whereas at lower concentrations (≤ 0.5 wt.%), they were uniformly distributed. The non-dispersion of the nanoparticles will affect the homogeneity of the composite during the sintering process and negatively affect the composite properties. These observations also emphasize the premixing process, such as ultra-sonication, magnetic stirring, and mechanical stirring, in overcoming the tendency of the nanoparticles to form clusters due to their Van Der Waals forces [20].

After the premixing process, the powders were subjected to ball milling and conventional sintering. The process parameters for the conventional sintering are shown in Table 2.

Table 2. Process parameters of conventional sintering

Compaction pressure	250 MPa
Compaction time	5 minutes
Sintering time	60 minutes
Sintering temperature	500°C
Atmosphere	Argon
Cooling	Furnace cooling

The actual and relative densities of hybrid AA7050 composites reinforced with 0.25 wt.% carbon fiber and varying hBN concentrations (0-2 wt.%) are shown in Fig. 6, which shows a clear densification trend. Both density metrics peak at the AA50 composition, corresponding to 0.50 wt.% hBN, indicating that this reinforcement level achieves the most efficient packing and the least porosity during conventional sintering. The efficient packing is due to the effectiveness of the premixing process, as shown clearly in Fig. 4.

Beyond AA50, both actual and relative densities begin to decline, suggesting that higher hBN content (0.75 wt.% and above) introduces microstructural challenges such as particle agglomeration, which is visible in Fig. 5. These agglomerations will hinder effective sintering and reduce the composites ability to achieve full densification. The consistent trend between the actual and relative density curves confirms that hBN concentration plays a critical role in determining the composites structural compactness.

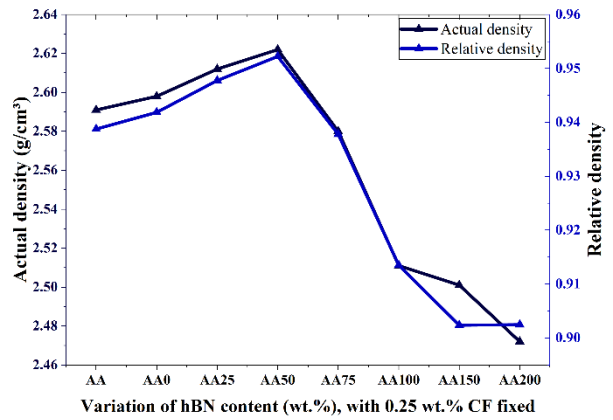


Fig. 6. Variation in density of the hybrid composites at different reinforcement concentrations

The micro hardness results are shown in Fig. 7, with a clear peak at the AA50 composition, indicating that the combination of 0.25 wt.% CF and 0.5 wt.% hBN yield the highest surface hardness. This enhancement is attributed to the synergistic effect of well-dispersed reinforcements, which restrict grain movement and improve load-bearing capacity. However, as hBN content increases beyond 0.5 wt.%, the micro hardness values begin to decline, with AA200 showing the lowest hardness. This drop is likely due to nanoparticle agglomeration and increased porosity, which disrupts matrix uniformity and reduces resistance to deformation.

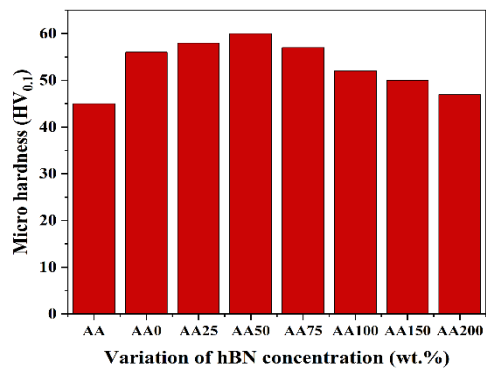


Fig. 7. Variation in microhardness of the hybrid composites at different reinforcement concentrations

4. CONCLUSION

The present research establishes a scientifically validated pathway for developing high-performance AA7050 hybrid nanocomposites with uniformly dispersed reinforcement particles in the matrix. The results obtained provide a basic understanding and practical guidelines that position the developed material as a promising candidate for

next-generation lightweight structural applications. The study differs from the published literature in several key aspects. First, although most published studies have focused on AA2024, AA7075, or AA2219, the present work is based on a systematic investigation of AA7050, a high-strength precipitation-hardenable alloy that remains under explored in hybrid nanocomposite form. Second, while published studies are mostly related to mono-reinforced systems, the present study, for the first time, demonstrates the synergy advantage of CF + hBN hybrid reinforcement, which clearly outperforms the individual reinforcements.

One of the major scientific contributions of this work is to systematically establish the role of premixing strategies, such as ultra-sonication, magnetic stirring, and mechanical stirring, in achieving effective dispersion of nano hBN and carbon fiber within the AA7050 aluminium matrix. FESEM analysis confirmed that reinforcement concentration is a critical control parameter: uniform dispersion was observed at lower concentrations (≤ 0.5 wt.%), whereas pronounced agglomeration was observed at higher concentrations (≥ 0.75 wt.%). To prevent agglomeration at higher reinforcement contents, future research may focus on improving the development and processing characteristics of hybrid reinforcements, such as surface functionalization of nano hBN and carbon fiber. The effect of the premixing process is validated through evaluations of microstructural and mechanical properties. Due to the premixing process, better densification of nearly 95.2% and enhancement of 33.3% of micro hardness are reported for 0.25 wt.% CF and 0.5 wt.% hBN addition.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

- [1] A. Kumar, V.P. Singh, R.C. Singh, R. Chaudhary, D. Kumar, A.-H.I. Mourad, A review of aluminum metal matrix composites: fabrication route, reinforcements, microstructural, mechanical, and corrosion properties. *Journal of Materials Science*, 59(7), 2024: 2644-2711. <https://doi.org/10.1007/s10853-024-09398-7>
- [2] C.O. Ujah, D.V.V. Kallon, Trends in aluminium matrix composite development. *Crystals*, 12 (10), 2022: 1357. <https://doi.org/10.3390/cryst12101357>
- [3] K. Velavan, K. Palanikumar, G. Perumal, N. Senthilkumar, Investigating the corrosion activity of boron carbide and mica particle hybrid composites with an aluminum matrix prepared by stir casting. *Results in Engineering*, 26, 2025: 105194. <https://doi.org/10.1016/j.rineng.2025.105194>
- [4] A.L.M. Carvalho, L.B. Renaudin, A.J. Zara, J.P. Martins, Microstructure analysis of 7050 aluminum alloy processed by multistage aging treatments. *Journal of Alloys and Compounds*, 907, 2022: 164400. <https://doi.org/10.1016/j.jallcom.2022.164400>
- [5] S.K. Patel, L. Shi, Recent advances in ceramic-reinforced aluminum metal matrix composites: a review. *Alloys*, 4(3), 2025: 18. <https://doi.org/10.3390/alloys4030018>
- [6] F. Czerwinski, Thermal stability of aluminum alloys. *Materials*, 13(15), 2020: 3441. <https://doi.org/10.3390/ma13153441>
- [7] K. Palanikumar, J.M. Prabhudass, P.S. Prabha, N. Senthilkumar, Sustainable optimization of abrasive water jet machining for MWCNT/bamboo/Kenaf hybrid polymer composites. *International Journal on Interactive Design and Manufacturing*, 19, 2025: 3765–3782. <https://doi.org/10.1007/s12008-024-02009-4>
- [8] M.S. Surya, S.K. Gugulothu, Fabrication, mechanical and wear characterization of silicon carbide reinforced aluminium 7075 metal matrix composite. *Silicon*, 14(5), 2022: 2023-2032. <https://doi.org/10.1007/s12633-021-00992-x>
- [9] R. Chandel, N. Sharma, S.A. Bansal, A review on recent developments of aluminum-based hybrid composites for automotive applications. *Emergent Materials*, 4(5), 2021: 1243-1257. <https://doi.org/10.1007/s42247-021-00186-6>
- [10] A. Atmakuri, A. Palevicius, A. Vilkauskas, G. Janusas, Review of Hybrid Fiber Based Composites with Nano Particles—Material Properties and Applications. *Polymers*, 12(9), 2020: 2088. <https://doi.org/10.3390/polym12092088>
- [11] N.K. Bhoi, H. Singh, S. Pratap, Developments in the aluminum metal matrix composites reinforced by micro/nano particles – A review. *Journal of Composite Materials*, 54(6), 2020: 813–833. <https://doi.org/10.1177/0021998319865307>
- [12] S.R. Bakshi, D. Lahiri, A. Agarwal, Carbon nanotube reinforced metal matrix composites - a review. *International Materials Reviews*, 55(1), 2010: 41–64.

- <https://doi.org/10.1179/095066009X12572530170543>
- [13] G. Perumal, N. Senthilkumar, D. Satheshkumar, S. Anandhakumar, Comparative analysis of solution treatment with short and long-term aging on mechanical, tribological, and corrosion potential of Ti-6Al-4V alloy. *Multiscale and Multidisciplinary Modeling, Experiments and Design*, 8, 2025: 159.
<https://doi.org/10.1007/s41939-025-00759-6>
- [14] P. Madhukar, N. Selvaraj, C.S.P. Rao, G.V. Kumar, Fabrication and characterization two step stir casting with ultrasonic assisted novel AA7150-hBN nanocomposites. *Journal of Alloys and Compounds*, 815, 2020: 152464.
<https://doi.org/10.1016/j.jallcom.2019.152464>
- [15] V. Singhal, D. Shelly, A. Saxena, R. Gupta, V.K. Verma, A. Jain, Study of the influence of nanoparticle reinforcement on the mechanical and tribological performance of aluminum matrix composites—a review. *Lubricants*, 13(2), 2025: 93.
<https://doi.org/10.3390/lubricants13020093>
- [16] M.K. Akbari, H.R. Baharvandi, K. Shirvanimoghaddam, Tensile and fracture behavior of nano/micro TiB₂ particle reinforced casting A356 aluminum alloy composites. *Materials & Design*, 66, 2015: 150-161.
<https://doi.org/10.1016/j.matdes.2014.10.048>
- [17] N. Mahaviradhan, S. Sivaganesan, N.P. Sravya, A. Parthiban, Experimental investigation on mechanical properties of carbon fiber reinforced aluminum metal matrix composite. *Materials Today: Proceedings*, 39, 2021: 743-747.
<https://doi.org/10.1016/j.matpr.2020.09.443>
- [18] P. Loganathan, A. Gnanavelbabu, K. Rajkumar, Investigation on mechanical and wear behaviour of AA2024/hBN composites synthesized via powder metallurgy routine. *Materials Today: Proceedings*, 45, 2021: 7865-7870.
<https://doi.org/10.1016/j.matpr.2020.12.503>
- [19] D.H. Nam, Y.K. Kim, S.I. Cha, S.H. Hong, Effect of CNTs on precipitation hardening behavior of CNT/Al–Cu composites. *Carbon*, 50(13), 2012: 4809-4814.
<https://doi.org/10.1016/j.carbon.2012.06.005>
- [20] Z. Li, G. Fan, Z. Tan, Z. Li, Q. Guo, D. Xiong, D. Zhang, A versatile method for uniform dispersion of nanocarbons in metal matrix based on electrostatic interactions. *Nano-Micro Letters*, 8(1), 2016: 54-60.
<https://doi.org/10.1007/s40820-015-0061-5>
- [21] A. Maqbool, F.A. Khalid, M.A. Hussain, N. Bakhsh, Synthesis of copper coated carbon nanotubes for aluminium matrix composites. *IOP Conference Series: Materials Science and Engineering*, 60(1), 2014: 012040.
<https://doi.org/10.1088/1757-899X/60/1/012040>
- [22] B. Chen, K. Kondoh, H. Imai, J. Umeda, Effect of initial state on dispersion evolution of carbon nanotubes in aluminium matrix composites during a high-energy ball milling process. *Powder Metallurgy*, 59(3), 2016: 216-222.
<https://doi.org/10.1080/00325899.2016.1144375>
- [23] S. Thomas, L.K. Pillari, V. Umasankar, J. Pious, Effect of sonication in enhancing the uniformity of MWCNT distribution in aluminium alloy AA2219 matrix. *Materials Today: Proceedings*, 18, 2019: 4058-4066.
<https://doi.org/10.1016/j.matpr.2019.07.349>
- [24] S. Thomas, N. Menachery, L.P. Thomas, N. Santhosh, G.S.P. Kumar, G.S. Hebbar, Influence of nano hexagonal boron nitride on the wear properties of aluminium alloy. *Advances in Materials and Processing Technologies*, 10(3), 2024: 2483-2499.
<https://doi.org/10.1080/2374068X.2023.2216422>
- [25] T. Arunkumar, V. Pavanan, V.A. Murugesan, V. Mohanavel, K. Ramachandran, Influence of nanoparticles reinforcements on aluminium 6061 alloys fabricated via novel ultrasonic aided rheo-squeeze casting method. *Metals and Materials International*, 28(1), 2022: 145-154.
<https://doi.org/10.1007/s12540-021-01036-0>