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Effect of h-BN solid nano lubricant on the dry sliding wear behaviour of Al-B_4C nanocomposites

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ABSTRACT

Purpose: In this paper, three composites with different B_4C content and fixed h-BN nanoparticles reinforced aluminium composites were fabricated through ultrasonic cavitation assisted casting. The role of the B_4C and h-BN nanoparticles content on the mechanical and tribological properties of the aluminium composites was evaluated. This study presents the report on characterizion and evaluation of mechanical properties of h-BN and B_4C nanoparticles reinforced aluminium composites.

Design/methodology/approach: Al-B_4C-h-BN composites are fabricated using stir and ultrasonic cavitation-assisted casting processes. The prepared composites are characterized using X-ray diffraction, Scanning Electron Microscopy and Energy Dispersive Spectroscopy. The dry sliding wear behaviour of the Al-B_4C-h-BN composites are investigated using pin-on-disc wear test.

Findings: The results of microstructural study reveal that uniform distribution, grain refinement and low porosity in composite specimens. The wear properties of the hybrid nanocomposites, containing 4 wt% B_4C and 2 wt. % h-BN, exhibit the superior wear resistance properties as compared to unreinforced aluminium matrix.

Practical implications: The interest in use of hexagonal boron nitride nanoparticles (h-BN) as solid nano lubricant for aluminium has been growing considerably due to its self lubricating properties.

Keywords: Aluminium nanocomposite; B_4C and h-BN nanoparticles; Ultrasonic dispersion; Dry sliding wear behaviour

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MATERIALS

1. Introduction

The demand for light weight, inexpensive and energy efficient aluminium metal matrix nanocomposites (AMNCs) has been increasing for automobiles, aircraft and other applications. Several types of ceramic reinforcements can be incorporated with aluminium such as SiC [1,2], Al_2O_3 [3], WC [4], TiB_2 [5], ZrB_2 [6], TiC [7] and B_4C [8]. B_4C can be considered as a proper ceramic reinforcement in aluminium matrix composites due its high hardness, low density, high wear and impact resistance, high melting point, good chemical and thermal stability [9]. The nano B_4C particles content increases the mechanical strength and wear resistance of the metal matrix nanocomposites (MMNCs). The MMNCs require not only good mechanical strength and high wear resistance but also self-lubrication and good machining properties. One of the major problems with the addition of single hard nano ceramic particle reinforcement in MMNCs makes machining difficult. Therefore, it is essential to identify ways to retain the improved mechanical and tribological properties of MMNCs while attending the problems of machining.

The incorporation of two different nanoparticles into aluminium matrix has led to the development of hybrid nanocomposites. The hexagonal boron nitride (h-BN) is an effective reinforcement for metal matrix composites which acts as a solid lubricant and makes the composites as self-lubricating composites [10,11]. The addition of h-BN nanoparticles improves the machinability and wear resistance of the Al-B_4C nanocomposites. The hybrid composite contains B_4C and h-BN nanoparticles, has the advantage of one type of nanoparticles which could complement to what is lacking in the other. Earlier research reported that the addition of graphite with MMNCs could reduce the wear rate of the composites [12,13]. However, its lubricating performance is decreased when operating temperature is increased. The main drawback of the graphite reinforced aluminium composites is the formation of brittle interfacial phases leading to a decrease in composites strength as graphite materials can react with aluminium at elevated temperature. The formation of an effective lubricating film is essential for the improvement of wear resistance with addition of h-BN nano solid lubricant as it possesses thermal stability, high melting point and high thermal conductivity.

In this paper, three composites with different B_4C content and fixed h-BN nanoparticles reinforced aluminium composites were fabricated through ultrasonic cavitation assisted casting. The role of the B_4C and h-BN nanoparticles content on the mechanical and tribological properties of the aluminium composites was evaluated. This study presents the report on characterization and evaluation of mechanical properties of h-BN and B_4C nanoparticles reinforced aluminium composites.

2. Experimental work

2.1. Materials

Commercially available aluminium was used as a matrix material. The pure aluminium was purchased from M/s BMC Enterprises, Bangalore, India. The B_4C particles with an average particle size of 70 μm were used as starting material to synthesize the nanoparticles. The B_4C nanoparticles were synthesized by milling the purchased B_4C particles in a high energy planetary ball mill (Fritsch, Model Pulverisette 6). Commercial h-BN nanoparticles with an average particle size of 70 nm were used as solid nano lubricant.

2.2. Preparation of composites

Figure1 shows the experimental setup for the ultrasonic cavitation assisted stir casting fabrication of B_4C and h-BN nanoparticles reinforced aluminium metal matrix hybrid nanocomposites. The melting of pure aluminium was carried out in an electrical resistance heating furnace. A specially designed EN8 steel crucible, with 55 mm in inner diameter and 150 mm height, was used for melting and ultrasonic processing. The ultrasonic probe, made of titanium was used to generate 20 kHz ultrasonic wave with a 2 kW power output for melt processing. The titanium probe is 20 mm in diameter and 200 mm long. The required amount of aluminium scraps was melted in a crucible at about 750°C under a protection of inert argon gas by using an electrical resistance-heating furnace. The mechanical stirrer was used for about 10-15 minutes at an average speed of 500-600 rpm for agitating the molten metal by creating turbulence motion. The depth of the immersed mechanical stirrer was approximately 2/3 of the height of the molten metal from the bottom of the crucible. During mechanical stirring the required B_4C nanoparticles were added to the molten aluminium from the top of the crucible in the wt. % of 2, 4 and 6 and followed by addition of 2 wt. % of h-BN. After mechanical stirring, the ultrasonic vibration was applied into the molten aluminium for 30 minutes to break up the clustered B_4C and h-BN nanoparticles and degas the molten metal as well. Finally, the molten metal was poured into the mild steel die, which was preheated at about 500°C. Specimens were prepared from the castings as per ASTM standard to evaluate dry sliding wear behaviour. Details of the prepared composites, used for mechanical and tribological analysis, were given in Table 1.

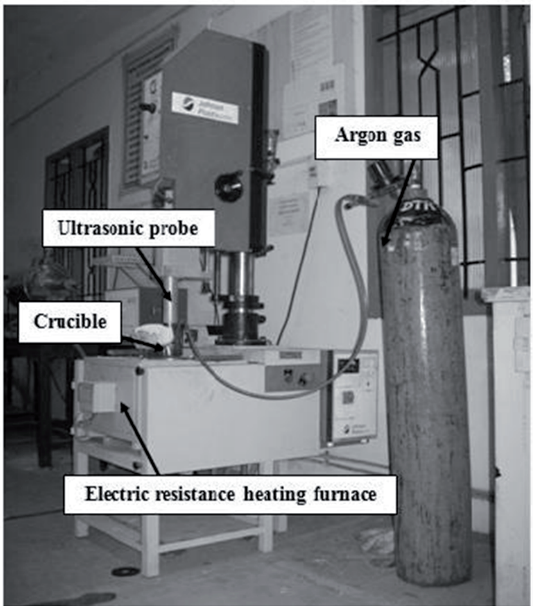

Fig. 1. Experimental setup for fabricating composites

Table 1.
Composition designation and details of fabricated composites

Composites code	Composition
H2	Al-2 wt. % of B_4C- 2 wt. % of h-BN
H4	Al-4 wt. % of B_4C- 2 wt. % of h-BN
H6	Al-6 wt. % of B_4C- 2 wt. % of h-BN

2.3. Characterization

Scanning Electron Microscopy (SEM) (SU510 Hitachi, Japan) was used for morphological characterization of the synthesized B_4C nanoparticles and as received h-BN solid nano lubricants. Scanning electron microscopy (Bruker) with EDX energy dispersive X-ray spectroscopy was used to evaluate the microstructural changes in the prepared metal matrix hybrid nanocomposites. X-ray powder diffraction (XRD) analysis was obtained for the prepared composites using a Bruker D8 X-ray diffractometer with Cu Kα radiation (λ = 0.15406 nm) at an accelerating voltage of 60 kV over the range of 2θ = 10-90° with a step size of 0.01708 and a step time of 15.5076 seconds. The phase purity of hybrid MMNCs were determined by XRD analysis.

2.4. Hardness test

The hardness of the pure aluminium and hybrid MMNCs was evaluated using Vickers micro hardness tester (Everone MVH-1, Everone Enterprises Ltd, China) according to the ASTM standard E381. The applied load and dwell times for the hardness measurement were 1 kg and 5 seconds, respectively. Each specimen was indented five times at different locations to determine the average hardness.

2.5. Wear test

The dry sliding wear tests were conducted on a pin-on-disc wear testing machine (Model TR-20, Ducom, Bangalore) according to the ASTM standard G99-05. The disc material used was EN31 hardened steel with a hardness value of 60 HRC and ground to a 1.6 Ra surface roughness. Cylindrical pins of 12 mm in diameter and 30 mm long were used as an abrasive wear test specimen. Each specimen was polished and cleaned thoroughly with acetone and subsequently dried. The weight of the specimen was recorded before and after the test using an electronic balance with an accuracy of 0.001 mg. The wear tests were conducted at room temperature for a sliding speed of 500 rpm under normal loads of 4 N, 8 N, 12 N and 16 N. The sliding distance and track diameter were maintained constant at 1000 m and 100 mm, respectively, for all the wear tests. Three tests were carried out for each set of parameters, and their average values were considered as the wear loss. The coefficient of friction was determined from the applied normal loads and obtained frictional force from the computer aided data acquition system. The worn surfaces of the pins were analyzed using SEM with EDX (Energy Dispersive X-ray Spectroscopy).

3. Results and discussions

3.1. Microstructural characterization

Figure 2a shows SEM image of as-received B_4C particles with the mean particle size of 70 μm which is used as the starting material. SEM micrograph of as-received B_4C particles reveals that the particle has a wide size distribution and stone-like irregular shape. Figure 2b shows SEM image of the 30 h ball milled B_4C nanoparticles. The B_4C nanoparticles are spherical and have a uniform distribution. SEM micrograph of the 30 h ball milled B_4C particles confirms the generation of nano sized B_4C

particles. Further Figure 3 presents SEM image of as-received h-BN nano-particles. It can be observed clearly that the raw h-BN nanoparticle has an average particle size of 70 nm.

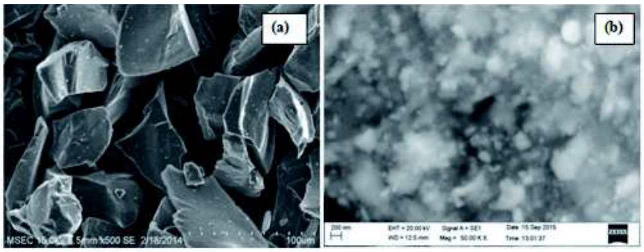

Fig. 2. SEM micrographs of B_4C particles: (a) as received and (b) after 30 h of milling

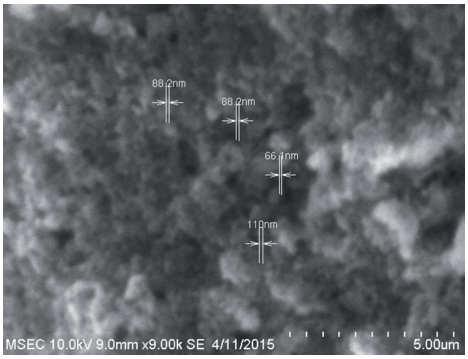

Fig. 3. SEM micrograph of received h-BN nanoparticles

X-ray diffraction is a material characterization technique that can be useful for analysing the structural changes of the composite after processing. The XRD patterns of the h-BN nanoparticles reinforced MMNCs are shown in Figure 4 for three different compositions. The peaks at Bragg angle values of 38.472, 44.720, 65.133 and 78.227 belong to aluminium (JCPDS 85-1327, 65-2869) with miller indices of (111), (200), (220) and (311) respectively. A single distinct peak appears at Bragg angle value of 82.44 with miller indices of (128) indicates that the crystallinity of B_4C agrees with the JCPDS file No. 75-0424.

The XRD patterns of the h-BN nanoparticles reinforced MMNCs reveal the presence of hexagonal boron nitride in addition to aluminium and boron carbide phases. The peak at Bragg angle value of 43.871 with miller indices plane (101) corresponds to the h-BN (JCPDS 85-1068). The peaks corresponding to aluminium matrix are also seen. This observation leads to a conclusion that the B_4C and h-BN nanoparticles are thermodynamically stable at the applied casting temperature.

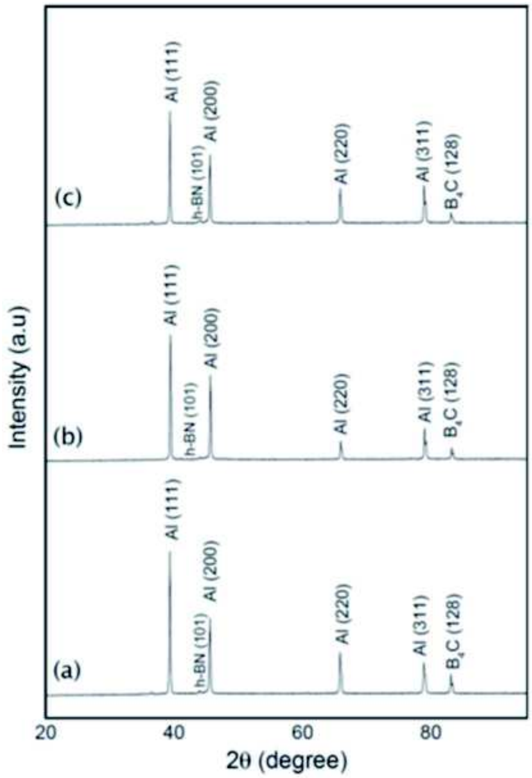

Fig. 4. X-ray diffraction pattern for the samples: a) H2, b) H4 and c) H6

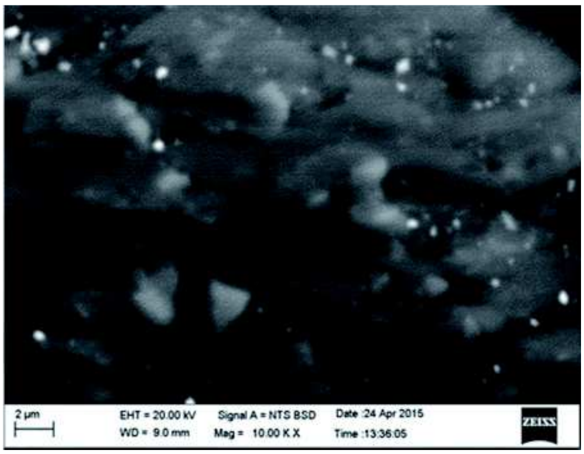

Fig. 5. SEM images of 2 wt. % nano B_4C and 2 wt. % h-BN nanoparticles reinforced Hybrid MMNCs

The SEM micrograph of the Al-B_4C-h-BN hybrid nano-composites is shown in Figure 5. It is further evident from micrographs of the prepared nanocomposites that B_4C and h-BN nanoparticles are distributed uniformly in the aluminium matrix. The homogeneous particulate dispersion in the aluminium matrix is an essential requirement to obtain higher mechanical properties of the composites. Moreover, the common casting defects such as porosity, oxide inclusion are not visible in the micrographs of the nanocomposites due to the ultrasonic processing.

To analyse the presence of elements in the Al-B_4C-h-BN hybrid nanocomposites, energy dispersive X-ray spectroscopy is used. The EDAX analysis Al-B_4C-h-BN hybrid nanocomposites are shown in Figure 6. Aluminium, boron, carbon and nitrogen elements are detected in the EDAX analysis of the Al-B_4C-h-BN hybrid nanocomposites. It is also clear that there is no oxygen element in the prepared composites from EDAX analysis. This can be primarily due to a shield of argon gas maintained during processing of composites.

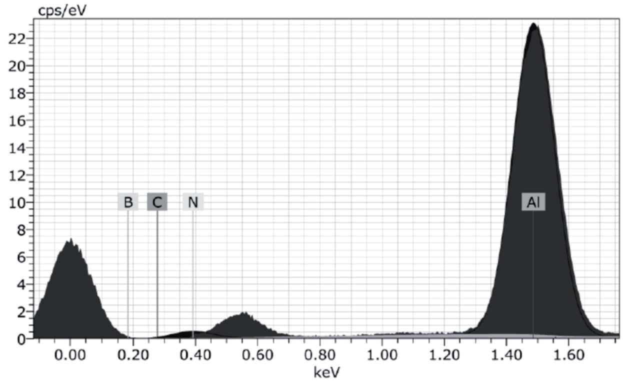

Fig. 6. EDAX spectra showing the elements present in the Hybrid MMNCs

3.2. Mechanical characterization

The microhardness values of Al-B_4C-h-BN hybrid nanocomposites are shown in Figure 7. It is observed that the addition of B_4C nanoparticles to aluminium matrix significantly enhances the hardness of the composites. It can be understood that the hardness of the composites is improved with the increase in weight percent of B_4C nanoparticles from Figure 6, it is also observed that the hardness of the Al-B_4C-h-BN hybrid nanocomposites increases with the addition of B_4C nanoparticles. Hardness of the hybrid nanocomposites is significantly greater than that of the unreinforced aluminium matrix. The hardness of the hybrid MMNCs at 6 wt. % B_4C and 2 wt. % h-BN decreases due to the presence of micro porosities and agglomeration of the particles. Reduction of hardness due to porosity and agglomeration of particles was noticed by some researchers [14].

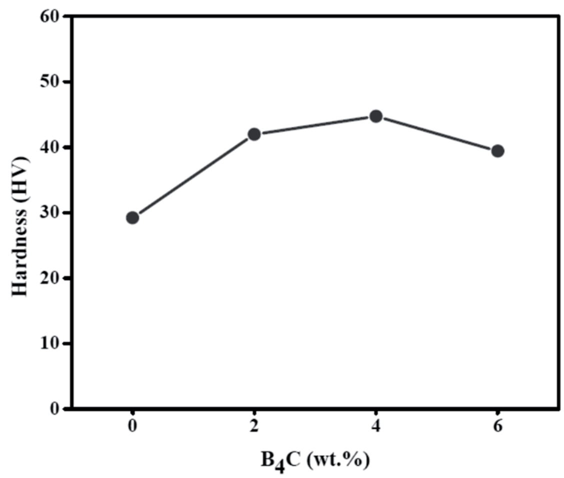

Fig. 7. Comparative hardness chart of Al-xB_4C-2h-BN hybrid nanocomposites

3.3. Tribological properties of the composites

Figure 8 shows the variation of wear rate as a function of load for Al-B_4C-h-BN hybrid nanocomposites. The wear rate of both composites decreases with increase in B_4C content and reaches a minimum at 2 wt. % h-BN- 4 wt. % B_4C and it is 30% lower than that of the aluminium matrix. The wear rate increases with increasing applied load and it is minimum for hybrid nanocomposites as compared to unreinforced aluminium matrix. This high wear resistance of the Al-B_4C-h-BN hybrid nanocomposites as compared to aluminium is due to the presence of h-BN in addition to hard B_4C particles. The h-BN is a solid lubricant which is usually decreases the wear rate of the composites by forming a thin protective lubricant layer between pin and disc during sliding. The increase in wear resistance can be attributed to the strengthening of matrix due to hard particle dispersion, which results from an increase in the dislocation density as reinforcement content increases. However, when the combined weight percentage of the B_4C and h-BN nanoparticles are more than the 6 wt. %, the wear rate of the hybrid nanocomposites increases. The increasing tendency in wear rate of the hybrid nanocomposites at 2 wt. % h-BN- 4 wt. % B_4C is due to the presence of voids and agglomeration of nanoparticles.

Figure 9 shows the coefficient of friction values for Al-B_4C-h-BN hybrid nanocomposites. It is observed that there is an increase in the coefficient of friction with increasing normal load for composites. It can also be observed that coefficient of friction value of the hybrid nanocomposites is lower than that of aluminium matrix.

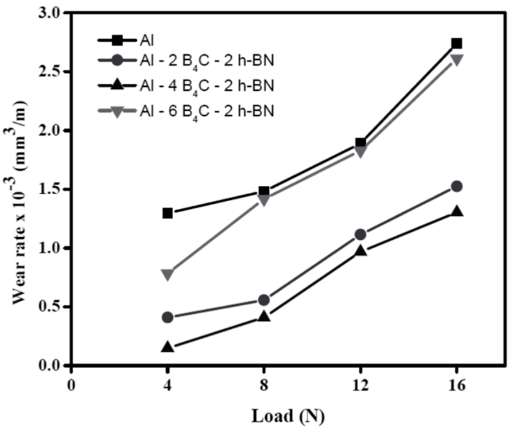

Fig. 8. Variation of wear rate as a function of normal load for Al-B_4C-h-BN hybrid nanocomposites

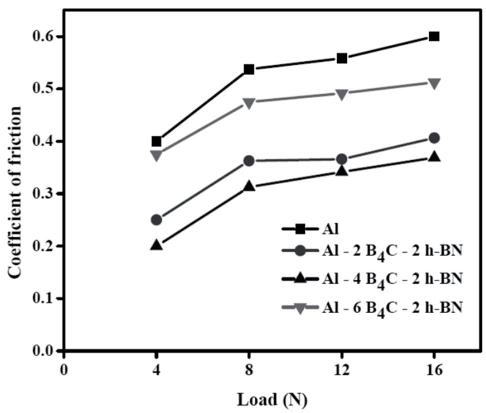

Fig. 9. Variation of coefficient of friction of the Al-B_4C-h-BN hybrid nanocomposites

The results show that by increasing the amount of reinforcement from 2 to 6 wt. % in the nanocomposites, the coefficient of friction of the composites decreases. However, at all applied loads, the coefficient of friction for 2 wt. % h-BN- 4 wt. % B_4C hybrid nanocomposites is lower when compared with aluminium matrix The reason for decreasing the coefficient of friction with the addition of h-BN is lamellar crystalline structure [14], which acts as a layer of lubricant film. Formation of such a lubricating film on the pin surface of the hybrid nanocomposites during sliding wear reduces the coefficient of friction value.

The SEM micrographs of the worn surface of hybrid nanocomposites tested at 16 N load are shown in Figure 10. From the analysis of wear surface at 16 N, it can be seen distinct grooves in the sliding direction. The h-BN nano-particles on the worn surface of the hybrid nanocomposites form a thin rich tribofilm between the sliding surfaces, which prevent direct metal contact. This clearly indicates that thin lubricant film prevents the pulling of hard B_4C nanoparticles from the hybrid nanocomposite pin surface. Figure 11 show the EDAX analysis of the worn surface of the 2 wt. % h-BN- 4 wt. % B_4C hybrid nanocomposites. It can be attributed that transfer of iron form the counter disc surface and formation of MML on the surface. The area of surface damage is less for hybrid nanocomposite pin surface when compared to nanocomposite because of the combined effect of lubricating film and thin protective layer of MML.

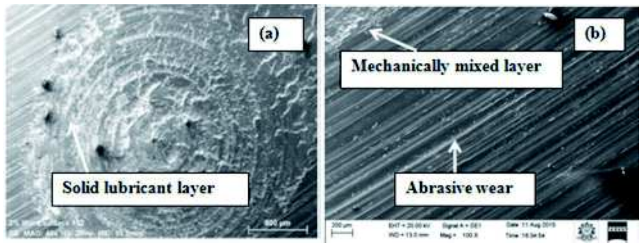

Fig. 10. SEM micrographs of the worn surfaces of: a) Al-2 wt. % B_4C- 2 wt. % h-BN, b) Al- 4 wt. % B_4C- 2 wt. % h-BN hybrid nanocomposites under 16 N

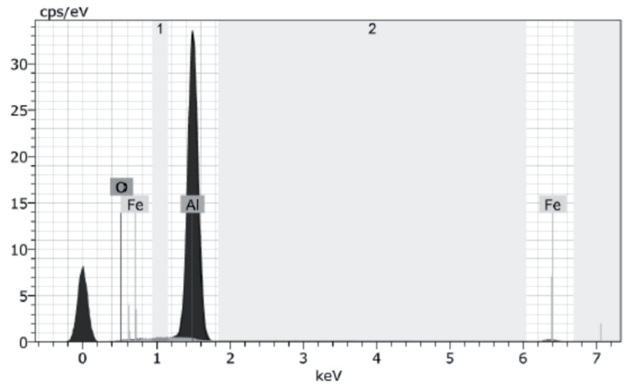

Fig. 11. EDAX analysis on worn surface of the Al- 4 wt. % B_4C- 2 wt. % h-BN hybrid nanocomposites under 16 N

4. Conclusions

The effects of h-BN nanoparticles on the mechanical and tribological behaviour of Al-B_4C-h-BN hybrid nanocomposites are investigated. The following conclusions are drawn from this experimental work.

- The hardness of hybrid nanocomposites increases with increasing B_4C and it is higher than that of unreinforced aluminium matrix. Addition of h-BN nanoparticles to the aluminium matrix decreases the hardness and ultimate tensile strength and it is overcome by the addition of B_4C in the hybrid nanocomposites.

- The wear resistance of the hybrid nanocomposites is increased with the addition of 4 wt. % B_4C and 2 wt. % h-BN nanoparticles. The wear resistance is significantly improved for the hybrid nanocomposites compared to unreinforced aluminium matrix and B_4C reinforced nanocomposites.

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