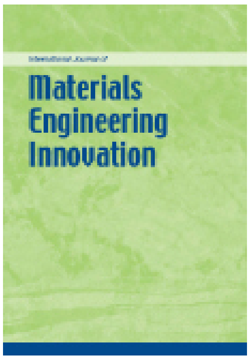

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An experimental evaluation of mechanical properties and tribological behaviour of A380/NanohBN composite

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Abstract: Aluminium metal matrix composites (AMMC) find its extensive usage and applications in automotive and aerospace industries. Present study deals with exploring the effect of adding hexagonal boron nitride (0, 0.5, 1 and 1.5 weight percentage) as reinforcement in matrix material Al A380 alloy, on the mechanical and tribological properties using mechanical stirring. Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) are used to characterise fabricated composites. Next, tensile, hardness and wear tests by varying applied loads and sliding speeds using pin on disk tribometer are performed on fabricated composites. It concludes that mechanical stirring distributes the nano powder uniformly and efficiently. The improved ultimate tensile strength, hardness, and tribological properties are observed for fabricated composite as compare to base alloy. Scanning electron microscopy images are used to analyse the worn out surfaces.

Keywords: nanocomposites; metal matrix composite; aluminium A380; hexagonal boron nitride; stirring; mechanical properties; wear; coefficient of friction; pin on disk; tribological.

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1 Introduction

With the advancement in technology, the demand for the low cost, light weight and quality product is increasing and continuous efforts have been made by researchers and industrial persons to meet the current scenario demands. Aluminium and its alloys are the better choice due to light weight with considerable properties. Aluminium alloy A380, is widely used in the manufacturing and die casting industries of brake casting, gear cases, cylinder head and engine blocks. To fulfil market demands, the materials must provide better mechanical and tribological properties, which are difficult for a monolithic material and alloy. To achieve improved properties, aluminium metal matrix composites (AMMC) are the promising materials for automobile, aerospace, structural, military, and marine industries. AMMC provides high strength to weight ratio, high hardness, high compressive strength, low coefficient of thermal expansion, improved wear and corrosion resistance properties as compared to aluminium alloy. Further to enhanced properties, the ceramics particles are added as reinforcement in the aluminium metal matrix. The common reinforcements are alumina, B4C, SiC, TiC, BN, MoS2, graphite, Fly-ash, red mud, and rice husk. The use of hexagonal boron nitride (hBN) as a reinforcement in aluminium metal matrix composites increases due to low density, chemical inertness and stability to thermal shock. Furthermore, hBN provides better lubricating and high temperature stability properties as compared to other solid lubricants. In lieu to comparison with other ceramics hBN is having better wettability with aluminium, which is important factor for fabrication of high strength composite (Sachit et al., 2018; Prasad and Asthana, 2004; Bhushan et al., 2009; Liu et al., 2019; Qiu et al., 2020; Karuppasamy et al., 2020; Gencalp and Saklakoglu, 2010; Zheng et al., 2013, Kumar and Singh, 2019; Sivananth et al., 2019; Lee et al., 2002).

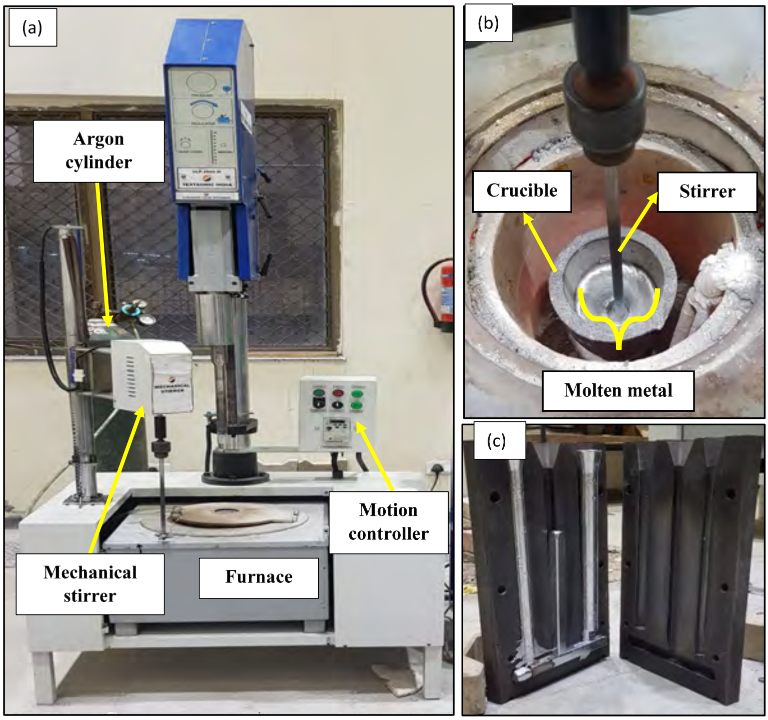
In order to fabricate AMMC, different liquid state processing methods such as stir casting, ultrasonic assisted casting, compocasting, squeeze casting and in-situ synthesis are used. In above processes mechanical stirring is the simple and economical method used for mixing of particles which is dependent upon the stirring speed and time. García-Rodríguez et al. (2012) analysed the flow patterns to identify the better conditions for use mechanical stirring for the distribution of particles and to achieve homogeneous mixing. Auradi and Kori (2014) used stir casting two step addition method for Al 6061 and 5, 7 weight percentage of B_4C particles with K2TiF6 to avoid agglomeration and improved wettability. Yu et al. (2016) used modified vacuum mechanical stirring equipment for 31% mass fraction of B_4C as reinforcement in AA6061 aluminium matrix. Park et al. (2020) used stir casting and an automated quantification technique for dispersion of reinforcement in aluminium matrix. In order to achieve the proper mixing Singh et al. (2019) prepared hybrid nanocomposite of Al 7075 with alumina and graphite as reinforcement materials using stir and ultrasound assisted casting method. The authors studied the effect of temperature on wear properties of prepared composite.

Many methods are used for fabrication of AMMC such as mechanical alloying (Khakbiz and Akhlaghi, 2009; Nie et al., 2007), high energy ball milling (Alizadeh and Taheri-Nassaj, 2012), powder metallurgy, spray deposition and laser deposition, etc. The above solid state methods are expensive, energy consuming and limitations of size and complexity in parts (Liu et al., 2014). Mechanical stirring process is low cost, simple operation and no size limitation in parts fabrication mostly used as liquid state method. Further, stir casting process uniformly distribute micro size particles efficiently (Harichandran and Selvakumar, 2016) and there is formation of cluster (Sun et al., 2011) with reduction in reinforced particles size. After going through the literature it is observed that the quantity of reinforced material is high in matrix material due to which many issues like porosity (Bouazara et al., 2015), non-uniform particles distribution and particles agglomeration raised (Kareem et al., 2021; Ezatpour et al., 2014). Using high quantity reinforcement, the manufacturing cost of product is increased which includes cost of reinforced particles and post processing cost. Furthermore, to overcome these issues in the casted samples less quantity of reinforcement is the possible solution. After going through the literature, it is observed that the effect on mechanical and tribological properties of adding nano particles of hexagonal boron nitride in aluminium matrix A380 is not explored. The purpose of this work is to fabricate A380/nhBN (0, 0.5, 1 and 1.5 weight percentage) composites with enhanced properties using mechanical stirring (MS) process. Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) are used to characterise fabricated composites. The fabricated composite samples are tested for mechanical properties tensile strength, % elongation and hardness. Furthermore, wear and coefficient of friction (COF) of fabricated samples are investigated considering different parameters, applied load (10, 30, 50 N) and sliding speed (1.25, 2.5, 3.7 m/s) with constant sliding distance of 1,500 m.

2 Experimental procedure

The composition of ingot A380 provided by Century NF casting Faridabad, India and nano hBN (nhBN) powder supplied by Nano Research Elements India are characterised using X-ray diffractometer (XRD) (3rd generation Empyrean from Malvern Panalytical). Further, the particles size of nhBN powder measured using field emission scanning electron microscope (FESEM) (JEOL, model: JSM7610F). Samples are cut from A380 ingot (Century NF casting, India), as base data values for the fabrication of the different A380/nhBN composites. Samples are prepared for fabrication of A380/nhBN (0, 0.5, 1 and 1.5 weight percentage) composites using the mechanical stirring (MS) set-up shown in Figure 1(a). The mechanical stirrer has maximum rotation speed of 1,000 rpm in both the directions (clockwise and anticlockwise). It consists of a steel rod and 3 blades impeller of titanium material. The blades of impeller are inclined at angle of 30° with 5 mm thickness, 15 mm height and periphery of 40 mm. The impeller is dipped in molten metal up to one third position from bottom at a rotation speed of 700 rpm shown in Figure 1(b). The graphite crucible has outer diameter 105 mm, height 127 mm, bottom outer diameter 70 mm and capacity of 3.7 kg is used for experimentation. The electric muffle furnace of 3 kg capacity, 5 kW power, with a nichrome 80–20 heating element and 1.83 mm diameter, 10 mm coil diameter and maximum temperature up to 1,000°C (Kanthal, UK). The mould used in experimentations is shown in Figure 1(c).

Figure 1 Experimental setup used in this study, (a) mechanical stirring set-up (b) impeller position during processing (c) mould (see online version for colours)



The matrix metal A380 is cut into small pieces and properly cleaned and reinforced material samples are prepared for 0% (as reference), 0.5, 1 and 1.5 weight percentage nhBN powder. The nano powder samples are preheated to remove moisture in muffle furnace and the mould is also preheated upto 350°C. The matrix alloy is melted in graphite crucible and after melting, samples are prepared using mechanical stirring. The mechanical stirrer is introduced in the melted metal up to one third position from the bottom with a stirring speed 700 rpm. The preheated nhBN particles are added with a pouring rate of 1 g/min (approximately) in molten metal and stirring process is continued for 10 minutes. The prepared melted metal matrix composites are poured in preheated mould and after solidification cast samples are prepared following the above steps.

After, solidification samples are cut and prepared for characterisation and testing. The characterisation is performed by SEM and EDS using field emission scanning electron microscope (FESEM) (JEOL, model: JSM7610F). The samples prepared according to ASTM standards are used for measuring mechanical properties: hardness using Brinell hardness testing machine (B 3000 H, Saroj), with a steel ball intender of 10 mm diameter and 500 kgf load for 15 seconds dwell time (ASTM E10) and tensile testing samples (ASTM E8) prepared with gauge length 50 mm, diameter of reduced section 12.5 mm and radius of fillet 10 mm. The tensile test is performed on a computerised universal testing machine (AEC1112-60T, Ashian Engineers). Further, dry sliding wear tests are performed using pin-on-disc tribometer (DUCOM, Model TR-20LE) at room temperature 28–32°C. The samples are prepared in pin form for wear test of diameter 10 mm and height 30 mm machined from fabricated composite. EN31 material rotating disc of hardness 63 HRC is used against the stationary pin which is held normal to the rotating disc surface. Before starting each experiment, the surface of pin and rotating disc is cleaned using acetone to ensure proper contact between pin and disc. The parameters considered for performing the wear experiments are applied loads of 10, 30 and 50 N, sliding speeds of 1.25, 2.5 and 3.7 m/s, constant sliding distance of 1,500 m and constant 120 mm sliding track diameters. In order to calculate the mass loss in pin, weight of pin before and after test is measured using electronic balance of 0.01 mg least count. The difference between initial and final weight of pin gave wear on pin. The computer interfaced with tribometer provided the value of friction force and mean value of COF.

Finally, using the results from the testing and characterisation, the discussion is based upon describing the characteristics of the base alloy with the addition of the different nhBN contents.

3 Results and discussion

It contains characterisation of aluminium A380, nhBN powder and fabricated A380/*x*-nhBN composite. Further, the mechanical properties Ultimate tensile strength (UTS), % elongation, Brinell hardness (BHN), wear and COF are measured for the base alloy and fabricated composites.

3.1 Characterisation of A380 ingot, nhBN powder and composite

The composition of aluminium A380 ingot and the nhBN powder are shown in Tables 1 and 2, respectively. Figure 2 shows XRD profile of ingot A380 and confirmed the presence of other elements with aluminium. The peaks at 2θ values for AlSi are 38.558°,44.821°, 65.253°, 78.428°, 82.650° (reference code – 98-060-9333) with Miller indices (111), (002), (022), (113), (222) respectively. ClCu shown in XRD profile with 2θ values of 28.501°, 47.404°, 56.246°, 76.558° (reference code – 98-007-8270) and (111), (022), (113), (133) Miller indices respectively. The presence of CFe in A380 is indicated by peaks with 2θ values of 39.901°, 42.604°, 46.839°, 50.041° (reference code – 98-003-1018) with Miller indices (123), (211), (132), (133) respectively. The composition of nhBN is confirmed by the XRD profile in Figure 3. The higher intensity peaks indicate hBN powder and no other peaks are identified which confirms the purity of hBN powder. The characteristic peaks with 2θ values of 26.746°, 41.614°, 43.872°, 50.159°, 55.106°, 75.941° (reference code – 96-900-8998) and corresponding miller indices are (002), (100), (101), (102), (004), (110) respectively. The nhBN powder having hexagonal structure with average particles size less than 100 nm as indicated in Figure 4. The mechanical stirring process distribute the nano powder uniformly in the casted samples and Figures 5(a), 5(b), 5(c) and 5(d) shows the distribution of nhBN powder with 0.5 and 1 weight percentage of reinforcement respectively and nhBN powder uniformly distributed as cleared in Figures 5(a) and 5(b). The presence of the nhBN is confirmed with the EDS analysis in Figure 6.

Table 1 Chemical composition of initial A380 ingot

Si	*Cu*	*Fe*	*Mg*	*Mn*	*Ni*	*Zn*	*Pb*	*Sn*	*Ti*	*Others*	*Al*
8.58	3.28	0.915	0.086	0.287	0.059	1.631	0.088	0.031	0.031	0.053	84.99

Table 2 Composition and characterisation of nhBN powder

Name	*Formula*	*Colour*	*Form*	*Molecular weight (g/mol)*	*Melting point (°C)*	*Particles size (nm)*	*Purity (%)*	*B*	*N*	*Others*
Hexagonal boron nitride	hBN	White	Powder	24.8177	2,450	<100	99.9	43.5	56.4	0.1

Figure 2 XRD profile of A380 ingot (see online version for colours)

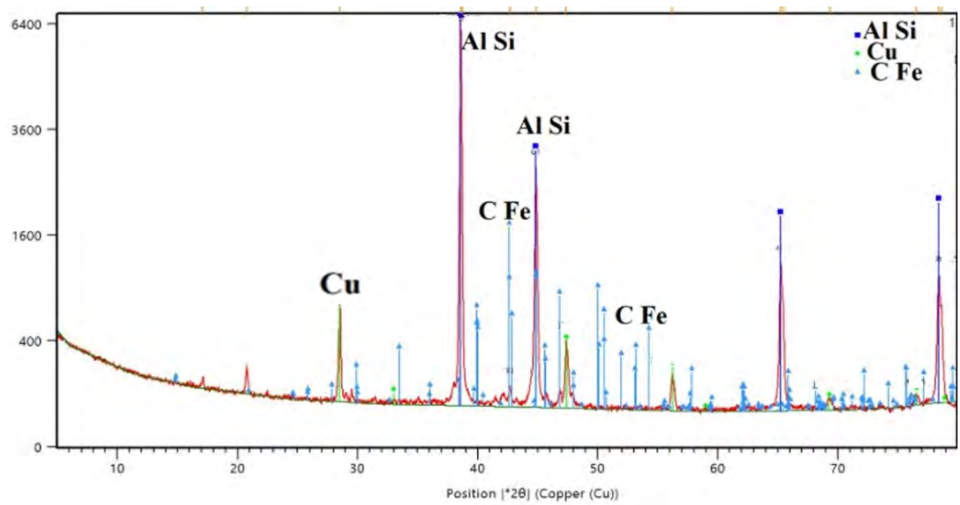


Figure 3 XRD profile of the nhBN powder (see online version for colours)

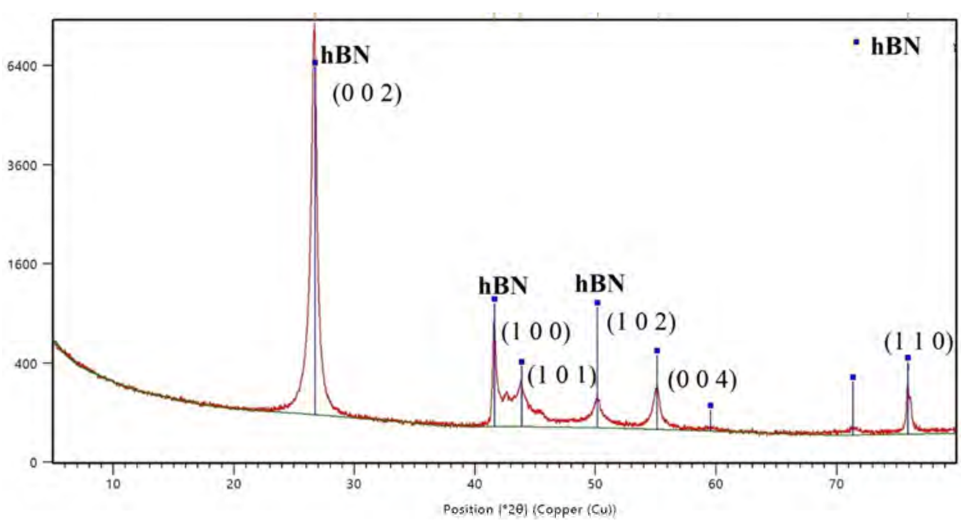


Figure 4 SEM image of nhBN powder

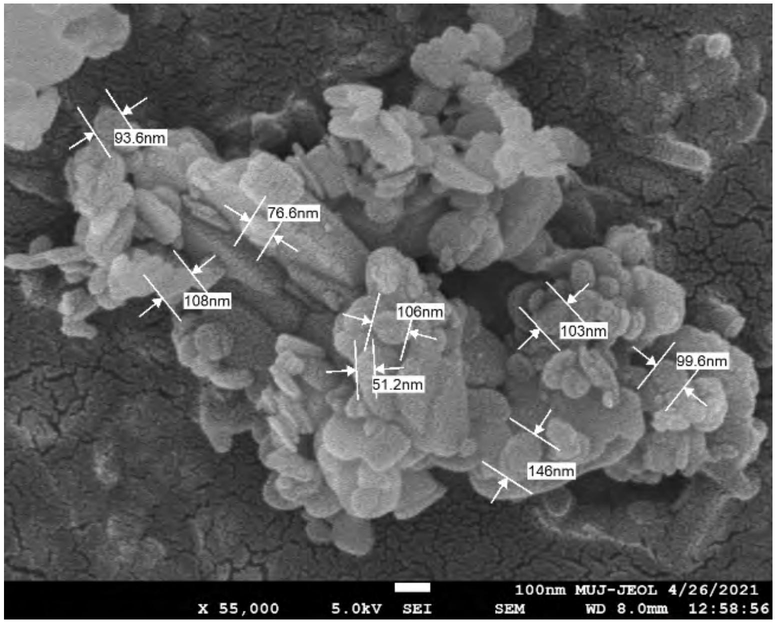


Figure 5 SEM images of samples, (a, c) A380/0.5nhBN (b, d) A380/1nhBN

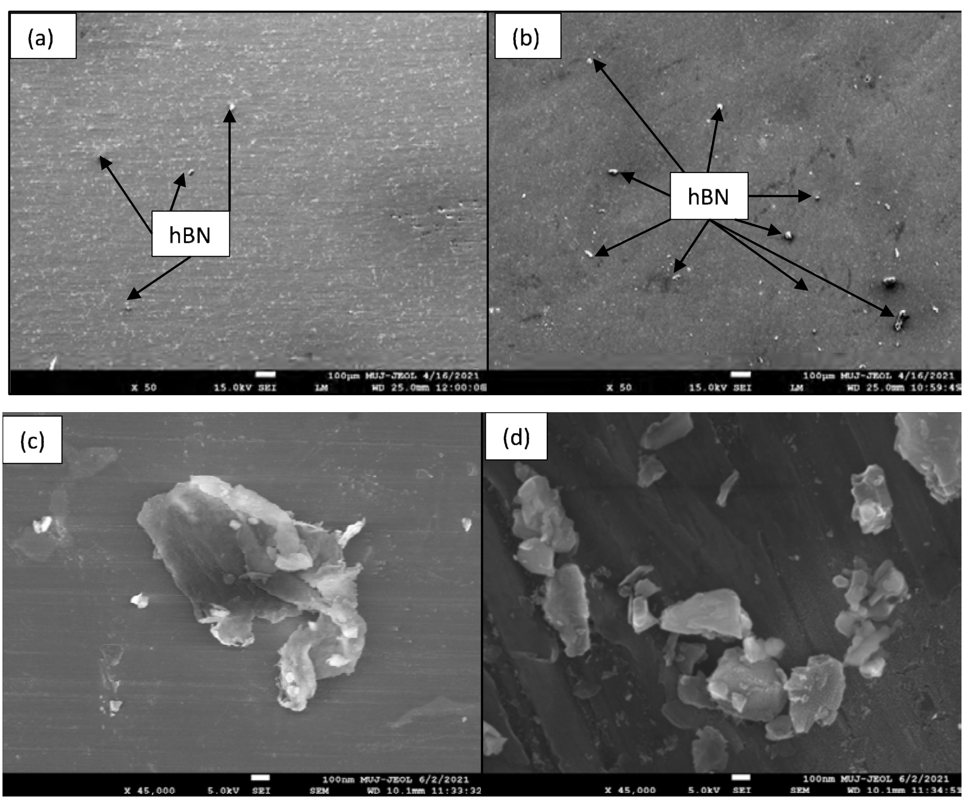
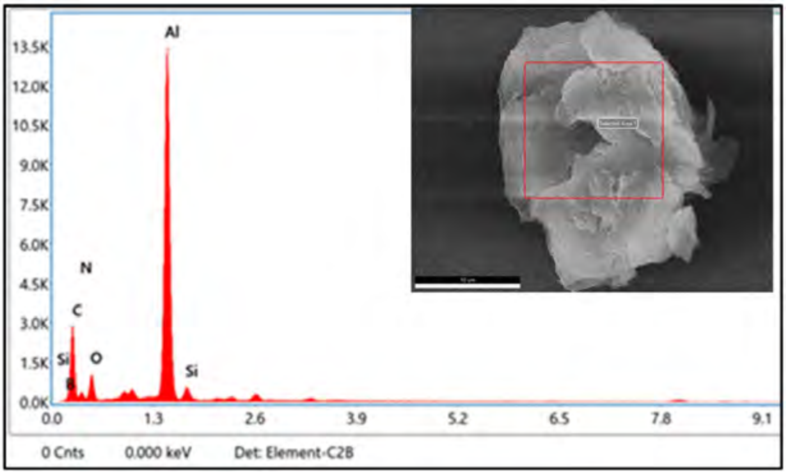


Figure 6 EDS image of A380/1nhBN (see online version for colours)



3.2 Ultimate tensile strength, % elongation and hardness

The ultimate tensile strength (UTS), % elongation and hardness for base alloy A380 and fabricated composites are represented in Table 3.

Table 3 Mechanical properties for each combination

Sr. no.	*Combination*	*UTS (MPa)*	*% elongation*	*Hardness (BHN)*
1	A380/0nhBN	123	1.65	64.2
2	A380/0.5nhBN	163	1.95	81
3	A380/1nhBN	178	2.15	84
4	A380/1.5nhBN	154	1.70	73

Figure 7 shows the stress and strain curve for base alloy A380 and fabricated composites. Improvements occurred in the fabricated composites and can vary because of the reinforcement percentage, distribution and dispersion of the reinforcements. Thereafter an increment in UTS of AMMC due to presence of nhBN particles in the matrix material. The tensile strength of the composites increased with the increase in weight percentage of reinforced particle up to a given percentage due to hard hBN phase particles larger surface area and higher dislocation between matrix material and reinforced particles. Furthermore, the tensile strength of the composite also increased due to the thermal mismatch strengthening mechanism. In this mechanism the residual stresses are induced in the composite due to the difference in thermal expansion coefficient of matrix material A380 and reinforcement nhBN. These residual stresses act as a barrier to the motion of dislocations after load is applied. Hence more loads is required to move the dislocations near the induced residual stresses area, which results in higher tensile strength. The properties are also enhanced because of uniform distribution of reinforced particles, capacity of more load transformation and larger interfacial area (Firestein et al., 2015; Chen et al., 2015). Also, Figure 8 shows the UTS and % elongation of A380/nhBN (0, 0.5, 1 and 1.5 weight percentage) fabricated composite. The elongation of the fabricated composites increased with increased in the weight percentage of the reinforced particles due to the good interface between aluminium matrix and hBN reinforced particles and also uniform distribution of reinforced particles (Harichandran and Selvakumar, 2018). The elongation of the fabricated composites follows same trend like ultimate tensile strength and increased with weight percentage 0.5 and 1.0 and then decrease at weight percentage 1.5 of nhBN due to presence of the voids and micro-cracks shown in Figure 9. Also, SEM images of tensile fractured indicates the brittle fracture cleared from the facets in large numbers [see Figures 9(a) and 9(b)].

Figure 7 Stress vs. strain curve for base alloy and prepared composites (see online version for colours)

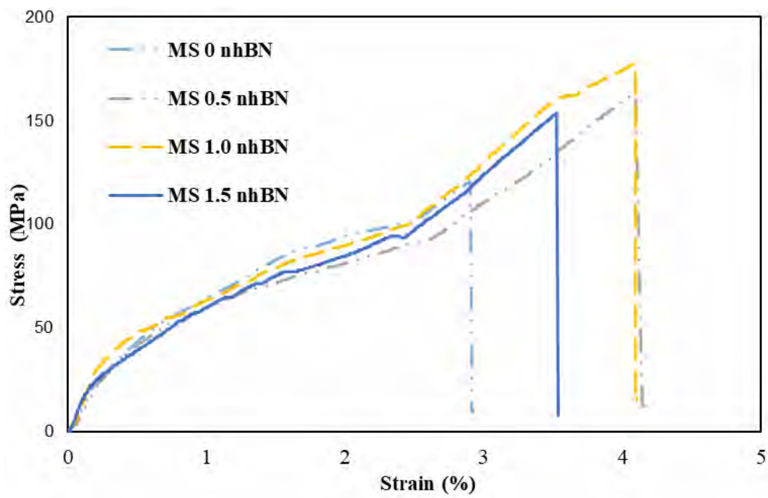


Figure 8 UTS, % elongation vs. reinforcement curve for base alloy and prepared composites (see online version for colours)

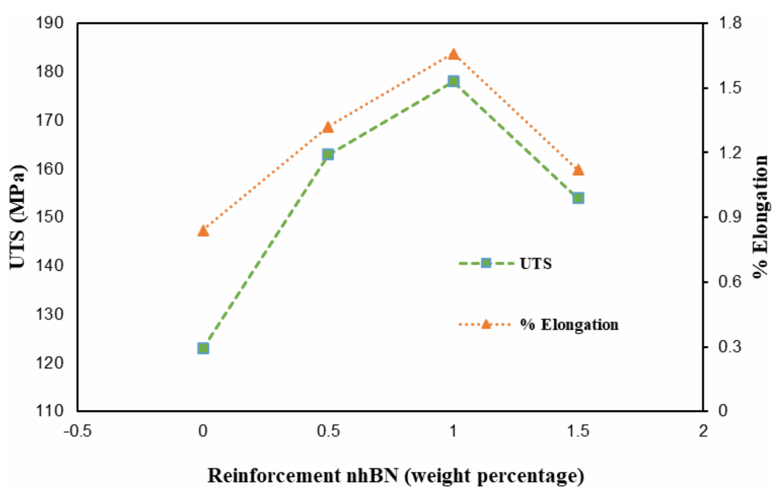
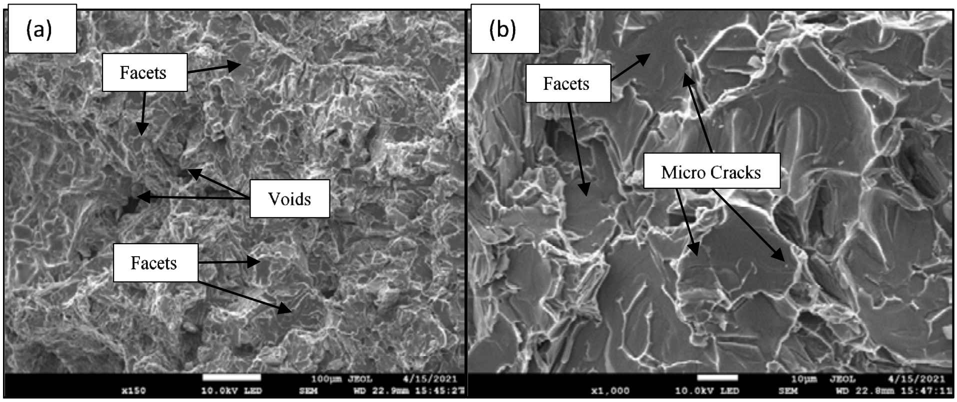
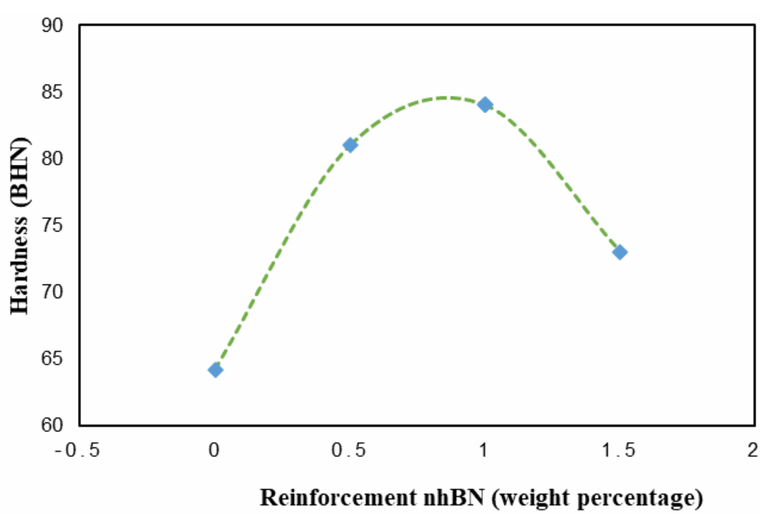


Figure 9 SEM images of fractured tensile specimens for A380/1.5nhBN



The hardness of the different A380/nhBN (0, 0.5, 1, 1.5%) fabricated composites are indicated in Figure 10. The hardness value of the fabricated composite increased with weight percentage 0.5 and 1.0 and then decreased at weight percentage 1.5 of nhBN. The addition of the nhBN particles in base metal, the hardness of composite increased due to resistance offered by hard particles of nhBN and shows resistance against the dislocation movement due to decrement in internal distance between particles (Soltani et al., 2013). During the test while steel indenter moves downward, nhBN particles present in sample act as barrier against indentations and shows higher value of hardness. The hardness values of fabricated composites are also enhanced due to hard phase particles properties of hBN and strong bond between matrix material and hBN reinforcement particles (Madhukar et al., 2020). Then, the hardness of the composites prepared using 1.5 weight percentage of nhBN particles shows decrement due to presence of voids in casted samples.

Figure 10 Hardness vs. reinforcement for base alloy and prepared composites (see online version for colours)



3.3 Tribological behaviour

The wear of the base alloy and fabricated composite is calculated in weight loss and measured in gram. The experiments are performed on pin-on-disk apparatus to evaluate the effect of load, sliding speed and reinforcement on wear and coefficient of friction (COF) at dry sliding condition.

The effect of different loads, sliding speeds and different weight percentages of reinforced particles is indicated in Figure 11. It is evident that weight loss in base alloy and fabricated composite increased with the increase in applied load. Furthermore, there is reduction in weight loss with the increase in weight percentage of the reinforcement. The higher weight loss is observed in base alloy as compare to fabricate composites for all the conditions due to the fact that non-reinforced aluminium alloy is softer as compared to reinforced composite. Also, with increased in load, the base alloy undergoes plastic deformation, exhibiting heavy weight loss at every applied load conditions. The fabricated composite showed less wear due to resistance offered by the hard nhBN particles. During the wear test, it is found that due to the presence of hard particles, the composites formed mechanically mixed layer (MML). The formed layer replaced the actual layer of composite to offer the resistance against the rotating disk. MML region showed higher hardness as compare to non-MML area (Rosenberger et al., 2005; Uvaraja et al., 2015; Demirel and Muratoglu, 2011). In case of composite, at 10-N load, 1.5 weight percentage nhBN and sliding speed of 3.7 m/s attained minimum weight loss as shown in Figure 11(c). The highest wear occurred at sliding speed of 1.25 m/s, applied load of 50 N and 0.5 weight percentage nhBN.

The effect of different load, sliding speed and weight percentage of reinforced particles on coefficient of friction as indicated in Figure 12. It is evident that COF of the base alloy directly affected by applied load and decreased with increase in sliding speed. In case of base alloy, at low load condition abrasive wear occurred, so there is smooth contact between pin and rotating disk as a result less COF. Furthermore, with the increase in applied load, COF increased because adhesion wear is dominating due to which roughness of pin surface increased. Next, with the increase in sliding speed, more frictional heat is generated and high temperature at counter surfaces. So due to the high temperature, the material of the pin is soft and created a layer on rotating disk. There is no direct contact between the counter surfaces, so coefficient of friction is reduced. The COF for composite increased with increase in applied load for all applied load conditions. Also, COF increased with increase in reinforcement at low and medium sliding speed. There is reduction in COF, with increase in quantity of reinforced at high sliding speed. At low sliding speed, with increased in applied load the composite show more wear due to which plastic deformation took place on the pin surface. The hard particles are directly in contact with counter surfaces, due to which scratches occurred on pin and disk surfaces which increased the frictional force. At higher sliding speed more heat is generated and temperature at counter surfaces is high. The exposed hard particles reacted with environmental air and formed B_2O_3 layer. Further, due to boron oxide layer there is no direct contact with counter surfaces and reduction in COF (Liu et al., 2019; Howell and Ball, 1995; Mazahery and Shabani, 2013; Soy et al., 2011; Madhukar et al., 2020). The maximum COF for developed composite occurred at sliding speed of 2.5 m/s, applied load of 50 N and reinforcement at 1.5 weight percentage. The minimum COF for composite is occurred at high speed 3.7 m/s, applied load 10 N and reinforcement with 1.5 weight percentage SEM images of wear surfaces for fabricated composites are shown in Figure 13. It is cleared from Figures 13(a) and 13(b), at low load conditions the composite showed abrasive wear for both low and high sliding speed with deep groove at high speed. At applied load 50 N, the composite follows abrasion wear with grooves at low speed and plastic deformation, delamination and abrasion wear at high speed as indicated in Figures 13(c) and 13(d).

Figure 11 Wear vs. reinforcement for base alloy and prepared composites (see online version for colours)

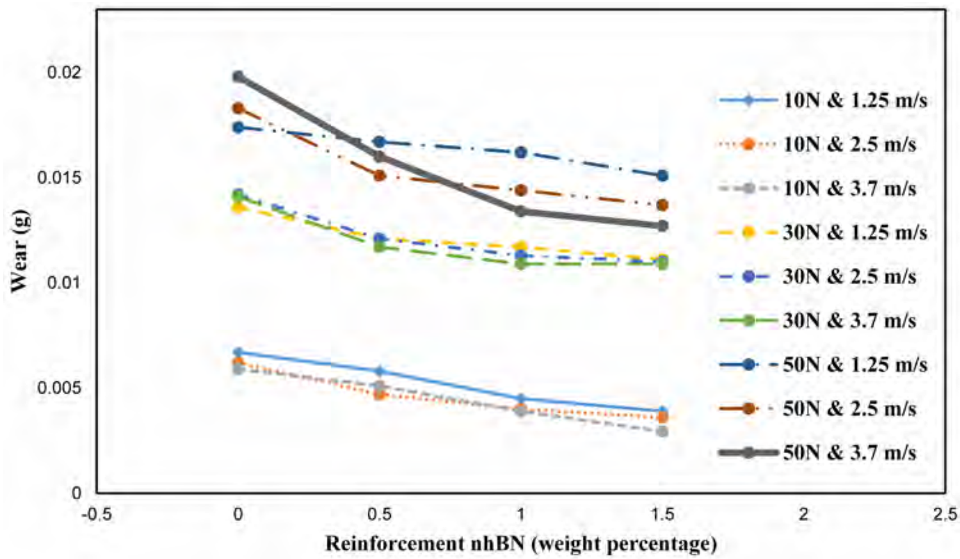


Figure 12 COF vs. reinforcement for base alloy and prepared composites (see online version for colours)

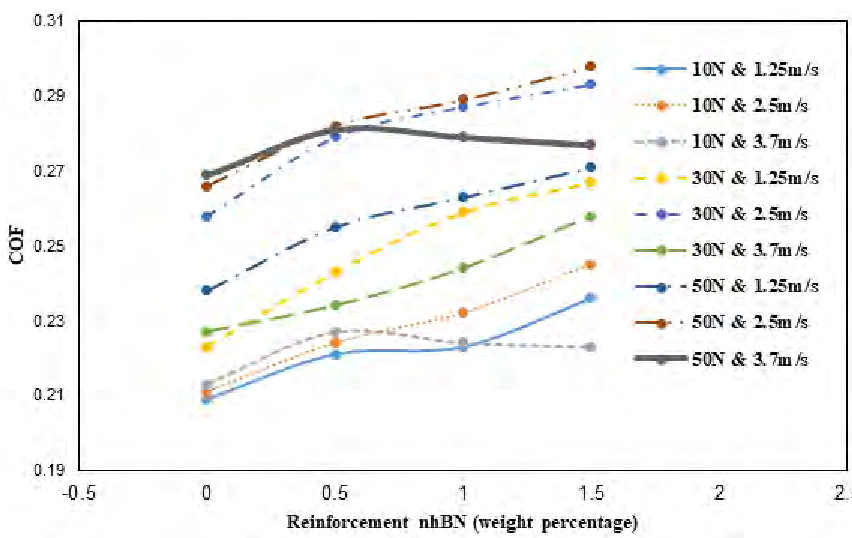
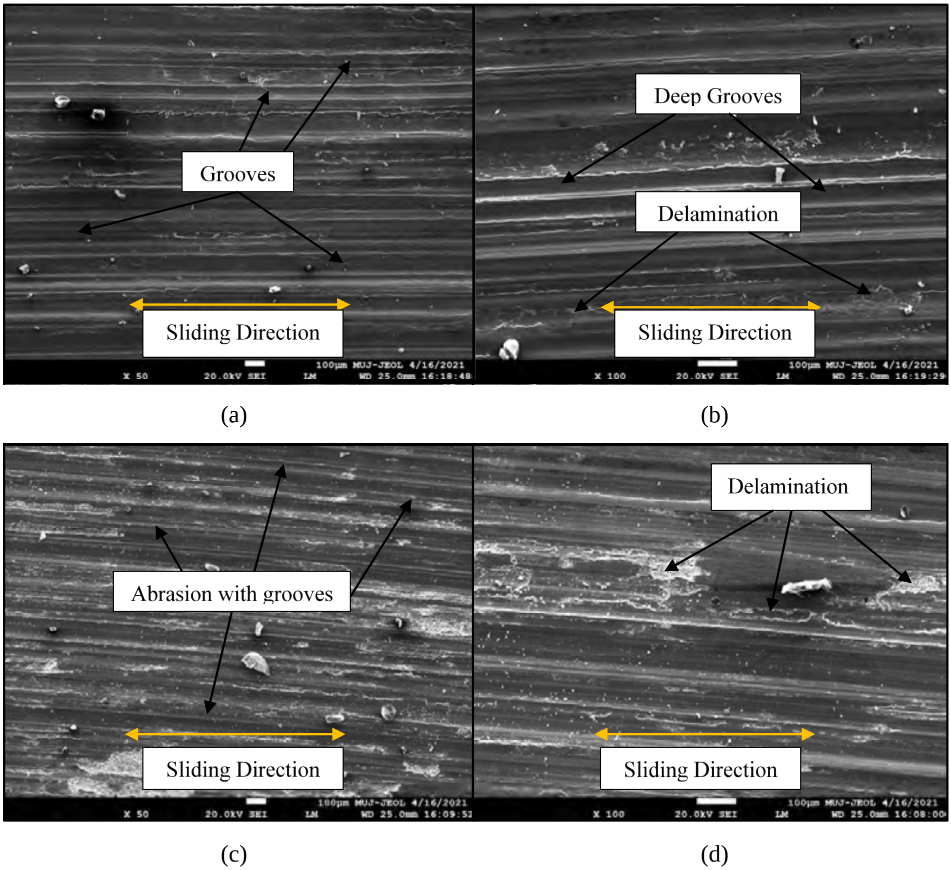


Figure 13 SEM images of wear surface for A380/1nhBN, (a) at load 10 N and 1.25 m/s sliding speed (b) at load 10 N and 3.7 m/s sliding speed (c) at load 50 N and 1.25 m/s sliding speed (d) at load 50 N and 3.7 m/s sliding speed (see online version for colours)



4 Conclusions

Aluminium A380/x-nhBN metal matrix composites are fabricated and the mechanical and tribological properties of the fabricated composites are investigated. The following conclusions are presented from this analysis.

- XRD analysis confirms the major elements present in A380 base alloy and the quality of hBN powder used for the study. Mechanical stirring process distributes the nhBN powder efficiently and uniformly in aluminium matrix.
- With the increase in weight percentage of reinforced nhBN powder, UTS, % elongation and hardness (123–178 MPa, 1.65–2.15, 64.2–84) also increased. The maximum values for above properties are achieved at A380/1nhBN particles. Further, with the increase in nhBN powder weight percentage, UTS, % elongation and hardness of fabricated composite decreased due to voids and micro crack.

- The wear of fabricated composites and base alloy increased with applied load and showed reverse effect with increase in quantity of reinforcement and sliding speed. COF increased with increase in applied load and reinforcement at sliding speeds of 1.25 and 2.5 m/s and decreased at sliding speed 3.7 m/s.
- SEM images of wear surfaces reveals that an abrasion wear occurred at 10 N applied load and plastic deformation and delamination at 50 N.

5 Implications and future scope

A380 aluminium alloy is used in the automotive industries for manufacturing of various parts like brake casting, gear cases, air cooled cylinder head and engine block due to its light weight, strength and wear properties (Gencalp and Saklakoglu, 2010; Qiu et al., 2020). The fabricated composite in this study achieved the enhanced mechanical and tribological properties as compare to base alloy A380. The functional life of the automotive parts manufactured with fabricated composite is more due to high strength and enhanced wear resistance properties as compare to A380 alloy. However, further investigations are necessary to study the alloy properties using different fabrication methods and optimising the method for composite preparation. Furthermore, tribological study is required taking into account different parameters and temperature conditions on pin-on-disk tribometer apparatus.

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