Mechanical and tribological behaviours of aluminium hybrid composites reinforced by CDA-B₄C

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Keywords: hybrid aluminium metal matrix, two stage stir casting, microstructure, SEM- EDX- XRD, mechanical and wear properties

Abstract
This study focuses on fabricating aluminium hybrid metal matrix composites reinforced with eco-friendly agro waste, cow dung ash and boron carbide by two stage stir casting. Weight percentage of cow dung ash and boron carbide were added in ratios of 2.5:7.5, 5:5, and 7.5:2.5. The effects on mechanical properties like hardness, tensile strength, impact strength, flexural strength and wear behaviour were studied. SEM and EDX analysis were employed to study the fracture mechanism for tensile, impact and wear specimens. Optical microstructure images reveal uniform distribution of particles and XRD analysis confirms the presence of reinforcements. Increasing CDA particles has reduced the density of the hybrid composite up to 8%. A maximum increase in hardness, tensile strength and wear resistance was up to 30%, 56% and 56% respectively, and then a slight decrease in impact was found in increasing the CDA particles. Dimples, transgranular cleavage facets, cracks and micro ploughing, micro cuttings are revealed from the fractured specimens of tensile, impact and wear respectively.

1. Introduction
Aluminium and its alloys are extensively used in many industrial applications mainly because of their light weight construction. Usually, the strength of aluminium alloys can be improved in many ways, comprising of, (i) adding insoluble reinforcement to form Metal Matrix composites [1, 2] (ii) by precipitation hardening [3], (iii) by cryogenic treatments [4], (iv) by surface coatings etc. Among the above processes, metal matrix composites have gained much attention in enhancing the mechanical and tribological properties of aluminium.

Generally, a composite material consists of two or more insoluble phases, and their properties might be greater than that of its constituents. Because of its low density, easy fabricability and good engineering properties [4], aluminium is preferred to be as matrix material in most circumstances. Mostly, aluminium matrix composites are fabricated by (i) solid state processing (includes-powder metallurgy, diffusion bonding and physical vapour deposition) (ii) Liquid state processing (stir casting, pressurized die casting, infiltration process) (iii) in situ processing. Among these procedures, researchers found that stir casting is the most profitable and hopeful route. Prior to the fabrication of composite, some vital parameters like stirring speed, stirring time, melt temperature, holding time, stirrer location, design, movement of the stirrer, preheating of die and reinforcements etc can be considered. The optimum selection of these parameters decides the properties of composite material [5–14].

In aluminium metal matrix composites, properties of matrix material (i.e. aluminium) are enhanced by adding single hard reinforcement. The reinforcement can be continuous type (continuous fibers like: carbon fiber, SiC fiber etc) or discontinuous type (short fibers, whiskers and particles). Among these, particle reinforced aluminium matrix composites are used widely. Here ceramic particles like carbide (SiC, B₄C, TiC etc), oxides (Al₂O₃, MgO, ZrSiO₄, ZrO₂ etc), borides (TiB₂, AlB₂ etc and nitrides—BN, AlN etc) are reinforced with aluminium melt [15–22]. Addition of these reinforcements improves the mechanical and tribological properties
of aluminium and thus makes it suitable for numerous fields of application including automobile, aerospace, defence, mineral processing, sports goods etc.

Hybrid aluminium metal matrix composites were introduced to enhance the properties of composites, than single reinforcement. Hybrid metal matrix is adding two or more synthetic ceramic in aluminium matrix. To utilize the industrial waste without affecting the property of composite, synthetic ceramic and industrial waste like fly ash, graphite, red mud etc are added and good results have been attained [23–31]. The major drawbacks in incorporating two synthetic ceramics in the matrix are it reduces ductility and increases brittleness in the composites materials. Due to increased brittle nature the machining characteristics affect the surface roughness and also the weight of the composite materials increases due to the difference in density between the particles and matrix. Usually the synthetic ceramics are hard in nature and commonly used as abrasives were the cost is high. To overcome the above drawbacks agro wastes are one of the promising alternatives.

The current scenario in developing hybrid aluminium metal matrix is reinforcing an agro waste with a synthetic ceramic. The benefits of adding agro waste are low cost, ease of access, low density and reduced pollution. Agro waste like ground nut shell ash (GSA), bamboo leaf ash (BLA), rice husk ash (RHA), bagasse ash, palm kernel shell ash, maize stalk ash, corn cob ash (CCA), bean shell waste ash etc are researched and promising results have been reported [32–44]. Fatile OB et al have reported by adding the corn cob with SiC has no significant rise of porosity but while increasing the percentage of corn cob reduces the mechanical properties gradually. CCA is suggested to be a promising low cost and high performing alternative hybrid material [31]. Venkatesh et al have studies the effects of reinforcing GSA and B₄C particles through squeeze casting and reported that hardness and tensile properties have increased by 17% and 18% respectively and the increase in GSA particles has slightly reduced the impact energy [36]. Alaneme et al investigated the influence of BLA and reported that the ductility of the matrix has increased yet tensile strength has slightly reduced [40]. Narasaraju et al reported that addition of rice husk ash (RHA) and fly ash particles has increased the hardness of the composite matrix fabricated through stir casting technique [41]. Singh et al studied the effect of percentage reinforcements of RHA and fly ash on impact strength and reported that increase in RHA and mixture of fly ash has increased the absorption capacity of the composite up to 15% [42]. Oghenevweta JE et al investigated on maize stalk and reported that the mechanical properties like tensile strength and hardness have increased and impact has reduced slightly when compared with the base aluminium [43]. From the literature review it is clear that the agro waste serve as promising reinforcement in enhancing the properties of composite materials.

Aluminium 7075 is well known for its high tensile strength which is widely used in aeronautical applications. Aluminium reinforced with B₄C exhibit high hardness, good impact and wear resistance, low specific density, low thermal conductivity and high stiffness. The elements present in CDA ash are SiO₂, Al₂O₃, Fe₂O₃, MgO etc which could enhance the properties of aluminium. The benefits of adding CDA are low cost, ease of access, low density and reduced pollution [34–41]. Hence an attempt has been made in reinforcing CDA as second reinforcement in the matrix.

Aluminium 7075 is well known for its high tensile strength which is widely used in automotive, aeronautical, sports and electronic applications. In automotive sectors components such as piston, brake calipers, wheels, and rocker arms are produced using Al 7075 alloy [42]. In the current study the percentages of reinforcements are varied and their effects are evaluated through mechanical properties like hardness, tensile strength, impact strength, flexural strength and the fracture mechanisms for tensile and impact strength are analyzed. Wear analysis are evaluated for the fabricated samples and surface morphologies are analyzed. The distribution of reinforcements and presence of compounds and elements in matrix are evaluated with optical microscope, SEM with EDX and x-ray diffraction analysis respectively.

**Table 1. Chemical composition of Al 7075.**

| Element (7075) | Zn | Cu | Mn | Mg | Fe | Cr | Ti | Si | Al |
|---------------|----|----|----|----|----|----|----|----|----|
| Weight %     | 5.4| 1.42| 0.12| 2.42| 0.42| 0.21| 0.11| 0.13| Remaining |

2. Materials and methods

2.1. Selection of materials

In this study, aluminium 7075 alloy was selected has the matrix material. The spectro analysis was taken for Al 7075 and the composition is given in table 1. Two reinforcements were added in the study, one was natural ceramic (CDA) and other was artificial ceramic (B₄C). Raw cow dung was collected and is thoroughly dried in sunlight for three days to remove the moisture content and to obtain the dung cake. The dunk cake was crushed into small pieces and burnt in a metal drum in open air to produce ash. The ash was collected and heated in
muffle furnace for two hour at 600°C to remove the carbonaceous materials present in CDA ash. XRF analyser was used to identify the chemical composition of CDA and is given in table 2. A sieving machine was used in screening the particles and also to determine the size range. The size of CDA was less than 40 microns and boron carbide was less than 10 μm was used in the current investigation.

2.2. Fabrication process
The Al 7075 alloy was purchased in the form of rod and melted in a graphite crucible in an electrical furnace at 1000 °C. For obtaining better uniform distribution of reinforcements two stage stir casting method was adapted. The process parameters selected for two stage stir casting are given in table 3. To remove the surface absorbed volatile contents, residues and loose scales in the particles the reinforcements are pre heated separately in a muffle furnace for two hours at 400 °C. In two stage stir casting process, aluminium is heated up to melting temperature and dropped down to semi solid state. At semi solid state the preheated CDA and B₄C are added and mixed manually. Once the manual mixing is over the molten composite metal was heated up to 1000 °C for different percentage of reinforcements which is given in table 4. A mechanical stirrer with four blades preheated to 300 °C was introduced once the melt has reached 1000 °C. For producing homogenous mixture, the mechanical stirrer was operated at a speed of 400–500 rpm. To reduce the undesired problem during casting process and also to elevate the solidification rate the composite melt was poured in a rectangular stainless steel mould having a cross section of 100 × 100 × 10 mm.

2.3. Testing methodology
A wire cut EDM (electro discharge machining) machine was used to obtain the specimens of dimensions 10mm × 10mm × 10mm. For obtaining a clear surface for microstructural analysis, the specimens are polished with different grades (400, 600, 800, and 1000) of emery sheets. A Keller’s reagents were etched on polished surface as per standard metallographic procedure for analysing the microstructure.

SEM analyses were carried out with an energy dispersive spectrocope (JEOL JSM-6390) and elemental analyses were taken using energy dispersive x-ray analysis (EDX) for all the samples. Energy dispersive x-ray Fluorescence (EDXRF - Bruker S8 Tiger) was used to identify the elements and compounds present in CDA. To identify the different phases present in the composite sample, x-ray diffraction (XRD) were obtained by using a Panalytical x-ray diffractometer.

The densities of aluminium alloy and the composite samples were calculated to identify the porosity levels for the fabricated samples. Good castings can be developed only by minimizing the porosity level in the

| Table 2. XRF analysis for CDA. |
|--------------------------------|
| Elements | SiO₂ | P₂O₅ | K₂O | CaO | MgO | Cl | Al₂O₃ | Na₂O | SO₃ | Fe₂O₃ | ZnO | MnO |
| Weight % | 67.39 | 8.57 | 7.29 | 6.92 | 5.79 | 1.48 | 0.84 | 0.52 | 0.50 | 0.44 | 0.07 | 0.06 |

| Table 3. List of process parameters for stir casting process. |
|-------------------------------------------------------------|
| Process parameters                                      | Selected parameters          |
| Processing Temperature                                      | 1000 °C                     |
| Preheat temperature of mould                              | 300 °C                     |
| Reinforcement particle preheat temperature                | 400 °C                     |
| Stirring speed                                            | 400–500 rpm                 |
| Stirring time(min)                                        | 3 min                      |
| Blade Angle                                               | 45°                        |
| No of Blades                                              | 4                           |
| Position of Stirring in the melt                          | Up to ¾ depth               |

| Table 4. Percentage of reinforcements.                   |
|-----------------------------------------------------------|
| Sample | Al 7075 (wt%) | B₄C (wt%) | CDA (wt%) |
|--------|---------------|-----------|-----------|
| S0     | 100%          | 0%        | 0%        |
| S1     | 90%           | 2.5%      | 7.5%      |
| S2     | 90%           | 5%        | 5%        |
| S3     | 90%           | 7.5%      | 2.5%      |
composites. The material properties and compactness of the fabricated composites are decided by the porosity level. To calculate the porosity level in the composites, the theoretical density of the samples and the experimental densities were calculated. The theoretical density was calculated by the rule of mixtures (equation (1)) and the experimental density was calculated by (equation (2)),

$$\rho_{th} = \rho m Vm + \rho r Vr$$

Where \(\rho_{th}\), \(\rho_r\) are the theoretical densities of matrix and reinforcements,

$$\rho_{(experiment)} = \frac{\text{Mass}}{\text{Volume}}$$

Here mass was calculated by using an electronic weighing machine and volume was calculate by multiplying the length and the cross sectional area of the specimens. From the calculated theoretical and experimental values the porosity of the fabricated samples were determined by (equation (3)) [35, 36].

$$\text{Porosity(\%)} = \frac{\rho_{(theoretical)} - \rho_{(experimental)}}{\rho_{(theoretical)}} \times 100$$

The hardness of the samples was examined using macro hardness tester. The experiments were conducted as per ASTM: E10 standard in Brinell scale; with 250 kgf load for 30 s and 5 mm diameter steel ball indenter. At room temperature, five indentations were taken and the mean value was calculated.

The ultimate tensile test was performed by an M 30-universal testing machine. Three specimens were prepared using wire cut electro discharge machining as per the ASTM: E08 standard. To reduce the possibilities of inaccuracy the mean value of ultimate tensile strength were calculated.

Charpy impact testing equipment was used to identify the energy absorption capacity of the specimens. The tests were conducted as per ASTM: E23 standard for three samples and the mean value of impact strength were calculated.

Three-point bending test with two specimens each was performed to examine the flexural strength as per ASTM: A370 standards. The maximum bending load during bending test was evaluated and was converted into flexural strength (MPa) value [16]. The formula used to calculate the flexural strength is,

$$\sigma = \frac{M y}{I}$$

Here, \(\sigma\) is the flexural strength, \(M\) is bending moment, \(I\) is moment of inertia and \(y\) is the distance the neutral axis. Since it is a three point bending test the load acting will be on the mid span for which,

$$M = \frac{P \times L}{4}$$

$$y = \frac{t}{2}$$

$$I = \frac{b \times t^3}{12}$$

$$\sigma_{\text{max}} = \frac{3 \times P \times L}{(2 \times b \times t^2)}$$

Here, \(P\) is the load applied, \(b\) is the breath of the specimen, \(t\) is specimen thickness and \(L\) is the length. For the current study the \(L = 100\) mm, span length = 80 mm, thickness 10mm and \(b = 10\) mm.

Dry sliding wear tests were conducted using a Pin-on-Disk apparatus according to ASTM: G99 standard. Cylindrical specimens of diameter 10 mm and height 28mm were prepared for the wear resistance study. A steel disk of material EN31 (about 165mm diameter) was used to slide against the pin. The volumetric loss (V) was calculated by finding out the height loss in the specimens and multiplied with the area of cross section of the test pin. The wear rate was calculated by dividing the volumetric loss by sliding distance (L) using the equation (9),

$$\text{Wear rate(Wr)} = \frac{V}{L}(\text{mm}^3 \text{ m}^{-1})$$

### 3. Results and discussion

#### 3.1. Evaluation of microstructure

The microstructure images for the reinforced samples are shown in figures 1(a)–(d). Uniform distributions of reinforced particles are clearly visible from the optical images. Intermetallic phases such as MgZn2, Al2Mg5Zn3, Al2CuMg, Al2Cu, Al2Cu2Fe, Al13Fe4 and Mg2Si can be formed during solidification of 7075 aluminum alloy.

The micro segregation of MgZn2 with fine grains are uniformly distributed in aluminium matrix as shown in sample S0. During plastic deformation stage, movement of dislocation takes place across the grain boundaries from one grain to another. The grain boundaries are comparatively large for sample S0 compared to other
samples. The mechanical properties rely on increased grain boundaries which are achieved by addition of reinforced particles. The increases in grain boundaries for the particle reinforced samples are clearly seen from images 1(b)–(d).

The reinforced particles act as a barrier where the dislocation movement from one grain to another has to change its direction resulting in an increase in ultimate tensile strength. Multidirectional stresses are observed in composite samples than monolithic aluminium due to grain refinement in composite samples with good distribution of reinforcements and low porosity. The two-stage stir casting method contributes a major part in uniform distribution of CDA and B₄C particles in the matrix. CDA is a soft and low density particle when compared with B₄C and aluminium alloy which tends to float or sink in the melt during casting process.

To retain the suspension of CDA particles for longer duration CDA particles are mixed manually in semi-solid melt. Selection of process parameters for stir casting also acts as a vital part in homogeneous distribution of reinforcements in the matrix.

The SEM and Energy dispersive x-ray analysis of the samples are shown in figure 2(a–d). From the SEM images it can be concluded that two stage stir casting method is better than conventional stir casting to attain uniform distribution of reinforcements throughout the matrix.

Better uniform distribution of reinforcements are achieved at higher temperature. The melting temperature of the particles is higher than molten aluminium and hence to reduce the formation of clusters in the matrix, high molten temperature (1000 °C) is selected.

It is well known that the thermal expansion coefficient of B₄C particle is $5 \times 10^{-6} \, ^\circ\text{C}^{-1}$ whereas for aluminium alloy it is $23 \times 10^{-6} \, ^\circ\text{C}^{-1}$. When CDA/B₄C increases slight clusters can be seen which is due to thermal mismatch between matrix and reinforcements. The solidification rate is delayed by the hard ceramics when the liquid alloy is surrounded among them which lead to formation of clusters. The density difference between CDA and aluminium matrix is also one of the reason for cluster formation in the matrix.

Boron carbide and cow dung ash reinforcement phases are effectively formed in aluminium 7075 alloy which are analysed by x-ray diffraction analysis as shown in figure 3 for sample S3. The major elements present in cow dung ash is Si and predominant peaks (Al, B₄C, Si and Ca) are observed which confirms the present of reinforced particles in the hybrid composite samples [45–47].
3.2. Evaluation of density

The density variation with various contents of CDA and B$_4$C particles are shown in figure 4. The theoretical density values are measured using equation (1) and the experimental values are calculated by using equation (2).

Figure 2. (a)–(d). SEM and EDX for fabricated samples.
From the result it is clear that increase in weight percentage of CDA particles decreases the density of hybrid composites. Alaneme et al has reported that increase in weight percentage of rice husk ash has reduced the density and on the other hand increased porosity in the composite [40]. Due to reduction in density it may be concluded that lightweight aluminium composites can be produced at low cost. Porosity of the composite material was calculated by using equation (3).

A reduction in experimental density was found to be 8% for sample S1, 5% for S2 and 3% for S3 against the base alloy. Increase in CDA particles shown increase in porosity level. The porosity level was lower than 4% for the composite samples which may be permitted in producing aluminium metal matrix composites [39, 40]. The lower porosity level observed was a good sign of reliability in using double stage stir casting method for producing composite materials. In the current study it is clear that the maximum porosity level was 2.12% for 7.5% CDA which is considered as an acceptable porosity for the fabricated hybrid composite which is given in table 5.

3.3. Evaluation of hardness

The effects of varying the percentage of reinforcements on hardness is graphically represented in figure 5. 

B$_4$C is well known particle for its hardness and its presence is one of the reasons for increase in hardness for all samples. Sample 1, having 7.5% CDA particles showed higher hardness (118 BHN) than sample S0 (110 BHN). The hardness has slightly increased when compared with sample S0. While increasing the CDA particle in the matrix the hardness has reduced, this may be due to the presence of refractory elements (SiO$_2$, Al$_2$O$_3$ and Fe$_2$O$_3$). Increasing the CDA particles in the matrix leads to assist in movement of fine CDA particles which easily
causing slip during indentation and causes decrease in hardness. The density difference between the reinforced particles and aluminium matrix may also be the reason for minor change in hardness for sample S1.

Even percentage of B₄C and CDA particles are added in sample S2. The presence of B₄C has restricted the flow movement of fine particles of CDA and increase the hardness more when compared to sample S1. The percentage of B₄C is more for sample S3 and hence during indentation, resistance to plastic deformation occurs which hardens the surface area by increasing the hardness of the composite material. Aluminium being a ductile material turns brittle when hard ceramics are added in the matrix which enhances the hardness. Uniform distribution of reinforcements, rate of solidification, density of reinforcement particle and less porosity are few parameters which influences the hardness of composites [23, 48].

The resistance against indentation on the reinforcements was identified by Brinell hardness value. The average hardness values are found to be 110, 118, 132 and 144 BHN for S0, S1, S2 and S3 samples respectively. The highest value was found in sample S3 having 7.5% B₄C - 2.5% CDA percentage of reinforcements and 30.90% of increment was achieved when compared to Al 7075.

### 3.4. Evaluation of tensile strength

The mean tensile strength of samples is graphical representation in figure 6. It was observed that the tensile strength has increased for all the composite samples when compared with Al 7075. Inclusion of B₄C particles increases the tensile strength in the composite samples. Addition of B₄C particles causes brittleness in the matrix which in turn increases the strength of composite material. Reinforcing B₄C and CDA has increased the tensile strength of composite material by 56%. The hard nature of B₄C and CDA acts as a barrier and restricts the crack propagation to generate which leads to dislocation of matrix, also called as Orowan mechanism. The increase in strength is achieved only when the dislocation density in the matrix increases and hence it is proved that the reinforcements have adequate impact in the fabricated hybrid composite material. The grain boundaries play a vital role in composite materials. The strength and restricted growth of micro cracks are achieved only with increased grain boundaries. Addition of CDA and B₄C has increased the grain boundaries in the matrix.

Dispersion of reinforcements uniformly and interfacial strength in the aluminium matrix can be attained by preheating the CDA and B₄C particles during casting process. The preheating provokes the reinforcements in generating the thermal stress which may influence the strength in composite material. The thermal mismatch between B₄C-CDA and the matrix was also one of the reasons for increase in tensile strength. The uniform dispersion of B₄C and CDA particles without any flaws and defects produces excellent bulk mechanical properties. It was clear from the result that the fabricated hybrid composite materials induce high strength to Al.
7075 alloy and increased the resistance to tensile stresses leading to superior ultimate tensile strength [49–51]. The resistance against tensile force on the reinforcements can be identified by the ultimate tensile strength value. The average tensile strength values are found to be 184.8, 249, 265 and 288 MPa for S0, S1, S2 and S3 samples respectively.

In general failure in a composite material can be categorized into brittle and ductile fracture. The major causes for failure in composite materials are due to non-uniform distribution of reinforcements in the matrix and also due to the secondary phase formation. When reinforcements are added to the soft ductile aluminium alloy the nature of the alloy changes into hard and brittle material. The non-uniformity of reinforcements causes variation in strain carrying capability between the reinforcements (B4C and CDA) and the aluminium matrix. The secondary phase formations are due to differences in the coefficient of thermal expansion among the reinforcement particles, 7075 aluminium alloy matrix and the precipitated phases.

The failure patterns in the tensile fracture are revealed by cleavage facets and micro void coalescence through SEM images. Brittle fracture occurs when very less plastic deformation are formed which can be identified by transgranular cleavage facets. Ductile fracture occurs due to necking in specimens which can be identified by microvoid. Failure mechanism occurring through increased crack propagation through grains then it can be exhibited that transgranular facets are formed. When the applied load is greater than the tensile strength of the composite samples then the crack formed exhibits micro voids. Microscopically, ductile and brittle attribute dimples and cleavage facets respectively [45–47, 52, 48–51, 53, 54].

Figures 7(a)–(d) shows the SEM and EDX images for the fracture tensile specimens. The combination of both ductile and brittle failure has occurred in the tensile samples. The initial resistance of crack and its growth decides the ultimate strength of the materials. From figure 7(a) for sample S0 more dimple structures are identified than cleavage facets. Aluminium is a ductile material and sample S0 contains only Al 7075 which causes ductile failure and minor brittle failure during crack propagation through grains. From figure 7(b) it is clearly observed that ductile failure has occurred with small dimples and necking with initial crack propagation. CDA being a soft ceramic increase the elastic nature of aluminium alloy and provides slow propagation of cracks.

From figure 7(c) for sample 2, it can be identified that brittle failure has occurred more than ductile failure when compared to that of sample S1. The increase in percentage of the hard ceramics in the matrix has led to more facets causing brittle failure. The presence of hard ceramic particles in the matrix resist the applied load during plastic deformation. This resistance was due to the thermal mismatch between reinforced particles and aluminium matrix. The coefficient of thermal expansion is high for aluminium matrix and is low for the reinforced particles which causes thermal mismatch in the composite materials. From figure 7(d) for sample S3 increase in percentage of B4C causes more cracking of particles and brittleness along the surface of composite material. Significant clustering and debonding of reinforcements in the matrix alloy causes voids and micro cracks in the composites. The EDS result also proves the reinforced elements are present in the tensile fractured surfaces.

3.5. Evaluation of impact strength

It is observed that impact strength has reduced for all reinforced samples when compared with base aluminium alloy. The graphical representation of the average impact strength is shown in figure 8. High impact energy in aluminium alloy exhibits ductile nature which undergoes plastic deformation at room temperature than the
Figure 7. (a)–(d) SEM and EDX analysis of fractured tensile samples.
composite materials. The impact strength in composite materials has slightly reduced due to the presence of reinforced particles which exhibit brittle nature and act as stress concentration areas. The heterogeneous dispersion of reinforced particles in the matrix results in the formation of clusters which also decreases the matrix-reinforcement bonding and reduces the impact strength of the composites [45–47, 52, 48–51, 53, 54].

The resistance against energy absorption on the reinforcements can be identified by impact strength value. The average impact strength values are found to be 3.2, 2.9, 2.8 and 2.6 J for S0, S1, S2 and S3 samples respectively. The lowest decrement in impact strength was identified for sample S1 (9.3%) having 7.5% CDA and the highest decrement value was found for sample S3 (18.75%) when compared to base material. Figures 9(a)–(d) shows the SEM and EDX analysis images for fractured impact specimens. The impact strength of sample S0 is more than other samples due to higher ductile property. Dimples are observed more, than cleavage facets in sample S0. When ceramics are added in aluminium alloy, transformation of ductile to brittle phase takes place in the matrix. The crack propagation and cracked particles are clearly seen from figures 9(a)–(d). The river lines represent the transgranular cracks which occur between the cleavages which initiates local cracks [45–47, 52, 48–51, 53, 54].

Crack propagation occurs on the grain boundaries in the matrix which leads to formation of transgranular facets. The reinforcement acts as stress concentration area which leads to unstable crack resulting low energy absorption in resisting load. Void nucleation around the particles of reinforcements can be seen which initiates the crack between the matrix and reinforcements which in turn converts into cavity. From the literature survey it is evident that when tensile strength increases the impact strength will reduce due to the presence of brittle and cavity area in the fractured surface.

### 3.6. Evaluation of flexural strength

Figure 10 shows the effect of reinforcements on flexural strength. Flexural strength has increased with increase in CDA content. The soft nature of CDA particles has increased the elongation property of the matrix by producing high flexural strength. The increase in hard ceramic particle (B$_4$C) has caused brittleness in the matrix which in turn has reduced the flexural strength when compared with base aluminium alloy. The peak flexural strength was identified for sample S1 having 7.5% CDA with an increase of 11.8% was achieved when compared with the base alloy. A decrease in flexural strength of 6% was inferred for sample S3 when compared with sample S0. The average flexural strength values are found to be 320, 358, 334 and 300 MPa for S0, S1, S2 and S3 samples respectively.

### 3.7. Evaluation of wear rate and coefficient of friction

Three constant process parameters were selected to conduct wear experiments namely, sliding velocity (2.997 m s$^{-1}$), load (30 N) and time (15 min). The graphical representation of wear rate and coefficient of friction are shown in figures 11 and 12 respectively. Wear and coefficient of friction are studied to identify the materials resistance against sliding or rubbing action with other surfaces.

Wear rate reduces due to less plastic deformation between the sliding contact area and the sliding material. Less plastic deformation can be achieved due to the presence of reinforcements which minimizes the shear stress transfer while sliding. During sliding action oxidation of metallic particles occurs and a layer will be formed on the pin surface. The layer formed undergoes distortion, spalling and fracture during sliding action. This layer formed between the mating surface offers resistance due to dilution of metallic contact on the surface [55–62].
The wear rate was found to be 0.005016, 0.003541, 0.002851 and 0.002027 and coefficient of friction was found to be 0.394, 0.357, 0.341 and 0.310 for samples S0, S1, S2 and S3 respectively. The wear rate gradually decreases for all composite samples when compared with the base alloy. The lowest wear rate value was found for Figure 9.

![SEM and EDX analysis of fractured impact for sample S0](image1)

![SEM and EDX analysis of fractured impact for sample S1](image2)

![SEM and EDX analysis of fractured impact for sample S2](image3)

![SEM and EDX analysis of fractured impact for sample S3](image4)

Figure 9. (a)–(d) SEM and EDX analysis of fractured impact samples.
sample S3 having 7.5% B$_4$C—2.5% CDA composition of reinforcements and 60% of increased resistance was achieved when compared with base alloy.

The presence of B$_4$C and CDA in the composite decreases the coefficient of friction. The release of soft CDA during wear process acts as the solid lubricant which reduces the coefficient of friction in the composites. The
(a) SEM and EDX analysis of worn surface for sample S0

(b) SEM and EDX analysis of worn surface for sample S1

(c) SEM and EDX analysis of worn surface for sample S2

(d) SEM and EDX analysis of worn surface for sample S3

Figure 13. (a)–(d) SEM and EDX analysis of worn surface for sample.
presence of hard B\textsubscript{4}C particles in the matrix resist the material removal during the wear process thus producing less wear rate in the fabricated samples.

When the pin surface slides over the abrasive disc, material removal occurs due to microscopic removal mechanisms in sliding or rolling contact. Abrasive wear are caused by micro-cutting and micro-ploughing. Micro-cutting occurs due to microchips formation during material removal and micro-ploughing occurs due to material displacement in the side edges. Literature reports that when wear is low, deformation occurs by micro-ploughing and at high wear, deformation occurs by micro-cutting mechanisms. The wear resistance is governed by transition from micro-ploughing to micro-cutting mechanisms for composite materials against sliding force.

The SEM and EDX analysis for worn-surface for the fabricated samples are shown in figures 13(a)–(d). From the SEM images for sample S0 it is clear that both micro-cutting and micro-ploughing has occurred on the surface of the base alloy. The material removal rate was high for the aluminium 7075. The worn-surface of the Al7075–2.5 B\textsubscript{4}C–7.5 CDA composite is shown in figure 13(b). The morphology of the worn-out surfaces changes from fine scratches to distinct grooves while increasing CDA reinforcement. The worn surfaces in some places reveal patches from where the material was removed from the surface of the material during the course of wear. It was established that the thickness of the CDA rich lubricating layer at the sliding surface plays a significant role in the wear behaviour of composites.

The worn-surface morphology of Al7075–5B\textsubscript{4}C–5CDA composite is shown in figure 13(c). The worn surface was characterized by plastic deformation and clear evidence of micro-ploughing occurred resulting in reduction of wear loss. For sample S3 the percentage reinforcement of boron carbide is more which forms into a high hard material. It is evident that when the hardness increases the wear rate decreases. The hard surface resist the removal of material during sliding action from the matrix which exhibits good resistance to wear.

The EDX analysis shows the peaks of aluminium and reinforced particles along with Fe and O elements. The O peak confirms the oxidative wear and Fe confirms the mating of steel material. It is clear that the reinforced particles colloid with the steel surface material leading to transfer of iron and produce a mechanical mixed layer. The mechanically mixed layer formed between the pin and the surface plays a vital role in reduction of wear in the composite samples [55–62]. The oxide and iron peaks present in sample S3 is more when compared with other samples and it has been concluded that wear resistance has increased.

4. Conclusion

The following conclusions were made on the study of reinforcing Al 7075– B\textsubscript{4}C - CDA are summarised below:

- Two stage stir casting technique was used to fabricate the hybrid composite samples.
- A uniform distribution of reinforcements was revealed through optical microstructure and SEM images. The presence of particles in the hybrid composites were identified through EDX and XRD analysis.
- Hardness has increased in the hybrid composites by adding CDA. Maximum of 31% increment in hardness for composites was found to that of aluminium alloy for sample S3.
- The tensile strength has increase up to 56% to that of base alloy. Addition of CDA and B\textsubscript{4}C particles has slightly decreased the impact strength of the composites.
- Flexural strength has fluctuations for different percentages of reinforcements. Maximum of 12% increment in flexural strength for sample S1 is achieved when compared with base alloy.
- Wear rate has gradually decreased for all the composites and a maximum of 59.58% increase in wear resistance was found to that of aluminium alloy for sample S3.
- SEM analysis for the fractured specimens reveals that both ductile and brittle fractures have occurred in the fabricated samples. Dimples, transgranular clevages, cracks, necking, particle cracks and micro ploughing, micro cutting etc are seen in the fractured and worn specimens.
- The study has proved that the CDA particle has the potential to serve as reinforcement to improve the mechanical and wear properties of hybrid composites.

Acknowledgments

Authors wish to acknowledge Faculty of Mechanical Engineering, Coimbatore Institute of Engineering and Technology and Sri Ramakrishna Institute of Technology, Coimbatore, India for providing facilities to carry out research work and also timely supports rendered during this work.
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