Mechanical and tribological behavior of Al composites containing varying beryllium aluminum silicate and constant CeO₂

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Abstract

The main aim of the present work is to see the performance of “Al–Beryl” composites processed via stir casting route with or without CeO₂ on their mechanical, wear and corrosive properties for structural applications in heavy machinery and watercrafts. Hardness and ultimate tensile strength increased with 36% and 43%, respectively, with 9% Beryl addition. Further, effect of addition of constant 0.5 wt.% CeO₂ in “Al–Beryl” composite was evaluated and remarkably improvement in corrosion resistance was observed. Tribological performance of the composites was investigated by conducting sliding wear tests against steel at different loads in dry and wet conditions. Characteristic features of adhesion, fracture and delamination were observed in SEM micrograph of the worn composite having low beryl content slid in air whereas abrasive wear predominates in water or oil. Addition of increased wt.% of beryl particles led in reduced wear of the composite at all loads. Increase in corrosion resistance by 45% decrease in weight loss with 0.5% CeO₂ addition was observed. “Al6061–9% Beryl–0.5% CeO₂” composite with high hardness, wear and corrosion resistance is found most promising for structural applications.

Article Highlights

- (1) An increase of 36% in hardness and 43% in ultimate tensile strength was found in Al composites with 9% Beryl addition;
- (2) Coefficient of friction was found least for “Beryl–CeO₂” added composites in wet sliding conditions;
- (3) A transition in wear mechanism occurred with adhesion, fracture and delamination of the worn composite with low beryl content slid in air;
- (4) Corrosion resistance increased by 45% with 0.5% CeO₂ addition in Al composites.

Keywords Metal matrix composites · Stir casting · Beryl · Cerium oxide · Sliding wear · Corrosion

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1 Introduction

Since the last century, aluminum metal matrix composites (MMC's) are a matter of interest for researchers because of their easy and economical processing with vast structural industrial use in defense, aerospace, marine and automobile components [1–9]. To obtain desired properties, Al is reinforced with varying percentage of different metallic and ceramic reinforcements having limitations of poor wettability between matrix and reinforcements and their instability at higher temperature [10–14]. With time, different processing routes were studied and liquid metallurgy technique was found suitable for processing large size components [15–19]. Stir casting technique is generally preferred because of its simplicity, cost-effectiveness and applicability for mass production. Stir casting with increase in holding time, temperature and periodic stirring results in homogenized mixing and reduction in porosity [19–22]. Reinforcements like MnO_2 addition in Al MMC resulted in high hardness and strength with increased holding time during casting and Al–Mn precipitate formation further strengthened the composite [23–25]. It was found that Al MMC processed via fly ash addition resulted in effective casting with increased wettability [18, 26]. Jokhio et al. [27] observed Mg addition in Al matrix imparted good bonding between reinforcement and matrix. It has been observed that addition of AlN or ceramic particles like SiC increases the composite strength significantly [28, 29]. Optimum wt.% addition of reinforcement in Al matrix results in less agglomeration and clustering of particles. Increase in strength with decrease in ductility was found with increase in volume % of oxide or ceramic particles in Al composite [30–33]. McDanel [34] reported that addition of more harder discontinuous SiC in Al MMC led to increase in yield and tensile strength by 60% in comparison with unreinforced matrix. Strengthening of Al composite with strong discontinuous SiC fibers is confirmed by Arsenault and Fischer [35], Arsenault [36] and Taya et al. [37]. Reddappa et al. [38] studied the effect of quenching on Al6061 composite with increasing beryl addition (2–12 wt.%) and found improved hardness and strength in heat treated and aged samples. Beryl particle additions have given rise to large residual compressive stress developed during solidification due to difference in coefficient of expansion between ductile matrix and brittle ceramic particles. Al MMC's are generally used in making of piston, connecting rod, castings for railways, brake drum, equipment of mining, etc., where wear has a great role in long life functioning of these components; excessive wear of the mating components sometimes lead to catastrophic failure [39, 40]. So, the study for tribological properties of Al MMC's has become the need of time. Wear properties

Table 1 Chemical composition of the “as casted” Al6061 — in wt.%

Chemical element	% (in weight)
Si	0.50
Fe	0.30
Cu	0.28
Mn	0.12
Mg	0.91
Cr	0.14
Zn	0.20
Ti	0.11
Al	97.44

Table 2 Batch compositions of processed Al MMC's

Specimen N°	Composition (in wt.%)
A1	Al6061 as casted
A2	Al6061–3% Beryl
A3	Al6061–6% Beryl
A4	Al6061–9% Beryl
A5	Al6061–3% Beryl–0.5% CeO_2
A6	Al6061–6% Beryl–0.5% CeO_2
A7	Al6061–9% Beryl–0.5% CeO_2

of many MMC's having fly ash, Al_2O_3 , glass, graphite, mica and SiC, as reinforcements have been reported [39–52].

However, literature survey revealed that very little is reported about effect of beryllium aluminum silicate ($\text{Be}_3\text{Al}_2(\text{SiO}_3)_6$) (beryl) and cerium oxide (CeO_2) addition on properties of Al composites. Cerium oxide has a unique property of having stability in chemical attack and high temperature [53, 54]. Al MMCs are used in different areas of industries for making different machine components which are prone to corrosion [52, 55–60]. To protect them from corrosion anti-corrosive coatings of zinc chromate is done which is in general toxic in nature and hazardous to the environment. In the present investigation focus is on effect of CeO_2 which is less toxic than zinc chromate on “Al–Beryl” MMC to have an optimized Al MMC's composition having superior wear and corrosive properties.

2 Materials and methodology

2.1 Materials

For the fabrication of hybrid “Al6061–Beryl–CeO₂” composites, “as casted” Al6061 was used, having following chemical composition in weight percent, as determined by ED-XRF spectrophotometer — Table 1:

High-purity commercially available beryl and CeO₂ powders (particle size: 20–30 µm) were taken as starting materials. Powders were ball milled in zirconia vial with zirconia balls (ball to powder ratio of 10:1) for 4 h at 250 rpm to obtain uniform size of particles. The powders were, however, heated at 850 °C in order to dehydroxylate the surface to minimize H₂ porosity [25]. Following batch compositions (in wt.%) were prepared — Table 2:

2.2 Methodology

2.2.1 Processing

Al6061 MMC's were prepared by melting half kg of “as casted” Al6061 ingot in a 2.2 kW capacity kanthal wound resistance heating furnace. Varying beryl and constant CeO₂ particles were added during stirring. Ingot is put in the crucible made up of very high refractory material and after superheating aluminum melts at 850 °C, preheated beryl, CeO₂ powders were gradually added. Beryl does not contain carbon, so formation of Al₄C₃ is restricted at high temperature which otherwise deteriorate the properties of the composite. The stirred slurry was poured in alloy steel die at a temperature of 750 °C. Stirring speed was kept at 800^{±50} rpm to increase wettability and good bonding between reinforcement with the matrix. Stirring temperature was kept at 620 °C where Al is in semisolid state to have effective wettability. Porosity is generally the prime defect in casting so while pouring the molten metal the pouring rate was kept constant and the bubble formation was avoided. Prepared composites were investigated for the phases evolved during casting using an X-ray diffractometer with CuK_α radiation of 1.54 Å wavelength and the polished surfaces of cast composites were subjected to microstructural characterization.

2.2.2 Hardness and strength tests

Cast components of “Al6061–Beryl–CeO₂” composites were machined and samples for tensile, hardness and wear tests were prepared. Samples were polished using emery papers of different grit sizes, and subsequently by 1 µm alumina powder suspension so as to obtain finished

Fig. 1 Schematic diagram of tensile and impact strength specimen as per standard ASTM E8M-89b — Unit: [mm]

surfaces. The polished samples were ultrasonically cleaned in acetone and then dried in a hot air stream.

Hardness was measured using Brinell hardness testing machine at 500 kgf with 10 mm diameter hardened steel ball as penetrator. Five indentation marks were taken, and their average is reported. Tensile tests were done on H75KS Hounsfield testing machine at an extension rate of 1 mm/min. Tensile specimens were prepared on lathe machine according to ASTM E8M standard with diameter 5 mm and gauge length 25 mm. The specimens were tested and average of five readings is reported. Schematic diagram of tensile specimen is shown in Fig. 1.

2.2.3 Tribology tests

Sliding wear tests were conducted in dry (air) and wet (distilled water or automotive oil) conditions. Polished composite samples were subjected to sliding tests using a ball-on-disk wear tester (TR-201EM2-DUCOM). Commercially available bearing grade steel balls (Hardness: 140–160 HB) of 10 mm diameter were used as counter body.

Sample disk was rotated at 500 rpm (0.261 m/s) with a load of 5–20 N and the wear tests were done in different medium in ambient conditions for 20 min (total sliding distance of 314 m). Wear tests were repeated three times for each sample and average is reported. Coefficient of friction (COF) was estimated during the test. For lubricated contacts, commercially available automotive oil and distilled water were used. During test runs, frictional forces were recorded using a force sensor to generate real-time COF data. A stylus profilometer was used to trace surface profiles of worn disk specimen to measure the depth, width of the wear tracks of the specimens after each test.

Fig. 2 XRD patterns of (a) "Al6061-9% Beryl" and (b) "Al6061-9% Beryl-0.5% CeO₂" composites

2.2.4 Corrosion test

Corrosion tests were performed by placing the samples in 3.5% hydrochloric acid — HCl — solution for 48 h, 96 h and 144 h. Tests were repeated four times, initial and final weight of the samples was recorded and gravity weight loss in grams was measured. Hydrochloric acid (HCl) is an important inorganic acid known for its high corrosivity and has been extensively used as industrial cleaning solution [61].

Al6061 having poor mechanical properties was discarded and "Al6061-Beryl" and "Al6061-Beryl-CeO₂" composites were selected for wear and corrosion study.

3 Results and Discussion

3.1 XRD and microstructure study of processed "Al6061-Beryl-CeO₂" MMC's

Typical XRD spectra of "Al6061-9% Beryl" and "Al6061-9% Beryl-0.5% CeO₂" composites obtained from X-ray diffractometer (XRD) are shown in Fig. 2a and 2b, respectively. Lattice points of Al, Al₂O₃ and beryl peaks are shown in Fig. 2a and lattice points of CeO₂ peaks are shown in Fig. 2b. XRD pattern represents the presence of Al₂O₃, beryl and CeO₂ phases in Al composites evolved during

Fig. 3 Representative microscopic images of (a) "as casted" Al6061, (b) "Al6061-6% Beryl," (c) "Al6061-9% Beryl" and (d) "Al6061-9% Beryl-0.5% CeO₂" composites

casting. Major beryl peaks were identified till 40° and further they were found unnoticeable. Al_2O_3 and CeO_2 peaks were identified till 90° . Any other unwanted phase was not observed in XRD pattern. XRD spectra of Al6061 after stir casting were also studied which revealed the presence of major phase Al_2O_3 which evolved due to oxidation.

SEM analysis of processed composites was done and evolution of dendrite structure was observed which extended as branches on the whole surface area upon solidification. Figure 3 shows representative microscopic images of “as casted” Al6061 (Fig. 3a), “Al6061–6% Beryl” (Fig. 3b), “Al6061–9% Beryl” (Fig. 3c) and “Al6061–9% Beryl–0.5% CeO_2 ” (Fig. 3d) composites.

Figure 3a shows the irregular oxide layer particles distributed in the Al matrix. It was observed that there was formation of oxide layer on the surface of Al melt due to oxidation which broke on stirring and gets distributed in the matrix. Figure 3b represents the micrographs of Al composites with 6 wt.% beryl addition which show formation of dendrite structure with clear interface between beryl particle and Al matrix. Dendrite structure prevented cracks and their propagation. Figure 3c and 3d show developed dendrite structure and good visual bonding evolved due to the presence of Al_2O_3 , beryl and CeO_2 particles. Micrograph also shows the presence of particles distributed in the matrix which were believed as oxide

and reinforcement particles. In general, dendrite structure breaks on stirring resulting in globular morphology and breaks in dendrite branches. Addition of 0.5% CeO_2 due to its metallic behavior increased the wettability between ceramic particles in Al matrix during casting. No segregation of the particulates was observed due to the efficient mixing of reinforced particles in base matrix. Summarizing, perfect grain boundaries with the absence of voids resulted in processed composites which show strong adhesive and cohesive bonding between particles and molten matrix.

3.2 Mechanical properties of “Al6061–Beryl– CeO_2 ” MMC's

The hardness and ultimate tensile strength of the processed composites are shown in Fig. 4a and 4b. With 3–9 wt.% Beryl addition, hardness is increased to 75 BHN from 55 BHN of “as casted” Al6061. With 0.5% CeO_2 addition in “Al6061–9% Beryl” further increased the hardness to 78 BHN. Uniform dispersion of hard beryl particles and wettability effect of CeO_2 led to increase in hardness and strength. Formation of hard oxide phase Al_2O_3 in all the composites also resulted in increase in hardness. The ultimate tensile strength (UTS) of “as casted” Al6061 alloy is 76.4 MPa which increased to 110 MPa with 3–9 wt.% beryl addition. It was found that addition of 0.5 wt.% CeO_2 in Al-beryl composites resulted in negligible effect on hardness or strength of the composite. Close packing of reinforcement resulted in small interparticle spacing in the matrix [38, 53, 54]. The ductility of the composite is measured in terms of percent elongation and it was found that with increase in tensile strength, ductility decreased. Ductility ($21.58\% \pm 2\%$ elongation) was found highest in Al6061 (as casted composite) and lower ductility ($17.35\% \pm 2\%$ elongation) was found in “Al6061–Beryl” with and without CeO_2 composites. This behavior may be due to increase in brittleness of the composite with increase in hardness.

Fig. 4 (a) Hardness and (b) ultimate tensile strength of “Al6061–Beryl– CeO_2 ” composites

3.3 Friction analysis

The investigated composites subjected to sliding wear reflected identical evolution of friction. Generally, COF in its initial stage increased (50–200 s) and further attained a steady state due to the breakage of mechanical bonds between the asperities of two mating faces. Average steady-state COF value is high for the tests conducted in dry conditions, it decreased with increasing load.

Typical plots of COF versus time for “Al6061–Beryl” composites worn against steel ball in air with and without CeO_2 is shown in Fig. 5a and 5b. COF value was found less for “Al6061–9% Beryl” composite due to its superior

Fig. 5 Typical plots of COF as a function of time for “Al6061–Beryl” composites worn against steel ball in air with and without CeO_2

mechanical properties. COF graphs show fluctuations in the COF because of variation in contact between sample and disk due to debris.

Figure 6a–d shows the vertical bar charts of average COF value. COF varied from 0.85 to 0.16 under different conditions of load in dry and lubricated wear tests. A decrease in COF values was observed with increase weight % addition of beryl particles. Generally, during the initial stages, the surfaces of both the composite specimens and the steel counterpart were rough and thus strong interlocking took place, resulting in high friction coefficient. COF decreased in air to oil medium with increasing load with respect to increasing beryl content. This is

because at heavy load continuous sliding led to the compaction of debris as lubricated layer due to water or oil which prevented the two-body direct contact resulting in reduced COF in comparison with dry conditions. The compacted debris washes off during continuous sliding. It was observed that 0.5% CeO_2 addition has not affected the wear of the composite significantly.

3.4 Wear analysis

Wear is a complex process that depends not only on the material properties but also on the testing parameters and environmental conditions. In the present work, the

Fig. 6 (a)–(d): Steady-state average COF of “Al6061–Beryl” and “Al6061–Beryl–CeO₂” composites in different mediums at varying loads (5–20 N)

Fig. 7 Representative wear track of “Al6061–9% Beryl–0.5% CeO₂” composites in air under load of 20 N

phenomenal effects of composition, lubrication and load on wear of “Al6061–Beryl” and “Al6061–Beryl–CeO₂” composites are discussed. Typical SEM micrographs of wear track of “Al6061–9% Beryl–0.5% CeO₂” composite is shown in Fig. 7.

Wear track width and depth were measured at eight locations on the wear track of each worn sample. The

average of wear track width and depth was used in computing the wear volume (V) and subsequently specific wear rate (k) was calculated from wear volume normalized for total sliding distance and load of the disk specimens, according to Eqs. 1 and 2, respectively.

$$V = 2 \cdot \pi \cdot r_t \cdot t_w \cdot t_d \quad (1)$$

where “ V ” is the wear volume (in [mm³]), “ r_t ” is the track radius (in [mm]), “ t_w ” is the track width (in [mm]) and “ t_d ” is the track depth (in [mm]);

$$k = \frac{V}{F \cdot S} \quad (2)$$

where “ k ” is the specific wear rate (in [mm³/N.m]), “ F ” is the load (in [N]) and “ S ” is the sliding distance (in [m]).

Depth and width of wear track were measured from profiles obtained from surface profilometer. It was observed that the depth and width of wear tracks was more in profile of “Al6061–3% Beryl” composite and it reduced with “9% Beryl–0.5% CeO₂” addition. Comparing with respect to medium it was observed that high hardness of the composite and presence of oil during sliding has significantly reduced the width and depth of wear track. In general wear volume increased with increase in load but is found

Fig. 8 Specific wear rate of “Al6061–Beryl” and “Al6061–Beryl–CeO₂” composites in different medium and varying load. (a)–(b): Air; (c)–(d): Oil

less in higher beryl content containing composites in wet conditions. No significant change was observed in wear with 0.5% CeO₂ addition in “Al6061–Beryl” composites. Specific wear rate of the processed composites is shown in Fig. 8a–d. Specific wear rate ranged from $\approx 3.8 \times 10^{-8}$ mm³/N.m to $\approx 5 \times 10^{-7}$ mm³/N.m in dry to wet condition. A decrease of at least one order of magnitude in wear rate was observed in composite with higher beryl content in wet conditions. Increased material transfer and formation of oxide-rich tribo-chemical layer were also responsible for the reduction in friction and wear at heavy load in dry conditions and due to lubrication in wet conditions. Summarizing, increased wt.% beryl addition with CeO₂ lowered the coefficient of friction and wear attaining a sustainable wear resistance.

3.5 Microstructure analysis of worn surfaces

Worn surface images of casted “Al6061–Beryl–CeO₂” MMC’s were studied to understand the dominant wear mechanisms under different sliding conditions. Micrographs were compared and representative SEM images of the worn surfaces of “Al6061–Beryl” and “Al6061–Beryl–CeO₂” in air and oil at 20 N load are shown in Fig. 9a–c and Fig. 10a–b.

Figure 9a shows characteristic features of adhesion, fracture and delamination with 3% of beryl addition. Generally during sliding wear, wear debris gets generated as grains gets pulled out with repeated sliding and in course of time wear debris gets compacted and adhere on the worn surface. The adhered layer subsequently gets deformed and the layer gets fractured and delaminated from the surface due to course of sliding. With 9% Beryl and 0.5% CeO₂ addition, composite showed consistent behavior of less wear (Fig. 9b and 9c). Wear is accompanied with mild adhesion and abrasion of the surface. Addition of beryl and CeO₂ particles resisted the further fracture and delamination process. In general abrasion is the dominant wear mechanism observed when sliding wear tests were conducted in water or oil at varying loads.

Figure 10a and 10b shows cracking and fracture in “Al6061–3% Beryl” composite due to its poor mechanical properties whereas in “Al6061–9% Beryl” and “Al6061–9% Beryl–0.5% CeO₂” the dominant presence of mild abrasion wear mechanism was observed. Hardness of the composite restricted further crack and fracture. As wear process continued, the rough profiles of the steel rotating disk and the composite specimens were smoothed as a result of abrasion and debris is washed in water or oil. Worn surface

Fig. 9 Worn surfaces of (a) “Al6061–3% Beryl,” (b) “Al6061–9% Beryl” and (c) “Al6061–9% Beryl–0.5% CeO₂” at 20 N load in air

Fig. 10 Worn surfaces of (a) “Al6061–3% Beryl” and (b) “Al6061–9% Beryl” at 20 N load in oil

study has been conducted by other researchers on Al composites [39–46, 49–52, 55–60]. It was found that transfer layer of compacted wear debris along with the wear tracks form over the sliding surface with continuous sliding. The reason for lower wear rate in composites is also their high hardness as compared to base alloy. Yuvaraja and Sharma [55] in their wear study found that with increase in load from lower to higher values, the morphology of the worn surface gradually changed from fine scratches to distinct grooves and flake craters. The specimen shows a mixed

mechanism of fine scratches and larger grooves with indications of severe deformation and fracture resulting in more material loss.

Worn surfaces of counter steel ball were also studied to understand the wear mechanism and material transfer. It was observed that the elemental iron, chromium or nickel ejected out of the steel ball gets oxidized and abrade contacting surfaces during sliding against Al composites, forming hard oxide debris [40]. In case of lubricated sliding conditions, the friction and wear were

Fig. 11 Linear relationship between wear volume (V) and dissipated energy (E_d) during sliding of investigated “Al6061–Beryl–CeO₂” composites against steel in (a) air and (b) oil

Fig. 12 Corrosion behavior of (a) “Al6061–Beryl” and (b) “Al6061–Beryl–CeO₂” composites

considerably decreased due to the formation of lubricating film between contacting surfaces which continuously form and flow during sliding. Steel balls abraded more in air than in water or oil condition. Wear scar on ball is more in diameter when slid against “Al6061–9% Beryl” composite than in “Al6061–3% Beryl” composite as high hardness of the composite led to more wear of the ball.

3.6 Relationship between wear volume and cumulative dissipated energy

In general, there is rise in contact temperature of two sliding bodies and generated energy spent in deformation or wear. The relation between the wear volumes of processed composite against steel ball was studied in terms of dissipated energy under the given loading conditions. The cumulative dissipated energy can be calculated for such sliding conditions, using the following relation (Eq. 3):

$$E_d = \mu \cdot W \cdot v \cdot t_{\text{time}} \quad (3)$$

Fig. 13 Microscopic image after exposure in 3.5% HCl solution for 6 days

where the unit of “ E_d ” is [J], “ W ” is the normal load (in [N]), “ μ ” is the average COF, “ v ” is the sliding velocity (in [m/s]) and “ t_{time} ” is the total testing duration (in [s]) [57–59].

The linear increasing trend was observed in wear volume against the dissipated energy for the investigated composites in all medium as shown in Fig. 11a and 11b.

3.7 Corrosion test

Processed Al MMC was further tested for corrosion resistance property by placing the samples in 3.5% HCl solution for 2, 4 and 6 days. Initial and final weight of the samples was recorded and gravity weight loss in grams was measured as shown in Fig. 12a and 12b.

It was observed that corrosion resistance increased with 0.5% CeO₂ addition in “Al–Beryl” composite which facilitated formation of protective layer on the composite surface ultimately suppressing the corrosion.

Figure 13 shows microscopic image of A7 composite after exposure in 3.5% HCl solution for 6 days. It is observed that CeO₂ particles surrounded by aluminum solid solutions were intact even after continuous exposure in HCl solution. As reported in the literature, these CeO₂ particles could probably act as cathodic zones suppressing corrosion of the composite and remain stable in aggressive environment forming stable protective oxide film on the surface [53]. Also increase in beryl content increased corrosion resistance in “Al–Beryl” composites due to the fact that oxides being anti-corrosive in nature corrode less in corrosive environment. The present results lay strong emphasis on the potential scope of use of CeO₂ for protection of Al composite in marine environment as these composites have vast application in structural material of boats and ships [53, 54].

Summarizing the present research work shows that mechanical, wear and corrosive properties of Al MMC's are improved with optimizing its composition with beryl and CeO₂ addition. The results obtained with previous research conducted as discussed in literature review section clearly reflects that Al is reinforced with varying percentage of different metallic and ceramic reinforcements, which can be in particulate, whisker or fiber form to impart high strength and stiffness to the composite and distribute the applied load [10–13], where Al6061 with beryl and ceria is found to be structurally stronger material and wear resistant in the present investigation in comparison with other compositions of Al/A356/A380-MnO₂/graphite/SiCp/SiC fibers/fly ash/Mg₂Si [17, 18, 23, 29, 34–37, 49] or against other composites as carbon matrix composites reinforced with carbon nanotubes which is an excellent candidate for lightweight structural materials having potential use in aerospace, military and defense fields [62–64]. Further corrosion study shows CeO₂ as substitute of zinc chromate which is as reported in general toxic in nature and hazardous to the environment [52, 56]. Therefore, it can be summarized that beryl–CeO₂ added Al MMC's are more suitable

in different areas of industry, aerospace and marine for structural applications.

4 Conclusions

The main aim of the present work is to see the performance of “Al–Beryl” composites with or without CeO₂ on their mechanical, wear and corrosive properties. Following are the findings:

- (1) An increase of 36% in hardness and 43% in ultimate tensile strength was found in Al composites with 9% Beryl addition whereas no significant change in mechanical properties was observed with 0.5% CeO₂ addition;
- (2) Coefficient of friction was found least for “Beryl–CeO₂” added composites in wet sliding conditions. COF decreased with increasing load; continuous sliding at heavy load led to the compaction of debris which restricted wear and resulted in low friction in dry condition;
- (3) A transition in wear mechanism occurred with adhesion, fracture and delamination in SEM micrograph of the worn composite with low beryl content slid in air whereas abrasion predominates in water or oil with higher beryl and CeO₂ addition;
- (4) Reduced wear was observed in “Al6061–9% Beryl–0.5% CeO₂” composite at all load. Corrosion resistance increased by 45% with 0.5% CeO₂ addition in Al composites;
- (5) The corrosion of Al composites, in marine environments, can be suppressed significantly by reinforcing with cerium oxide. “Al6061–9% Beryl–0.5% CeO₂” composite with high hardness, wear and corrosion resistance has promising potential future for marine use.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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