

Influence of cerium oxide nanoparticles on the tribological behavior of AA8090 aluminum alloy composites for aero, military, and marine industrial applications

Research Article

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Abstract: This study aimed to enhance the wear resistance of the AA8090 material. Nanoparticle-reinforced AA8090 metal matrix composites were manufactured using the conventional stir casting process. Totally, three types of composites were fabricated by varying the cerium oxide (CeO₂) nanoparticle content. The different materials prepared were AA8090, AA8090/1.5 wt% CeO₂, AA8090/3 wt% CeO₂, and AA8090/4.5 wt% CeO₂. Properties like microhardness, tensile strength, wear rate, and coefficient of friction of the developed composites were determined. The results showed that the inclusion of CeO₂ nanoparticles improved the different properties of the AA8090 material. An optimum level of 3 wt% CeO₂ in AA8090 showed better performance. Furthermore, the AA8090/3 wt% CeO₂ composite exhibited a maximum hardness and tensile strength of 158 HV and 546 MPa, respectively, which was 18 and 20% higher than those of AA8090. Furthermore, the same composite displayed a slightest wear rate ($0.045 \times 10^{-3} \text{ mm}^3/\text{m}$) and coefficient of friction (0.2). Hence, it is concluded from this research that the AA8090/3 wt% CeO₂ could be a suitable material for aero, military, and marine applications as it showed a good performance.

Keywords: AA8090 aluminum alloy • Cerium oxide nanoparticles • Wear • Metal matrix composite • Tribological characteristics

1. Introduction

AA8090 aluminum alloy is applicable in aero, marine, and military fields because of its lightweight characteristics. This alloy is manufactured by combining lithium and aluminum. Due to the low density of lithium (0.534 g/cm^3), the AA8090 material achieved lightweight (2.48 g/cm^3) characteristics compared to pure aluminum (2.7 g/cm^3). The density of the AA8090 material is reduced by 3%, and the elastic modulus is increased by 6% with the addition of 1% of lithium with aluminum [1–3]. Hence, the AA8090 material possesses good specific strength along with lightweight characteristics.

Consequently, the AA8090 material finds applications in aero, marine, and armed fields [4–6].

Despite the AA8090 material showing good strength, it has some limitations, like low wear resistance. This led to wear and tear of the material and, hence, the performance of AA8090 material decreased while functioning at prolonged times. Furthermore, the life span of the AA8090 material is affected, which increases the maintenance and operational costs. Hence, this issue must be addressed to improve its performance against wear and tear.

Previous studies have focused on this issue and provided some positive results. Narasimmalu and Sundaresan [7] performed an investigation on the wear and mechanical properties of AA8090/B₄C/Al₂O₃ composites. They indicated that the AA8090/3 wt% B₄C composite exhibited a

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12.9% increase in microhardness compared to that of the AA8090 material. Similarly, the improvement in tensile strength was found to be 10.8%. Further, some composites recorded the lowest wear rate ($0.009 \times 10^{-3} \text{ mm}^3/\text{m}$).

Kalaiyaran et al. [8] conducted research on the tribological properties of the AA8090/WC/ZrC composite. The results showed that the AA8090/WC composite exhibited utmost hardness (160 HB) as well as maximum tensile strength (502 MPa). Further, a low wear rate ($0.0011 \times 10^{-3} \text{ mm}^3/\text{m}$) was reported for the AA8090/WC composite. Furthermore, a least coefficient of friction (COF) of 0.31 and a mass reduction of 0.0028 g were observed for the same composite. Kebriyaei et al. [9] developed the AA8090/6 vol% SiC composite and studied its properties. They performed heat treatment on the sample and compared its properties with the untreated sample. The results indicated that the heat-treated samples exhibited greater properties like tensile strength, Young's modulus, elongation, and hardness. However, the heat-treated samples showed higher wear loss compared to the untreated samples.

The literature summary revealed that AA8090 composites reinforced with B₄C and Al₂O₃ particles exhibited a 12.9% increase in microhardness and a 10.8% improvement in tensile strength for the AA8090/3 wt% B₄C composite, along with a wear rate reduction to $0.009 \times 10^{-3} \text{ mm}^3/\text{m}$. Similarly, the AA8090/WC composite showed the highest hardness (160 HB) and tensile strength (502 MPa), with a low wear rate of $0.0011 \times 10^{-3} \text{ mm}^3/\text{m}$, a COF of 0.31, and minimal mass loss (0.0028 g). In contrast, heat-treated AA8090/6 vol% SiC composites demonstrated improvements in tensile strength, Young's modulus, elongation, and hardness but experienced higher wear loss compared to the untreated samples.

Previous researchers used particle-strengthening methods to improve the wear resistance of the AA8090 material. Particles such as carbides and metal oxides were used. Nanoparticles play a significant role in enhancing the strength of the material [10–13]. Although previous studies have primarily focused on the reinforcement of AA8090 with particles such as B₄C, WC, ZrC, and SiC, this research uniquely explores the potential of CeO₂ (cerium oxide) nanoparticles as a reinforcing agent. CeO₂, known for its excellent heat and corrosion resistance, has been widely used in other fields, but its application as a reinforcement for AA8090 alloy remains underexplored.

The novelty of this study lies in the use of CeO₂ nanoparticles to enhance the wear resistance and mechanical properties of AA8090, filling a research gap not covered in the existing literature. By fabricating AA8090/CeO₂ composites using the stir-casting method and examining their wear performance, this research provides new scientific insights and contributes to the development of high-performance, wear-resistant materials for aerospace and other industrial applications.

Cerium oxide (CeO₂) is one of the nanoparticles used in automobile, chemical, and electronics industries. It has good heat resistance and corrosion resistance characteristics. In this research, CeO₂ nanoparticles are used as strengthening particles to improve the wear performance of the AA8090 material. Thus, the objective of this study is to fabricate the AA8090/CeO₂ material using the stir-casting procedure and study its wear performance.

2. Materials and methods

2.1 Materials

Fabrication of the AA8090/CeO₂ material was performed using the conventional stir casting process. The AA8090 material was selected as the base material. This material was obtained from M/S Bharat Aerospace Metals (Mumbai, India). Further, the CeO₂ particles were used for the reinforcement purpose. These particles were obtained from M/S Smart Nanos Private Limited (Pune, India). The different elements present in the AA8090 material are listed in Table 1. The characteristics of AA8090 as well as CeO₂ particles are presented in Tables 2 and 3, respectively.

2.2 Preparation of the composites

The metal matrix AA8090/CeO₂ material was synthesized using the conventional stir casting procedure [7,8]. The weight fractions of the CeO₂ particles varied from 1.5, 3, and 4.5. Figure 1(a) shows the various steps followed to prepare the composites. The process for fabricating the composite is described as follows. Initially, the AA8090 alloy and CeO₂ particles were placed in a furnace (chamber size:

Composition	Li	Cu	Mg	Fe	Zn	Ti	Zr	Cr	Mn	Si	Al
Weight (%)	2.6	1.3	0.6	0.3	0.25	0.1	0.01	0.1	0.1	0.2	Bal.

Table 1. Elements present in the AA8090 material [8].

Details	Values
Density (g/cm ³)	2.54
Hardness (HV)	158
Melting point (°C)	600
Modulus of elasticity (GPa)	77
Tensile strength (MPa)	515

Table 2. Characteristics of the AA8090 material [8].

Details	Values
Density (g/cm ³)	7.6
Melting point (°C)	2,340
Vickers hardness (MPa)	270
Young's modulus (GPa)	34
Molecular weight	172.12

Table 3. Characteristics of the CeO₂ particles [14].

100 mm × 100 mm × 250 mm; max. temperature: 1,100°C; and thermocouple; K type). The temperature was gradually increased to 750°C, with 15 min of stabilization time after every 100°C increase, ensuring uniform heat distribution. Next, carbon dioxide was introduced into the furnace at 400°C to prevent combustion of the metal mixture. As the temperature reached 700°C, argon gas was supplied to minimize oxidation of the materials. Upon reaching 750°C, the system was maintained at this temperature for 30 min to complete the process. Following this, mechanical stirring was carried out at 300 rpm for 5 min to achieve a homogeneous mixture. Finally, the molten composite was poured into the mold for solidification. Table 4 shows the design details of composites. The stir-casting equipment and stir-casted pieces are shown in Figure 1(b) and (c), respectively.

2.3 Experimental work

The hardnesses of the AA8090 material and AA8090/CeO₂ composite were determined using the Vickers hardness equipment (objective: 10×; size: 560 × 335 × 675 mm) as per ASTM E92. The material was tested using a 300 N load for a time period of 10 s using a diamond indenter. The hardness was measured at three different places and the average hardness was considered as the final value.

The tensile strengths of the AA8090 material and AA8090/CeO₂ composite were determined using a Universal Testing Machine (capacity: 100 kN; drive: electro-hydraulic).

The test was completed using an ASTM E8/E8M-16a standard. The dimensions of the tensile specimen are shown in Figure 2(a).

The wear study was carried out on the AA8090 material and AA8090/CeO₂ composite under dry sliding conditions [15,16] using a pin-on-disc tribometer (disc: 165 × 8; disc speed: 200–2,000 rpm; load: 5–200 N; sliding velocity: 0.5–10 m/s). Wear experiments were conducted in accordance with the ASTM G99-05(2010) norms. A cylindrical pin was made to conduct the wear test. The dimension of the cylindrical pin is shown in Figure 2(b).

Further, the wear test was completed using different process parameters, as detailed in Table 5. The test was conducted for various values of sliding speed and loads. The sliding distance was maintained constant at 1,000 m [17,18]. The counter disc was fabricated from EN31 steel, which was hardened to achieve a hardness of 62 HRC. The counter disc rotational speed was maintained as 150 rpm.

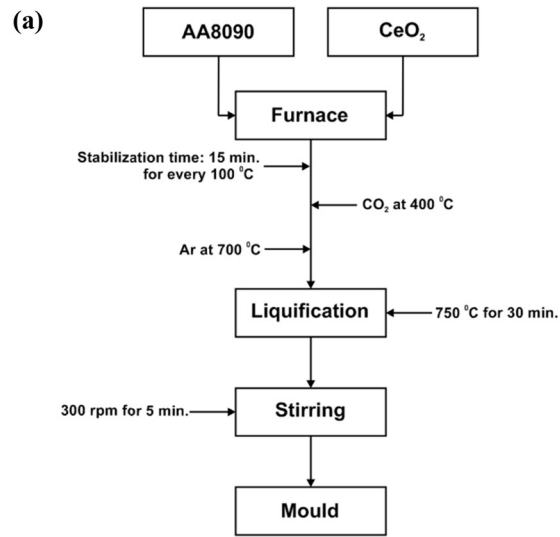
The process parameters used in this research were selected based on the previous reports [18–20].

The micrographs presented in this study were obtained following standard metallographic and scanning electron microscopy (SEM) techniques. The specimen preparation adhered to the guidelines outlined in ASTM E3 for grinding and polishing. After mechanical preparation, the samples were etched to reveal microstructural features. SEM was performed using a scanning electron microscope (ZEISS, Germany), operated at a 15 kV accelerating voltage with a working distance of 10 mm. Both secondary electron and backscattered electron detectors were used to capture surface topography and phase contrast, respectively.

3. Results and discussion

3.1 Microhardness

Figure 3 displays the microhardness results for the AA8090/CeO₂ composites. The results showed that AA8090 exhibited low hardness values, and the AA8090/CeO₂ composite displayed high hardness values. Because of the inclusion of CeO₂ particles, the hardness of AA8090 was improved. The particles added filled the space of the matrix; hence, a discontinuous structure was formed, which led to enhanced rigidity of the material. Further, it was observed that an increasing amount of CeO₂ assisted in improving the material's hardness up to a weight fraction of 3%. Beyond this limit, a decrease in hardness was noted. This could be due to the agglomeration of particles that led to the enlarged interfaces. This decreased the hardness of the material. This



(b)



(c)



Figure 1. (a) Composite preparation steps, (b) stir casting equipment, and (c) stir-casted pieces.

Composites	AA8090 (wt%)	CeO ₂ (wt%)
AA8090	100	0
AA8090/1.5 wt% CeO ₂	98.5	1.5
AA8090/3.0 wt% CeO ₂	97	3
AA8090/4.5 wt% CeO ₂	95.5	4.5

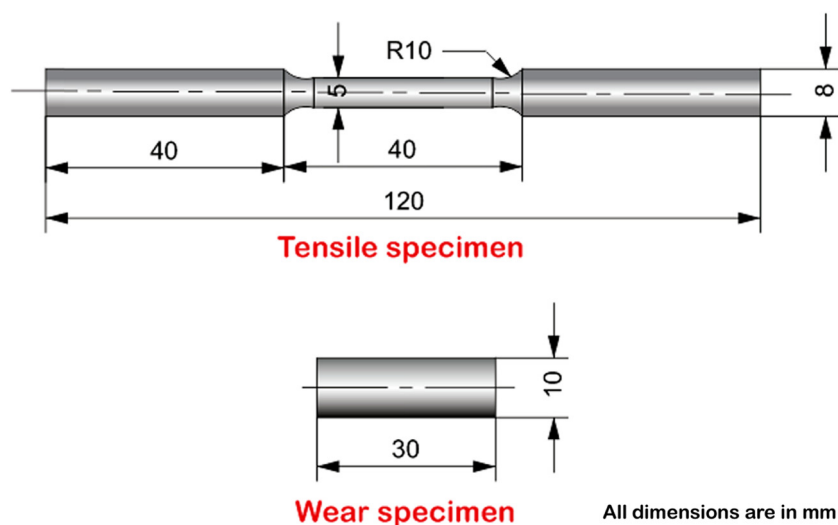
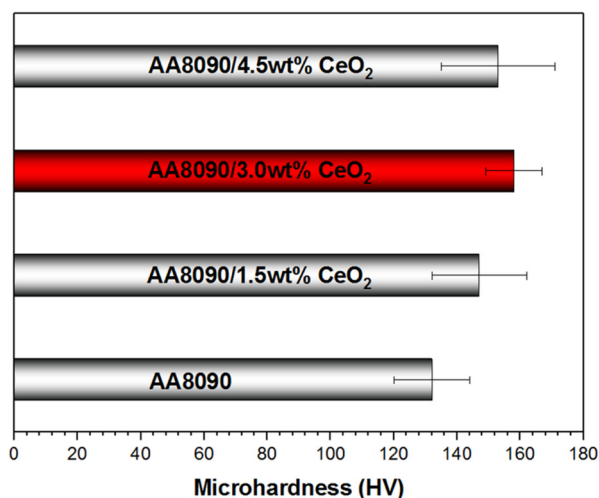
Table 4. Composite design details.

study provided that the AA8090/3.0 wt% CeO₂ material exhibited an utmost hardness (158 HV), which is 19.6% higher than that of the AA8090 material.

Parameters	Level 1	Level 2	Level 3
Load (N)	10	20	30
Sliding speed (m/s)	0.5	1	1.5
Sliding distance (m)	1,000	1,000	1,000

Table 5. Wear test parameters.

Mahan et al. [21] manufactured the AA2024/TiO₂ composite and studied its mechanical properties. They reported that the inclusion of 5 wt% TiO₂ nanoparticles increased the hardness of the AA2024 material. However, the addition of

**Figure 2.** Dimensions of tensile and wear specimens.**Figure 3.** Microhardness results of the AA8090/CeO₂ composite.

7.5 wt% TiO₂ resulted in decreased hardness because of the particle's distortion.

3.2 Tensile strength

Figure 4 shows the tensile strength results of the AA8090/CeO₂ material. The AA8090 material's tensile strength was augmented when CeO₂ was added. This indicated that the CeO₂ particles provided strength to the AA8090 material. This is articulated by the Orowan mechanism according to a previous study [22]. The CeO₂ particles provided a pinning effect to the AA8090 material by restricting the movement of dislocation. This decreased the plastic flow of the material and improved its strength. Further, due to the different melting temperatures of AA8090 and CeO₂ materials, a thermal mismatch occurred, which developed a fine grain size. This resulted in an enhancement in the tensile strength of the material. Moreover, the AA8090/CeO₂ material's tensile strength increased with increasing quantity of CeO₂ up to 3 wt% and then decreased.

The AA8090/4.5 wt% CeO₂ composite showed lower tensile strength compared to that of the AA8090/3 wt% CeO₂ composite. This could be due to the adherence of particles with each other while loading high quantities. This formed uneven interfaces and involved less stress transfer. This resulted in a decrease of strength. In this research, the AA8090/3 wt% CeO₂ recorded greater tensile strength (546 MPa), which is 17.4% higher than the AA8090 material. Narasimmalu and Sundaresan [7] reported that AA8090 alloy's strength was improved by 3.7% when 3 wt%

Al₂O₃ particles were added. This result is consistent with that observed in this study.

3.3 Wear rate

3.3.1 Effect of load on the wear rate of the AA8090/CeO₂ composite

Figure 5(a) shows the wear rates of the AA8090/CeO₂ composites with respect to the applied load. The wear rate of all samples increased with an increase in the applied load. For example, the wear rate of the AA8090 material was $0.054 \times 10^{-3} \text{ mm}^3/\text{m}$ at a load of 10 N. Further, the same material showed a high wear rate of $0.062 \times 10^{-3} \text{ mm}^3/\text{m}$ at a load of 30 N. Hence, the higher load led to more wear of the samples.

When a high load was applied, the pressure between the counter disc and the sample was increased. This resulted in more wear on the surface of the sample. Moreover, the wear rate of the AA8090 material decreased after including CeO₂ particles. However, the 3 wt% CeO₂ particles led to a decrease in the wear rate, and beyond that limit (>3 wt%), an increase in the wear rate was observed. This was attributed to the agglomeration of particles in the AA8090 material. Hence, the 3 wt% CeO₂ particle level was the optimal level to decrease the wear rate of the AA8090 material. Fahad [17] developed the Az91D/WC-SiO₂ composite and studied its wear behavior. The wear rate of the samples is augmented with the applied load. Further, the addition of WC and SiO₂ particles

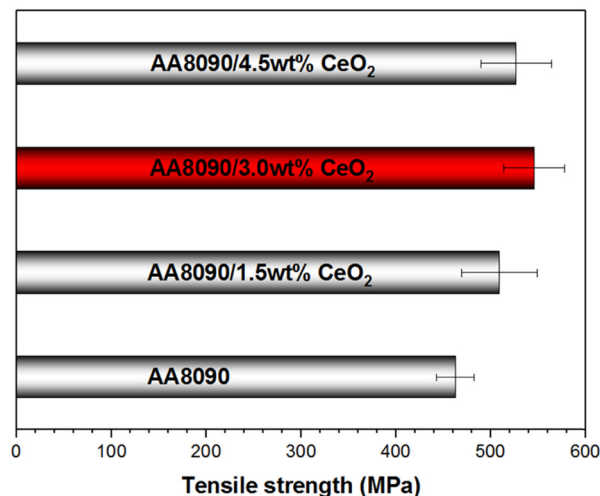


Figure 4. Tensile strength results of the AA8090/CeO₂ composite.

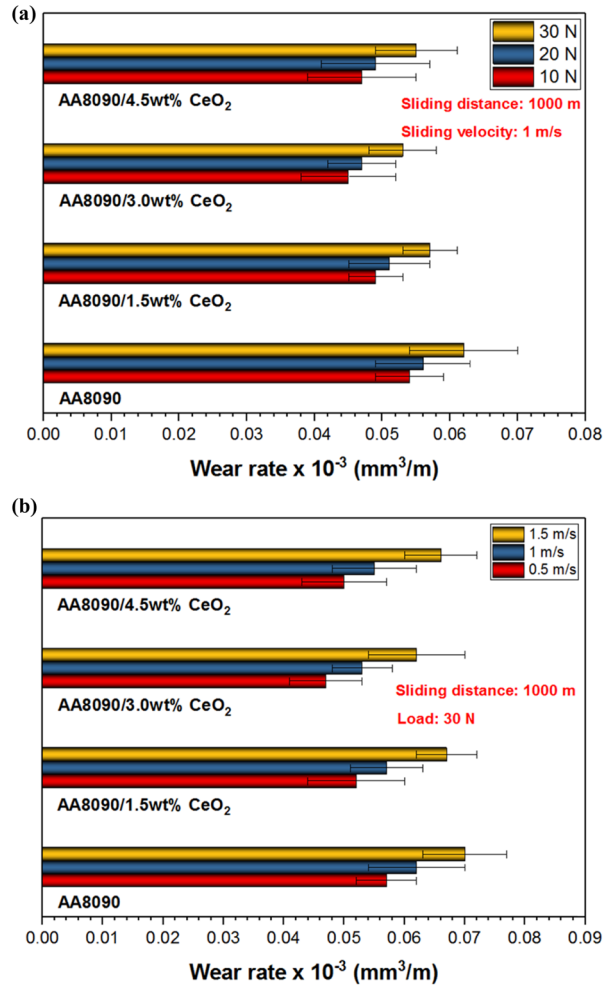


Figure 5. (a) The wear rate of the AA8090/CeO₂ composite with respect to load, and (b) the wear rate of the AA8090/CeO₂ composite with respect to sliding velocity.

decreased the wear rate. The results of the current study are consistent with the results of Fahad [17].

3.3.2 Effect of sliding velocity on the wear rate of the AA8090/CeO₂ composite

Figure 5(b) shows the wear rates of the AA8090/CeO₂ composites with respect to sliding velocity. The wear rates of all samples increased with increasing sliding velocity. With an increase in the sliding velocity, the rubbing action amid samples as well as counter discs increased, which led to high warmth development. Because of heat generation, the materials became soft, and the wear rate was increased. Further, more shear stress was created in the interface of the counter disc and sample, which resulted in more wear.

The AA8090 material exhibited wear rates of 0.057×10^{-3} and $0.07 \times 10^{-3} \text{ mm}^3/\text{m}$ at sliding velocities of 0.5 and 1.5 m/s, respectively. This confirmed that the higher sliding velocity showed a higher wear rate. Moreover, it was observed that the wear rate of the AA8090 material decreased after the addition of CeO₂ particles. This could be because of the particle strengthening, which delayed surface wear to some extent. In this study, the AA8090/3 wt% CeO₂ sample showed a low wear rate at all sliding velocity conditions.

Singh *et al.* [23] reported that the AA5083/B₄C composite showed a lower wear rate compared to the AA5083 material. Further, the wear rate of the AA5083/B₄C composite increased with an increase in the sliding velocity because of the development of high shear stress.

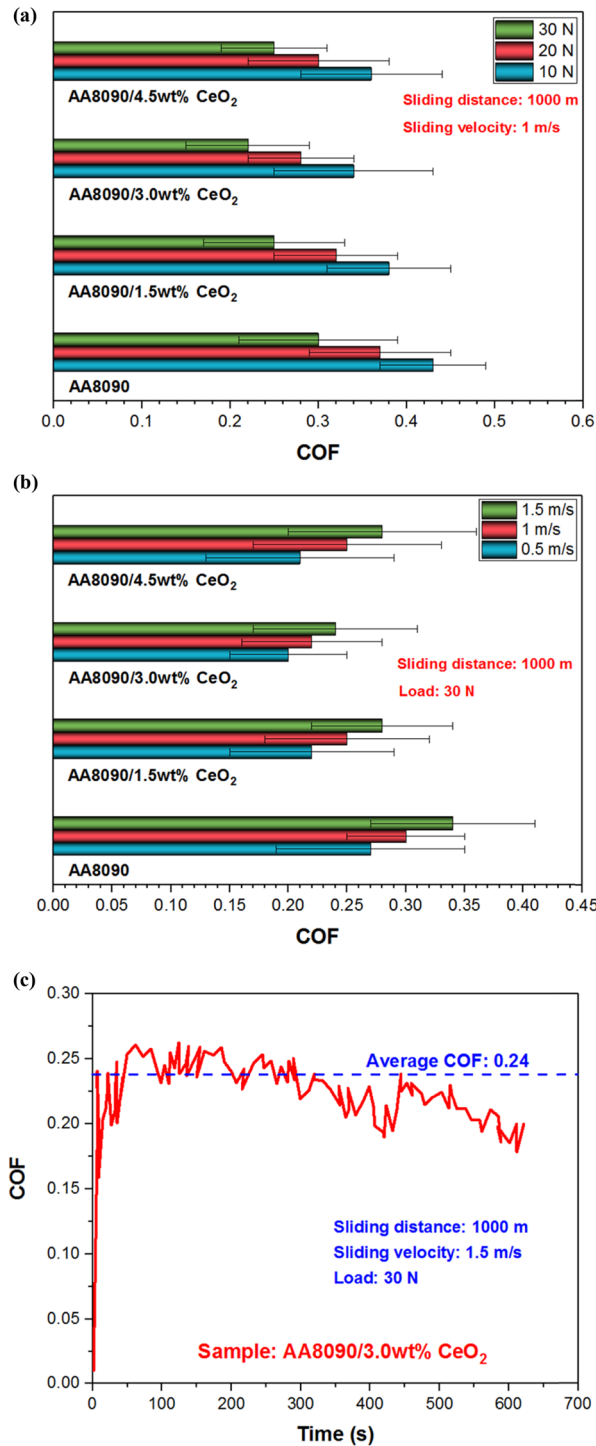


Figure 6. (a) COF values of the AA8090/CeO₂ composite with respect to load, (b) COF values of the AA8090/CeO₂ composite with respect to sliding velocity, and (c) COF values of the AA8090/3.0 wt% CeO₂ composite with respect to time.

3.4 COF

3.4.1 Effect of load on the COF of the AA8090/CeO₂ composite

Figure 6(a) depicts the COF result of AA8090/CeO₂ composite with respect to the applied load. COF decreased for the base alloy and composites with an increase in load. The load increased the pressure between the counter disc and sample. Hence, the normal force was higher than the frictional force, which resulted in the decrease of the COF values at higher loads. Further, the COF values of the AA8090/CeO₂ composites were lower than those of the AA8090 material. This could be due to the effect of CeO₂ particles, which decrease the frictional force during the sliding action by providing lubrication effects. Further, the inclusion of 1.5–3 wt% CeO₂ showed good results, and the addition of 4.5 wt% CeO₂ exhibited slight increase in the COF values. This indicated that the lubrication effect was affected due to the accumulation of more particles. In this study, it was observed that the AA8090/3 wt% CeO₂ composite displayed the lowest COF at all loading conditions.

Venkatesan *et al.* [18] fabricated AA5083-based aluminum alloy composites and studied their wear performance. They indicated that COF decreased because of the added particles compared to the AA5083 alloy. Further, the COF values of the alloy and composites exhibited a decreasing tendency with increasing load.

3.4.2 Effect of sliding velocity on the COF of the AA8090/CeO₂ composite

Figure 6(b) shows the COF values of the AA8090/CeO₂ composites with respect to sliding velocity. The COF values of all the materials showed an increasing tendency with

sliding velocity. Further, the frictional force was increased with high sliding velocity, which increased COF values. Further, the CeO₂ particles with materials showed less COF values than the AA8090 material. The reinforcement particles provided a lubrication effect to the AA8090 material during the sliding action. This decreases the frictional energy and the COF value. Further, the addition of the CeO₂ particles up to an optimum level of 3 wt% exhibited a decreasing tendency of COF, and beyond that limit, it showed an increase in the COF value. When the volume fraction of the particles was increased, particle aggregation occurred. This decreased the load-bearing ability of the material slightly. Further, the frictional force was increased in between the sliding materials, i.e., the counter disc and sample. This increased the COF. The AA8090 material exhibited the slightest COF values with the addition of 3 wt% CeO₂ particles.

Kalaiyarasan *et al.* [8] developed AA8090/WC/ZrC composites and investigated their wear behavior. The results showed that the AA8090 material exhibited lower COF values after including reinforcement particles compared to unreinforced AA8090 material due to a decrease in the adherence between the matrix and reinforcement. Fahad [14] reported that the introduction of CeO₂ with Az91D materials significantly decreased the COF to 0.23 from 0.26. These results are in accordance with the results of this study. The raw data of COF results for the AA8090/3.0 wt% CeO₂ sample with respect to time are shown in Figure 6(c).

3.5 Analysis of worn-out surfaces

A morphological study was performed on the wear test specimens. Figure 7 depicts micrographs of the AA8090 and AA8090/3 wt% CeO₂ sample surfaces.

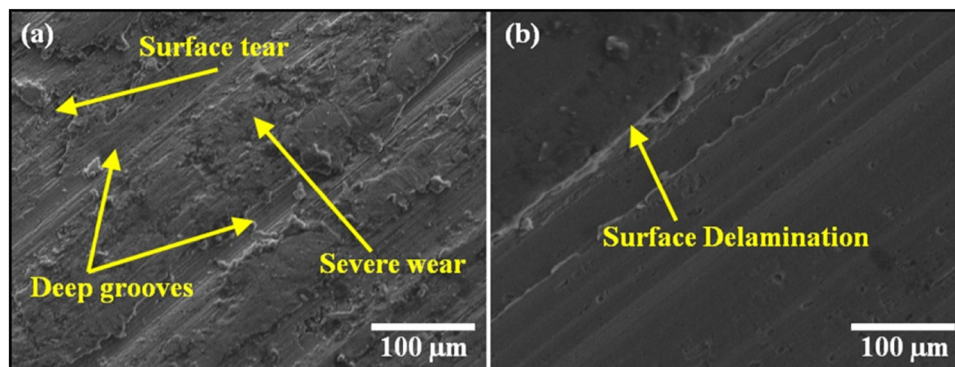


Figure 7. Micrographs of worn-out surfaces of (a) AA8090 and (b) AA8090/3 wt% CeO₂.

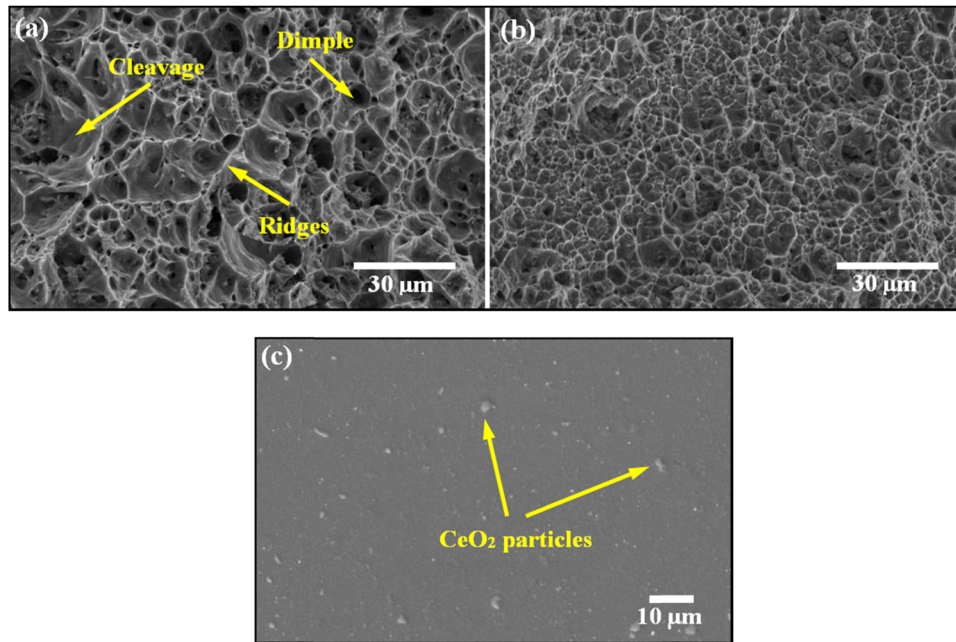


Figure 8. Micrographs of (a) the fracture surface of AA8090, (b) fracture surface of AA8090/3 wt% CeO₂, and (c) cross-sectional surface of AA8090/3 wt% CeO₂.

The wear test outcomes highlighted a stark contrast between the wear behavior of the base AA8090 aluminum alloy and the AA8090 alloy reinforced with 3 wt% CeO₂ particles. The AA8090 alloy exhibited severe wear characteristics during the test. The surface of the sample was marked by prominent grooves and surface tearing. These features were indicative of an abrasive wear mechanism [15], where the primary mode of material removal was due to ploughing forces. Abrasive wear occurs when hard asperities or particles slide across the surface, causing material to be gouged out, leaving behind these grooves. The extent of surface damage, including tearing, implied that the AA8090 matrix was unable to effectively resist the ploughing and cutting action, leading to significant material loss. The matrix material was prone to localized deformation due to a lack of reinforcements that could distribute stress.

On the other hand, the AA8090 alloy reinforced with 3 wt% CeO₂ exhibited considerably better wear resistance. The surface appeared smoother, with only minimal signs of delamination and no deep grooves like those observed in the unreinforced sample. This smoother wear surface suggested that the CeO₂ particles acted as load-bearing reinforcements within the aluminum matrix. These particles likely distributed the applied stress more evenly across the surface, reducing the localized stress concentrations that would otherwise lead to severe surface damage [16]. Additionally, the presence of CeO₂ likely helped to

reduce the friction during wear. By acting as a barrier to direct metal-to-metal contact, the CeO₂ particles minimized the ploughing action that was dominant in the unreinforced sample. The absence of deep grooves or tearing further indicated that the wear mechanism in the composite was more controlled and less aggressive, possibly transitioning from an abrasive wear mechanism to a mild adhesive wear mechanism, where wear occurs at a much slower rate.

The significant differences in wear behaviors between the two samples underlined the beneficial effects of adding CeO₂ as a reinforcing agent in the AA8090 matrix. The reduction in surface defects, such as deep grooves and tearing, in the AA8090/3 wt% CeO₂ composite confirmed the critical role of CeO₂ in mitigating wear damage, thereby making the material more suitable for applications where wear resistance is crucial. The composite's enhanced performance was attributed to the CeO₂ particles' ability to reduce friction, distribute applied loads, and resist the aggressive abrasive forces seen in the unreinforced AA8090 sample.

3.6 Micrograph analysis

Micrograph analysis was done on the tensile fractured sample using the micrographs shown in Figure 8(a) and (b).

The outcomes presented tensile fracture micrographs of AA8090 and AA8090/3 wt% CeO₂ materials. In the AA8090 alloy, numerous ridges and dimples were visible, while fewer cleavage features were present. In contrast, the AA8090/3 wt% CeO₂ material displayed a finer structure with fewer dimples, no observed cleavage, and shallower ridges. These characteristics suggested that the addition of 3 wt% CeO₂ improves the strength of the AA8090 alloy compared to the base AA8090 material. In addition, the micrograph taken at the cross section of the AA8090/3 wt% CeO₂ material is shown in Figure 8(c). It displayed the even distribution of CeO₂ particles without any agglomeration.

4. Conclusion

This study was conducted to investigate the effect of cerium oxide nanoparticles on the wear performance of AA8090 aluminum alloy for marine, military, and aero-industrial applications. The subsequent outcomes were deduced from these experiments.

- Microhardness learning exposed that the addition of CeO₂ particles assisted in enhancing the AA8090 material's hardness. Additionally, the AA8090 material showed greater hardness (158 HV) when 3 wt% CeO₂ particles were added. This is 19.6% greater than the AA8090 material's hardness.
- The tensile study showed that the AA8090/3 wt% CeO₂ material exhibited maximum tensile strength (546 MPa) due to the arrest of dislocation by the added particles.
- The wear study showed that the applied load and sliding velocity displayed a notable effect on the wear rate of the AA8090 material and AA8090/CeO₂ composites. Further, the AA8090/3 wt% CeO₂ exhibited the slightest wear rate of $-0.045 \times 10^{-3} \text{ mm}^3/\text{m}$ at a sliding distance of 1,000 m, a load of 10 N, and a sliding velocity of 1 m/s.
- The COF results depicted that the AA8090 material showed a lower COF of 0.2 when 3 wt% CeO₂ was included and exhibited a sliding velocity of 0.5 m/s, a sliding distance of 1,000 m, and a load of 30 N.

Author contributions

Kalaiyarasan Anbalagan: Research, plotting and manuscript preparation; Velmurugan Duraisamy: Material collections, research and manuscript preparation; Raja Velur Loganathan: Software handling, data processing and

manuscript preparation; and Peniel Pauldoss Sam: Experiment facility, research and manuscript preparation.

Conflict of interest statement

Authors state no conflict of interest.

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