Enhanced mechanical properties and wear resistance of 2024Al alloy with CeO2 addition

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Abstract: In this work, a study of the mechanical properties and wear resistance of CeO2 reinforced 2024Al matrix composites have been performed using servohydraulic universal testing machine and ball-on-disk wear system. The composites were fabricated through powder sintering and hot extrusion followed by T4 heat treatment. Matrix of pure 2024Al was used to which different mass fractions (0.2%, 0.5%, 1.5%, 2.5% and 4.0%) of CeO2 were added. Tensile tests were performed at room temperature and velocity of 2.0 mm/min. As the CeO2 content increased, mechanical properties were firstly increased and then decreased. The UTS, YS and elongation reached maximum values at 0.5 mass.% CeO2 addition, which were increased by 11.6%, 13.3% and 20.7% as compared to those of pure 2024Al alloy, respectively. While, wear tests were carried out under loads of 5-20 N with sliding velocity of 0.05 m/s for 60 min. For 0.5 mass.% CeO2/2024Al, the decrements in volume loss and average COF and maximum COF under load of 10 N were 48.0% and 35.3% and 8.1% respectively as compared with pure 2024Al, and the decrements in volume loss and average COF and maximum COF under load of 20 N were 34.0% and 2.3% and 8.9% respectively as compared with pure 2024Al. Therefore, both mechanical properties and wear resistance of 2024Al alloy were markedly enhanced through trace CeO2 addition.

1. Introduction
Due to their excellent mechanical and physical properties, such as their high specific strength, high corrosion resistance and good thermal stability, aluminum alloys are widely used in applications such as electronic industries, automotive, aerospace, as well as other manufacturing industries. Besides their advantageous features such as low density, low coefficient of expansion, excellent shaping ability and ease of production, pure Al alloys cannot exhibit sufficient strength against the applications that involve high stress and reciprocating sliding contacts [1-2]. Composites based on various Al alloys [3-7] have been developed to get rid of the weakness of strength and wear resistance in pure Al alloys series [8]. Among various Al alloys series, 2XXX (Al-Cu-Mg) can achieve significant increase in mechanical properties through heat treatment. This increase takes place due to the process of aging or termed as age hardening. Within various reinforcement particles, oxide ceramic (Al2O3 [9], SiO2 [10], TiO2[N], ZrO2[N], etc.) was one of most commonly used materials. To further improve the wear properties of aluminum matrix composites, it is feasible to add a reinforcing phase with antifriction characteristics to the Al matrix. Wear and friction become very important, where relative motion occurs between the sliding surfaces. Due to wear, there is a loss of material and sometimes it becomes major cause of composites failure [11]. Compared with other oxide ceramic particles, CeO2 is considered as one of the most effective reinforcing phases that strikes a balance between strengthening and wear-resisting.
properties. In literatures reporting on surface wear resistance of aluminum alloys [12-13], CeO₂ were used as additions of composite coatings.

The various fabrication methods have been developed for production of aluminum matrix composites. Among all of these, powder metallurgy (PM) is more frequently and extensively used. Usually, the matrix powders are blended with the reinforced particles via mechanical milling. To fabricate bulk composites, the mixed powders are subjected to powder sintering and extrusion followed by heat treatment. In the present work, 2024Al matrix composites containing varying contents of CeO₂ (0.2%, 0.5%, 1.5%, 2.5%, 4.0% mass.) were fabricated through PM and tested under servohydraulic universal testing machine and ball-on-disk wear system.

2. Materials and Methods

2.1. Preparation of materials

Atomized 2024Al powders and CeO₂ powders were used as starting materials. The composition of 2024Al powders contains 4.20 wt. % Cu, 1.48 wt. % Mg, 0.58 wt. % Mn, 0.16 wt. % Fe, 0.087 wt. % Si and Al in balance. In this work, pure 2024Al and its counterpart with CeO₂ addition were fabricated by powder sintering and hot extrusion followed by T4 heat treatment. The sintering process contains three sub-processes, i.e. powder mixing, vacuum degassing and hot isostatic pressing. Prior to vacuum degassing, 2024Al-CeO₂ powder mixtures with varying contents of CeO₂ (0.2%, 0.5%, 1.5%, 2.5%, 4.0% mass.) were prepared. Then the above powder mixtures were filled into pure Al containers and degassed through the ventilation tube at 723 K until the vacuum degree reached 10⁻³ Pa. After vacuum degassing, the samples were placed in a hot isostatic press and subjected to a hydrostatic pressure of 100 MPa at 723 K with 2 hours holding. After hot isostatic pressing, the bulk materials were hot extruded at 703 K and followed by T4 heat treatment according the procedure: solution at 743 K with 1h holding, natural aging with 3 days.

2.2. Methods

Tensile tests were carried out for the pure 2024Al and CeO₂/2024Al composites at a rate of 2mm/min at ambient temperature by using a servohydraulic universal testing machine (DNS-100, Sinotest Equipment Co., Ltd., China). The testing specimens have gauge length of 25mm and diameter of 3mm.

The dry sliding wear tests were performed on ball-on-disk system (MS-T3001, Lanzhou Huahui Instrument Technology Co., Ltd., China). Wear-testing samples were made of size ø25mm×12mm, and the sample surfaces were well polished to ensure the proper contact with Si₃N₄ ball (ø4mm). Sliding wear tests were conducted on loads of 5N, 10N and 20N with velocity of 50mm/s for 60 min. The COF (coefficient of friction) of each sample was recorded along the whole process. After sliding, the loss of mass was measured and then converted to volume loss.

3. Results

3.1. Mechanical properties

The mechanical properties of pure 2024Al and CeO₂/2024Al composites were assessed in terms of their tensile strength and elongation. The stress-strain curves are shown in figure 1(a). To compare mechanical properties, the variations of UTS (ultimate tensile strength), YS (yield strength) and elongation with CeO₂ contents are illustrated in figure 1(b). In CeO₂/2024Al, stress is transferred from soft 2024Al matrix to hard CeO₂ ceramic reinforcement. From figure 1(b), values of UTS and YS and elongation were increased firstly and then decreased as the CeO₂ content increased. This behavior might be attributed to improper bonding of CeO₂ with 2024Al and also clustering of particles in the matrix. The UTS, YS and elongation reached maximum values at 0.5 mass.% CeO₂ addition, which were increased by 11.6%, 13.3% and 20.7% as compared to those of pure 2024Al alloy, respectively.
Figure 1 (a) Stress-strain curves of pure 2024Al and CeO$_2$/2024Al composites. (b) Variations of UTS, YS and elongation with CeO$_2$ contents

3.2. Wear resistance

Figure 2 shows typical images of wear-tested samples of pure 2024Al and its counterpart with 0.5 mass.% CeO$_2$ addition after sliding wear test under loads of 5 N, 10 N and 20 N. Obviously, the wear scars of the 2024Al are wider and deeper than those of CeO$_2$/2024Al composite. For optical micrographs (figure 3), the wear width of pure 2024Al under load of 10 N was decreased through 0.5 mass.% CeO$_2$ addition.

Figure 2. Wear-tested samples of pure 2024Al and composite with 0.5 mass.% CeO$_2$ addition

Figure 3. Optical micrographs ($\times$500) of wear surfaces for (a) pure 2024Al and (b) composite with 0.5 mass.% CeO$_2$ addition under load of 10 N
Wear loss and COF (coefficient of friction) are the most two important indexes to evaluate the tribological properties. The effect of 0.5 mass.% CeO₂ addition in 2024Al on wear loss and COF are shown in Table 1. It is evident from Table 1 that the trace addition of CeO₂ resulted into decrease in wear loss and COF. Under load of 10 N, the decrements in volume loss and average COF and maximum COF of CeO₂/2024Al were 48.0% and 35.3% and 8.1% respectively as compared with pure 2024Al. Under load of 20 N, the decrements in volume loss and average COF and maximum COF of CeO₂/2024Al were 34.0% and 2.3% and 8.9% respectively as compared with pure 2024Al. Hard CeO₂ acts as a load bearing material, resulting into increase in antifriction characteristics.

| Table. 1 Volume loss, average COF and maximum COF for pure 2024Al and 0.5 mass.% CeO₂/2024Al under different loads |
|---------------------------------------------------------------|
| Pure 2024Al | 0.5 mass.% CeO₂/2024Al |
| 5 N | 10 N | 20 N | 5 N | 10 N | 20 N |
| Volume loss (%) | 0.0237 | 0.0712 | 0.1544 | 0.0463 | 0.0370 | 0.1019 |
| Average COF | 0.5793 | 0.6717 | 0.5782 | 0.5075 | 0.4348 | 0.5649 |
| Maximum COF | 0.2898 | 0.3091 | 0.3672 | 0.2826 | 0.2840 | 0.3347 |

The presence of hard CeO₂ acts as load-bearing material in 2024Al matrix, which can restrict the deformation of composite. Consequently, wear loss decreased with the CeO₂ addition. Friction curves of pure 2024Al and 0.5 mass.% CeO₂/2024Al as a function of the sliding distance are given in figure 4. Under relatively low load of 5 N (figure 4a), COF values of two samples varied with the same trend and basically remained stable in the whole test. When the load was increased to 10 N (figure 4b), COF value of pure 2024Al rapidly increased in a short sliding distance and then showed the same trend with that of CeO₂/2024Al up to the end of test. Under relatively high load of 20 N (figure 4c), the COF value of pure 2024Al varied in a highly scattered manner and it was quite loud as compared to CeO₂/2024Al.

Figure 4. Friction curves of pure 2024Al and composite with 0.5 mass.%CeO₂ addition as a function of sliding distance under loads of (a) 5 N, (b) 10 N and (c) 20N.

SEM images of worn out surfaces of pure 2024Al and 0.5 mass.% CeO₂/2024Al under load of 10 N are indicated in figure 5. Worn surfaces of two materials are different. The pure 2024Al shows more rough grooves and higher material flow along sliding direction, which indicate the presence of abrasive wear (figure 5a). Delaminated patches due to adhesion are also observed on wear scar. This imply that the wear mode is a combination of both abrasive and adhesion mechanisms. This combined wear mechanism also applies to the CeO₂/2024Al composite.
Figure 5. Worn out surfaces of (a) pure 2024Al and (b) composite with 0.5 mass.% CeO$_2$ addition by SEM

However, relatively shallow and narrow grooves are dominate on the surface of composite, and the wear scar is much smoother (figure 5b). This could be a contributing reason to the reduced COF of composite. There are few wedge sections and wear debris on the wear scar of composite, and these debris were a mixture of matrix and reinforcement.

4. Conclusions

In the present study, 2024Al matrix composites with different mass.% (0.2%, 0.5%, 1.5%, 2.5% and 4.0%) of CeO$_2$ were fabricated through powder sintering and hot extrusion followed by T4 heat treatment. The findings of the study led to draw the following conclusions:

1. Mechanical properties (UTS, YS and elongation) were firstly increased and then decreased as the CeO$_2$ content increased. The UTS, YS and elongation reached maximum values at 0.5 mass.% CeO$_2$ addition, which were increased by 11.6%, 13.3% and 20.7% as compared to those of pure 2024Al alloy, respectively.

2. Volume loss was found to decreased with 0.5 mass.% CeO$_2$ addition in 2024Al matrix. The decrement in wear loss percentage of composite were 48.0% and 34.0% under loads of 10 N and 20 N respectively as compared to pure 2024Al.

3. The COF (coefficient of friction) was found to decreased with 0.5 mass.% CeO$_2$ addition in 2024Al matrix. As compared to pure 2024Al, the decrements in average COF and maximum COF of CeO$_2$/2024Al were 35.3% and 8.1% respectively under load of 10 N, and the decrements in average COF and maximum COF of CeO$_2$/2024Al were 2.3% and 8.9% respectively under load of 20 N.

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