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Microstructure and dry sliding wear behavior of cast Al–Mg_2Si in-situ metal matrix composite modified by Nd

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Abstract The microstructure and dry sliding wear behavior of cast Al–18 wt% Mg_2Si in-situ metal matrix composite modified by Nd were investigated. Experimental results show that, after introducing a proper amount of Nd, both primary and eutectic Mg_2Si in the Al–18 wt% Mg_2Si composite are well modified. The morphology of primary Mg_2Si is changed from irregular or dendritic to polyhedral shape, and its average particle size is significantly decreased. Moreover, the morphology of the eutectic Mg_2Si phase is altered from flake-like to very short fibrous or dot-like. The wear rates and friction coefficient of the composites with Nd are lower than those without Nd. Furthermore, the addition of 0.5 wt% Nd changes the wear mechanism of the composite from the combination of abrasive, adhesive, and delamination wear without Nd into a single mild abrasion wear with 0.5 wt% Nd.

Keywords Al/Mg_2Si composites; Nd modification; Microstructure; Dry sliding wear behavior

1 Introduction

Recently, in-situ particles reinforced that aluminum matrix composites have attracted much attention in the academic community and industrial sector due to their inherent isotropic properties and much lower costs of production. Hypereutectic Al–Si alloys with high Mg content are considered in-situ aluminum matrix composites containing a large amount of hard particles of Mg_2Si, and the Al–Mg_2Si in situ metal matrix composites have high potential as candidates to replace Al–Si alloys used in aerospace and automotive applications because the intermetallic compound of Mg_2Si exhibits high melting temperature, low density, high hardness, low thermal expansion coefficient, and reasonably high elastic modulus [1]. However, their main limitation is the presence of coarse and brittle primary and eutectic Mg_2Si particles formed under conventional casting process conditions. These particles easily crack, causing the serious disseverance to the aluminum matrix and exposing the soft matrix to extreme wear, which results in poor mechanical properties and also makes wearing capacity unable to fully play. Therefore, it is essential for us to modify Mg_2Si-reinforced aluminum matrix composites to change morphology and distribution of primary and eutectic Mg_2Si phases with an aim of enhancing mechanical properties and wear resistance of the composites.

Several investigations have been carried out for the modification of primary and eutectic Mg_2Si crystals in Al–Mg_2Si or Al–Si–Mg_2Si composites by adding P [2], Sr [3], and RE, such as Y [4] and Ce [5, 6], Li [7], Na [8], and and K [9] to the liquid alloys. Y and Ce have been shown to be an effective modifier of Mg_2Si. However, little has been reported on the wear behavior of Mg_2Si-reinforced aluminum matrix composites with the addition of RE modifier. In the present study, pure Nd was adopted to modify Al–18 wt% Mg_2Si composites with an aim of investigating the effect of pure Nd on microstructure and wear resistance of Al–Mg_2Si in situ metal matrix composites. By observation and analysis of worn surfaces, the wear mechanism of the composites is investigated.

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2 Experimental

Commercially pure aluminum (ingot, 99.3 % purity), magnesium (ingot, 99.1 % purity), silicon (block, 98.7 % purity), and Al–10 wt% Nd master alloy were used as precursor materials to prepare Al–18 wt% Mg_2Si composite. Aluminum ingot and silicon blocks were charged into a graphite crucible and heated in an electric resistance furnace, and then, the different amounts of Nd were introduced into the melt by adding Al–10 wt% Nd master alloy at 800 °C. The Nd level, ranging from 0.1 wt% to 1.2 wt% in steps of 0.1 wt%, was added into the melt. After that, magnesium blocks that were cut from the magnesium ingot, wrapped in an aluminum foil, were added into the melt when temperature dropped to about 720 °C. Then, the melt was degassed with hexachloroethane. After gently stirring, the melt is cast into a steel mold preheated at 200 °C to produce 30 mm diameter rods.

All the specimens for microstructure characterization were cut from the same positions of the ingots at 10 mm from the bottom of the castings. The specimens were mechanically ground and then polished through standard routines. Each cross section was etched using 0.5 vol% hydrofluoric acid (HF) water solution. Phase constitution was carried out using X-ray diffraction equipment (XRD; Philips X'pert Pro) with Cu Kα as radiation and step size of 0.033°. The microstructures of the composites were investigated by an optical microscope (OM). The average grain size was measured by linear intercept method.

In order to evaluate the effect of Nd addition on the dry sliding wear behaviors of the composites, dry sliding abrasive wear tests were performed using a pin-on disk machine under loads ranging from 30 to 150 N. A bearing steel ring was employed as the counterface. Before and after the test, the pin was cleaned with ethanol and weighed. The wear rate was calculated from the results of the weight loss and sliding distance.

3 Results and discussion

3.1 Microstructure

Figure 1 shows the XRD patterns of the composites containing different amounts of Nd. The XRD patterns reveal that all the microstructures of the composites contain α-Al and Mg_2Si phases, and a few contain free Mg and Si. Some new peaks appear in the patterns of the composites with 0.8 wt% and 1.2 wt% Nd, and the diffraction patterns were identified as AlNd phase. Moreover, with the further increase in added amount of Nd, the diffraction intensity for the AlNd phase increases, showing the increase of AlNd phase, and at the same time, some unknown phases appear in the composite containing 1.2 wt% Nd. This phenomenon suggests that Nd-containing intermetallic compounds are formed in the microstructure of the Nd-modified samples when the amount of Nd is high.

Figure 2 shows the microstructure characteristic unmodified and modified composites containing different amounts of Nd. It is seen that the primary Mg_2Si phase of the unmodified composite shows typical coarse dendritic and polyhedral morphology, it is very coarse, the size of the phase even exceeds 70 μm, and the size distribution is far from uniform (Fig. 2a). With 0.1 wt% and 0.3 wt% Nd additions, the morphology of primary Mg_2Si does not need to be changed significantly, but their sizes are decreased to ~30 and 20 μm, respectively (Fig. 2b, c). As the addition level of Nd increases to 0.5 wt%, the size of primary Mg_2Si further is reduced to 13.0 μm or less, and its morphology transforms into fully polyhedral morphology (Fig. 2d). The addition of 0.8 wt% Nd does not obviously change the morphology and size of primary Mg_2Si, and its morphology still keeps the irregular and polyhedral modified morphology (Fig. 2e). However, when the addition level of Nd is further increased to 1.2 wt%, it is found that some coarse Mg_2Si are formed again, but it is smaller than that in the unmodified composite. Compared with those in Fig. 2d, e, Mg_2Si size increases to about 32.6 μm, although there is no obvious change in the modified morphology of primary Mg_2Si (Fig. 2f). It should be noticed that the addition of 0.5 wt% Nd not only considerably decreases the sizes of primary Mg_2Si particles but also makes the distribution of the particles more uniform, as shown in Fig. 2d. Based on the experimental results, it can be concluded that the addition of minor Nd (less more 0.3 wt%) results in partial modification on primary Mg_2Si, while more Nd additive (0.5 wt%–0.8 wt%) produces full modification. However, excess Nd (1.2 wt%) leads to the appearance of overmodification phenomenon.

It is also seen in Fig. 2 that the eutectic Mg_2Si morphology of unmodified composite is flake-like inside the eutectic

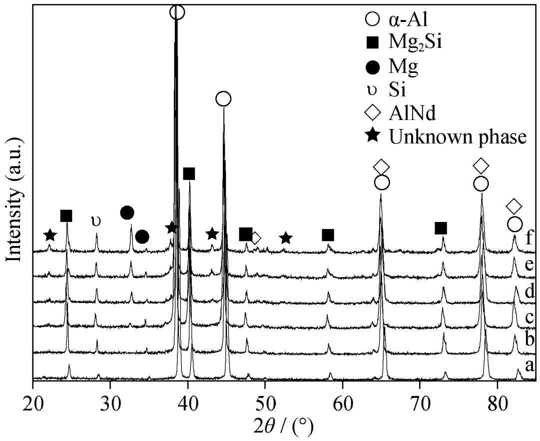

Fig. 1 XRD patterns of Al–18 wt% Mg_2Si composites containing different amounts of Nd (wt%): **a** 0, **b** 0.1, **c** 0.3, **d** 0.5, **e** 0.8, and **f** 1.2

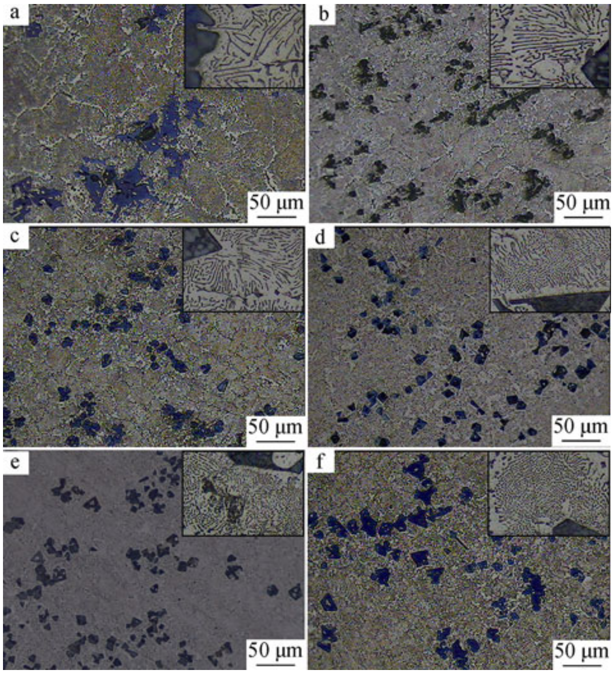

Fig. 2 Optical images of Al–18 wt% Mg_2Si composites containing different amounts of Nd (wt%): **a** 0, **b** 0.1, **c** 0.3, **d** 0.5, **e** 0.8, and **f** 1.2

cells (Fig. 2a). With Nd addition, eutectic Mg_2Si phase turns into a thin laminar structure at 0.1 wt% and 0.3 wt% Nd, and a very short fibrous, coral-like, or dot-like structure over 0.5 wt% Nd, respectively, as shown in Fig. 2b–f.

The refinement of Mg_2Si crystals by the addition of Nd might be related to the composition supercooling caused by the segregation of Nd at the front of the solid/liquid interface of Mg_2Si during solidification. It can be considered that because of the extremely low solidity of Nd in the Al matrix, the Nd element is easy to congregate at the growing interface of Mg_2Si, resulting in a local composition supercooling in the alloy melt. With the concentration increase of Nd, the composition supercooling is further increased. When the concentration of Nd reaches a certain extent, the growth of Mg_2Si phase can be suppressed, and thus, its crystals become fine. Another refining reason might be because Nd addition may create some distortion in the Mg_2Si lattice due to a high solidity limit of Nd in Mg_2Si and the larger radius size of Nd atom and thus changing the surface energy of the Mg_2Si crystals. Therefore, Nd addition may arrest and suppress the anisotropic growth of the Mg_2Si dendritic morphology. With regard to the detailed modifying mechanism of Nd on Mg_2Si, there is still a need for further research to be carried out.

3.2 Hardness

It is well known that there is a proportional relationship between wear behavior and the hardness of the material [10]. It is necessary to know the hardness of the materials before the wear test. The influence of Nd addition on the microhardness of the composites is shown in Fig. 3. The microhardness of the Al–18 wt% Mg_2Si composites increases with changes in Nd addition and reaches a maximal value in the range of 0.5 wt% Nd, which is about 1.4 times higher than that of unmodified composite. However, when Nd content exceeds 0.8 wt%, the hardness decreases gradually.

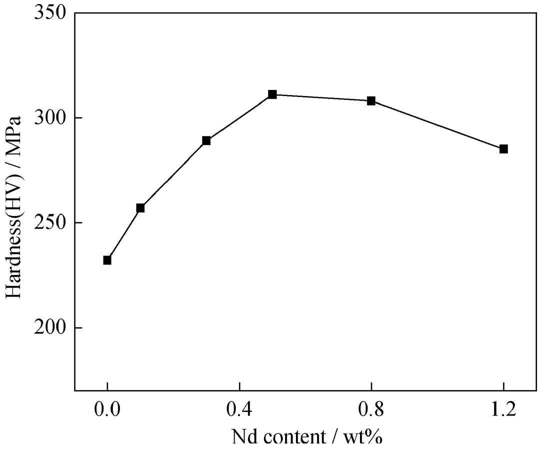

Fig. 3 Variation of the microhardness with the Nd contents

Variations in the hardness with the Nd contents can be due to the change in average size and morphology of primary and eutectic Mg_2Si. When Nd content is less than or equal to 0.5 wt%, the increase of hardness can be because the primary and eutectic Mg_2Si become smaller and finer, which reduce stress concentration at the interface of Mg_2Si and matrix, and increase the bonding of Mg_2Si crystals with soft matrix [11]. Thus, the microhardness of Al–Mg_2Si composite increases significantly, as compared to that of the absence of modifier. The decrease of the hardness is mainly due to the increase of the primary Mg_2Si in size when Nd content exceeds 0.5 wt%.

3.3 Wear behavior

3.3.1 Wear rates and friction coefficient

Figure 4 shows the effects of Nd contents on the wear rates and friction coefficient for the investigated composites under the load of 30 and 150 N.

Obviously, the relationships of the wear rates with Nd content are similar for the two loads. The wear rates decreased with Nd content at first, reached a minimum at 0.5 wt% Nd, then slightly increased with increasing of Nd, but were not larger than those of the Nd-free composite (Fig. 4a). The relationships of the friction coefficient with Nd content are similar to those of the wear rates with Nd content, namely, the friction coefficient decreased at first, and then slightly increased with increasing Nd (Fig. 4b).

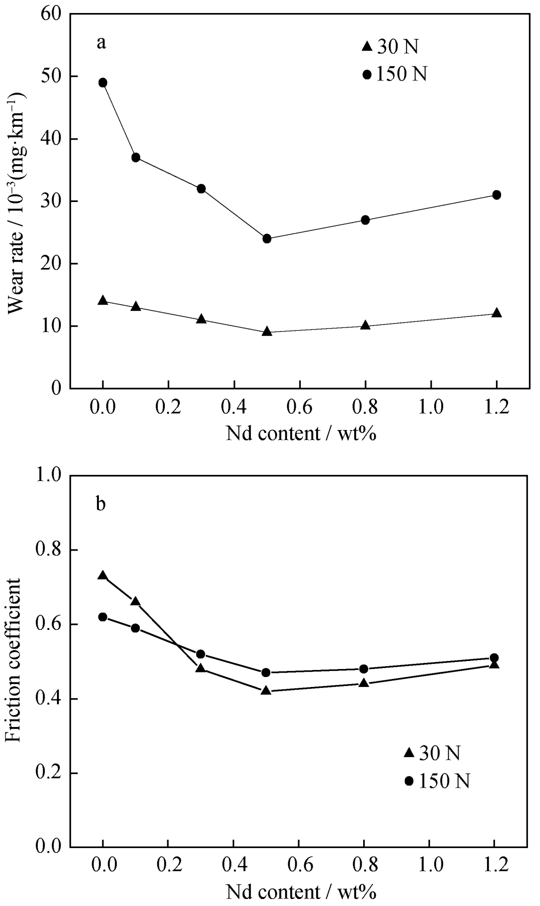

Fig. 4 Variation of wear rates **a** and friction coefficients **b** with the varying contents of Nd

Figure 5 shows the variation of wear rate of the unmodified and Nd-modified composites with applied load. It can be seen that the wear rates of the composites increase with increasing applied load irrespective of the material, and the wear rate increases more rapidly in high-load region than in low-load one. However, the rates of increase of wear with the increasing of load for 0.5 wt% Nd-modified composites are smaller than those for the unmodified composite. For example, the wear rate of the unmodified composite increased from 26 × 10^{-3} mg·km^{-1} at an applied load of 100 N to 49 × 10^{-3} mg·km^{-1} at an applied load of 150 N, while the wear rate of the 0.5 % Nd-modified composite increases from 17 × 10^{-3} to 24 × 10^{-3} mg·km^{-1} at the same applied load. The former increased by 188 %, whereas the latter by only 141 %. These results show that the wear resistance of Nd-modified composites is better than that of the unmodified composite.

3.3.2 Worn surface and mechanism

In order to reveal the wear behavior and mechanism, the worn surfaces of the composites without and with Nd were examined under SEM. Figure 6 shows SEM micrographs of worn surfaces of the composites, tested at a load of 150 N. It can be seen that the worn surface of Al–18Mg$_2$Si composite without Nd appeared deep and wide plowing grooves parallel to the motion direction of which their maximum width reached 50 μm; a lot of dimples, local adherent scars, and fractured primary Mg$_2$Si particles could be seen in the surface, and while some of the fractured particles are left in matrix surface, others are broken off during wear and form the dimples. This demonstrates that a combination of abrasion wear, adhesive wear, and delamination wear appear to be the main wear mechanism of the composite, as shown in Fig. 6a. With the addition of 0.1 wt% Nd, fractured primary Mg$_2$Si particles disappears; only grooves, dimples, and adherent scars are left, and these grooves become more shallow and narrow than those without Nd, which is the combination of mild abrasion wear and adhesive wear (Fig. 6b). After the content of Nd increases to 0.5 wt%, the worn surface of the composite has a rather smooth appearance only with grooves as a result of homogeneous wear, and the grooves become more shallow and narrow, and thus, the its wear mechanism is changed into a single abrasion wear, as shown in Fig. 6c. However, the dimples and local adherent scars again appear with increasing Nd content to 1.2 wt% (Fig. 6d).

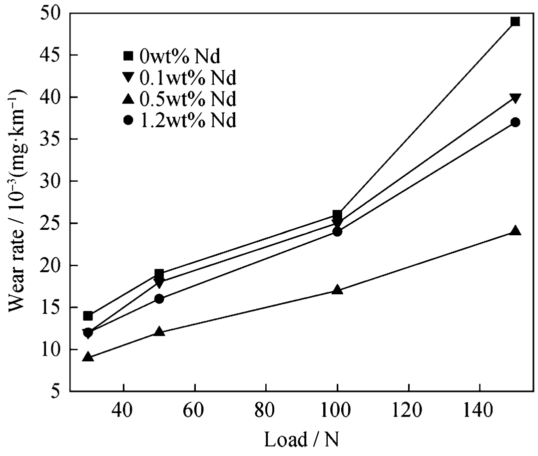

Fig. 5 Variation of wear rates with varying load

The wear and frictional properties supported by wear rate, friction factor, and worn surface in the present investigation together reveal that the wear resistance of the Nd-modified composites, especially 0.5 wt% Nd-modified one, is better than that of the unmodified composite within the experimental wear conditions used. The low friction coefficient, wear rates, and smooth worn surfaces for Nd-modified composites are mainly due to Nd modification on primary and eutectic Mg$_2$Si phases.

In particles-reinforced composites, the morphologies and the sizes of the primary and eutectic particles play critical roles in determining the wear behaviors of these materials

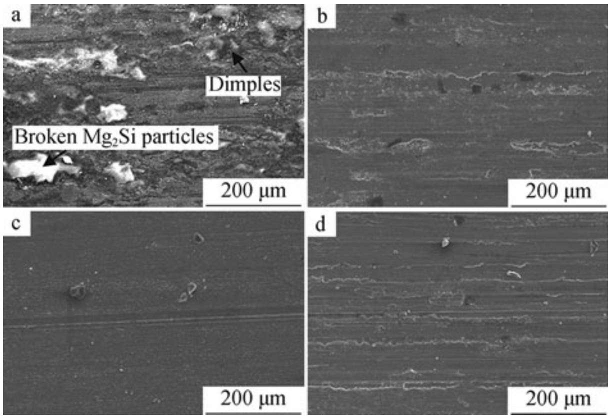

Fig. 6 SEM micrographs of worn surfaces of the composites with different amounts of Nd under 150 N load: **a** 0 wt%, **b** 0.1 wt%, **c** 0.5 wt%, and **d** 1.2 wt%

[12, 13]. For the unmodified Mg_2Si particles reinforced Al matrix composite, test load is carried by fewer particles in a certain area due to coarser primary Mg_2Si, which causes a higher contact stress on the tip of coarse abrasive particles than that of fine abrasive particles for the same applied load, and the coarse particles were found to contain more defects [14]. Thus, the coarse Mg_2Si phases appeared to fracture more frequently than fine Mg_2Si particulates during two-body abrasive wear, resulting in the formation of a lot of fractured particles on wear surface (Fig. 6a). Some of the fractured particles are easy to be removed from the matrix to leave lots of dimples on wear surface, as shown in Fig. 6a. Furthermore, these dropping hard Mg_2Si particles, entrapped between the counterface and the composite, make relative motion along the friction direction on the soft aluminum matrix under the act of inertial force and act as third-body abraders and aggravate the worn surface damage, causing the secondary cutting of the matrix, thus forming deep and wide plowing grooves on the composites (Fig. 6a) and resulting in a high friction factor and wear rate (Figs. 4 and 5). In contrast, finer primary Mg_2Si phase with large load-supporting ability in the 0.5 wt% Nd-modified composite has little effect on the formation of surface and subsurface microcracks, as shown in Fig. 6c, thus reducing the tendency for the finer primary Mg_2Si particles to be pulled out from the worn surface, which leads to less third-body wear during the wear process (Figs. 4 and 5) and a rather smooth appearance only with grooves (Fig. 6c).

The decrease of the friction coefficient and wear rates of the Nd-modified composites can also be attributed to the grain refining of eutectic Mg_2Si phase. The finer eutectic Mg_2Si phase forms a rough interface with the matrix, and their better bonding with matrix can effectively suppress the initiation and propagation of the cracks at the finer eutectic Mg_2Si/matrix interface, resulting in further improvement on the wear resistance of modified Al–Mg_2Si composite. The small increase of the wear rates and friction coefficient for 1.2 wt% Nd-modified composite is attributed to the slightly large primary Mg_2Si phase compared with 0.5 wt% composites. In addition, when the addition level of Nd exceeds certain value (0.8 wt%), brittle Nd-containing intermetallic compounds containing AlNd are formed (Fig. 1), resulting in the increase of wear rates of the composite, which has also been demonstrated in mischmetal (MM)-modified Al–7.0 wt% Si–0.3 wt% Mg alloy [15].

4 Conclusion

The influences of different Nd contents on the microstructures and dry sliding wear behaviors of in-situ Al–18 wt% Mg_2Si composites were investigated.

The addition of proper amount of Nd was found to be modifying both primary and eutectic Mg_2Si in the composites simultaneously. With the increase of Nd content, primary Mg_2Si particle morphology is changed from dendritic to polygonal, and its size decreases from 47.5 to 13.0 μm. Moreover, the morphology of the eutectic Mg_2Si phase is altered from flake-like to a thin laminar, short fibrous, and coral-like or dot-like structure. When the Nd exceeds 0.8 wt%, the size of the primary Mg_2Si becomes larger, while the eutectic Mg_2Si still exhibits modified morphology.

The wear rates and friction coefficient of the composites with Nd are lower than those without Nd, and the wear rates decrease at first, reaching a minimum at 0.5 wt% Nd and then increasing with the increase of Nd content; the improvement of the wear rates of the composites with Nd is more obvious in high-load region than in low-load one. The addition of Nd changes the wear mechanism of the composite from the combination of abrasive, delamination, and adhesive wear without Nd to mild abrasion and adhesive wear with 0.1 wt% Nd and then to a single mild abrasion wear with 0.5 wt% Nd. The low wear rate for the composites with Nd is mainly due to the size refinement and morphology change of primary and eutectic Mg_2Si.

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