Effect of nanodiamond particle sizes on damping properties of ZK60 magnesium matrix composites

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Abstract

The aim of the research is to ensure that the material has functional mechanical properties as well as high-damping value. The microstructure, elemental composition, second phase distribution and interface structure of the Mg-based composite with different particle sizes were characterized by Optical Microscope(OM), X-Ray Diffractometer(XRD), Scanning Electron Microscope(SEM), Transmission Electron Microscope(TEM) and Energy Dispersive Spectrometer(EDS). The mechanical and damping properties of the ZK60 magnesium matrix composites were investigated an Instron5982 universal tester and Dynamic Mechanical Analysis(DMA). The results indicate that nanodiamond(ND) can disperse well in the composites. The elastic modulus of composite can reach 9.9 GPa after reinforcement phase being added. Under certain conditions, the damping value can reach beyond $2.5 \times 10^{-1}$, which is 117% of other composite. High-temperature damping depends on grain boundary slip and interface slip. The interfacial damping depends on the difference in the incoherent interface and thermal expansion coefficient between the nanodiamond and ZK60 matrix to slip and improve the damping value.

1. Introduction

Aerospace and modern industrial development are increasingly demanding on the performance of metal materials. With damping capacity being one of the three major requirements for modern materials (shape memory properties, superplasticity, and damping capacity), the development of high-damping materials has stirred up a heated debate and attract the interest of scholars \cite{1}. In many engineering applications, the metal magnesium performs good high-temperature mechanical properties and dimensional stability. Whereas its disadvantages dwell in aspects of noise or collisions that would produce fatigue failure and dynamic instability, such as magnesium alloy under the condition of high temperature and high strain, hence improving the damping performance of industrial materials, and aviation is of evident significance.

In recent years, the literature \cite{2} has studied the influence of nanodiamond(ND) on the microstructure and mechanical properties, indicating that the addition and design of nanodiamond(ND) with enhanced phase have improved hardness and strength, but made plasticity whittled down in a minor way. Having studied on the damping performance of Fly Ash Cenosphere/AZ91D composite, Yuan Ming et al found that Mg$_2$Si wrapped Fly Ash Cenosphere was not evenly dispersed, resulting in reduced interface damping and deterioration of damping performance \cite{3}. In the literature \cite{4} AlN-reinforced Mg-Al matrix composites, when the reinforcement phase content is 6%, fine grain strengthening present an pleasant performance; and when the reinforcement phase content is 3%, the damping performance is the best. In the literature \cite{5}, the addition of nickel-coated short fibers improved the damping performance of AZ91D as well as the interface wettability, and increased the internal friction with the temperature rising. The damping peak appeared at 250 $^\circ$C–300 $^\circ$C, and
exhibited a process of thermal activation relaxation. Liu [6] studied the damping performance of a Mg-Zn-Nd-Cd-Zr alloy. If the interface type between the second phase and the matrix is coherent, the stability of the interface energy could be reduced, not to such an extent as to cause interface slip. If the interface energy is non-coherent, the interface energy is highly unstable, and the dislocation and interface interactions will enhance the damping performance. Gao found that in the $10 \text{s}^{-1}$ ~ $30 \text{s}^{-1}$ strain range, with the increase of the rolling strain rate, the dynamic crystal volume fraction and grain size increased, and the base plane texture strength weakened, resulting in a decrease in the mechanical properties of the material and an increase in the damping properties [7].

2. Experimental details

In this experiment, ND/ZK60 billet was prepared with the support of the powder metallurgy method. The matrix was ZK60 atomized spherical powder with a diameter of $30 \sim 50 \mu m$, composed of Zn 5.2%, Zr 0.3% and the remaining Mg. The reinforcement is nanodiamond in the form of granular $25 \sim 500 \text{nm}$, and the addition level is 0.05 at%. The specific preparation process is as follows: (1) add 500 ml ethyl alcohol into the beaker, add ZK60 powder and nanodiamond powder sequentially, stir the ZK60 powder and 0.05% nanodiamond powder for 2h until the material was fully dispersed and uniform, and dried in a vacuum drying oven to get ND/ZK60 powder. (2) Using a DYXQM-12 L planetary ball mill ball to grinding ND/ZK60 powder, adding 5 ml alcohol to prevent the sticking tank, vacuum treatment, aerating argon, cycling thrice this process, preventing ball grinding oxidation, ball material ratio of 25:1, ball grinding speed of 500 r min$^{-1}$, and ball grinding time of 120 min. (3) Vacuum hot pressing sintering of ND/ZK60 powder was conducted in a hot pressing sintering furnace (VHP300/35–2100) at a sintering temperature of 470 $\degree C$, sintering time of 120 min, sintering pressure of 100–150 MPa, vacuum degree of 10–1 Pa, subsequently obtaining a $\Phi 45 \text{mm} \times 30 \text{mm}$ sintering billet. (4) To diminish the microstructure defects and improve the density of the composite material, the sintered embryo was extruded, and the parameters (extrusion ratio 20:1, extrusion temperature 300 $\degree C$) were $\Phi 10 \text{mm} \times 400 \text{mm}$. (5) The extruded material was poured into a muffle furnace at 350 $\degree C$ for annealing, and cooled with the furnace after 60 min of heat preservation.

To investigate the effect of nanodiamond on the microstructure, a Leica DMIRM metallographic microscope (OM) was utilized to observe the microstructure morphology of the magnesium matrix composites. The phase composition and lattice parameters of the ND/ZK60 magnesium matrix composites were characterized by x-ray diffraction (XRD) with a scanning angle of $20^\circ$–$90^\circ$ and a step size of 5$^\circ$. The microstructure of the ND/ZK60 magnesium matrix composites was observed with the assistance of a ZEISS-Merlin Compact field emission scanning electron microscope (SEM); the phase identification and composition analysis were performed with the assistance of EDS; and the morphology, distribution and interface between nanodiamond and matrix were observed with the support of TEM.

For the tensile test, an Instron5982 universal testing machine was employed at room temperature with a tensile rate of 0.2 mm min$^{-1}$, tensile direction parallel to the extrusion direction, and tensile specimens turned by rod blank into specimens with threads, as shown in figure 1.

A dynamic mechanical analysis (DMA-242) was used for the damping performance test, of which method was the single cantilever bending method. As shown in figure 2, the sample was cut along the parallel line to the extrusion direction (ED), with a size of $30 \text{mm} \times 5 \text{mm} \times 1.5 \text{mm}$ with the room temperature damping was carried out at 25 $\degree C$. Four frequencies of 0.5 Hz, 1 Hz, 5 Hz and 10 Hz were used for oscillation, with a constant amplitude of 20 $\mu m$. Temperature range: 25 $\degree C$–350 $\degree C$. 

![Figure 1. Tensile Sample.](image_url)
3. Results and discussion

3.1. Microstructures of the magnesium matrix composite

Figure 3 shows the XRD patterns of the extruded ND/ZK60 magnesium matrix composites. It can be seen from the figure that the diffraction peak is mainly $\alpha$-Mg with high intensity, as well as a small amount of weak MgZn$_2$ phase and MgO, which implies that the main component of the prepared composite is $\alpha$-Mg phase, while MgZn$_2$ is part of the Zn precipitated in the Mg supersaturated state, and MgO may be produced by oxidation during the preparation process. The nanodiamond reinforcement phase of the composite materials is not reflected in the XRD diffraction pattern, because the addition amount of diamond powder in this experiment is only 0.05%, which is lower than the minimum detectable content of XRD. In addition, the fact of no other diffraction peaks indicates no interfacial reaction between the enhanced phase and the ZK60 matrix. In the subsequent EDS analysis, the main components were Mg, Zn, C, Zr, etc.

Figure 4 shows OM images of extruded ND/ZK60 magnesium matrix composites. ED is the extrusion direction (50 $\mu$m in figure 4), TD is transverse (20 $\mu$m in figure 4).

The black boundary line in the figure is the particle boundary composed of precipitates generated after the powder metallurgy process [8]. In the direction of TD, it can be seen that an obvious particle boundary (PPB) exists in the tissue after extrusion, and there are more and relatively continuous precipitates at the particle boundary. There are fewer precipitates at the particle boundary, as shown in figures 4(b) and (d). In the direction of the ED, the structure is pulled out but the particle boundaries remain there. (e) and (f) clearly show that the particle boundaries are desalted and relatively smooth inside with few point-like precipitates. In (a) and (c), the boundary is thicker and more precipitates are agglomerated, where as in (b), few boundary precipitates emerge. Different from other particle-size composites, a large number of point-like precipitates are distributed in the direction of the ED.
Figure 5. shows the results of EDS scanning of extruded 0.2 μm ND/ZK60 composite, where point scanning and plane scanning were performed so as to determine the composition and element distribution of the material. It is shown in the figure that MgO has a large distribution area and tends to agglomerate, making it the main component of the precipitates at the grain boundary, while carbon is mainly distributed at the grain boundary and inside the grain in a point shape. In addition, the main components of the magnesium matrix composites can be determined as Mg, Zn, C, O and Zr according to the spectrum of (g) plane. Combined with XRD results and (h)(i) spot scan results, it can be determined that there are also plenty of MgZn₂ phases in the grain boundary and grain interior of ND/ZK60 composite. The morphology is white and spot-like and widely distributed.

Figure 6 shows SEM images of ND/ZK60 magnesium matrix composites with six particle sizes. In (b) (d) (e) and (f), plentiful white spotty MgZn₂ exist in different degrees, while MgO is mainly distributed at the boundary of particles with white flocculent morphology. What determines the emergency of particle boundary is the carbon content: if the carbon content is too high, PPB will be easily formed; if the carbon content is too low, the hard phase cannot be strengthened. It can be observed in (a) and (c) in the figure that there are more MgO and less distribution of the second phase. In (d), the second phase MgZn₂ presented in a more distributed way, but the amount of MgO is increasing. In (e)/(f), clear particle boundary and the second phase MgZn₂ can be easily observed.
Figure 7 is TEM image of the extruded 0.025 μm ND/ZK60 composite, which is the Fourier filtered image formed with the removal of extra reflection spots.

As shown in figure 7(a), the hexagon-like regions in the ZK60 matrix exhibit different contrast degrees, the main ingredient is MgO, MgZn2, and ND. In accordance with figure 7(b), the crystal plane index after calibration is (0 0 0 1) located at the a base plane. Figures 7(c) and (d) show the nanodiamond particle and its scale diagram, as well as the interface between the matrix and nanodiamond, respectively. In figure 7(d), the interface is separated by an obvious white band, and the crystal plane index of α-Mg is (2 1 1 0). According to the calibrated crystal plane index, the interface between the two is non-coherent. Combined with the XRD results, no other phase was generated and the chemical properties of diamond were extremely inactive. It is difficult for the interface reaction between the ND and ZK60 matrix to occur. Therefore, the interface bonding mode belongs to mechanical interlocking. Figures 7(e) and (f) show the MgZn2 phase with a crystal plane index of (1 1 0). The crystal structure was a complex hexagonal structure. A semi-coherent interface with the matrix can be seen there, and the interface energy is relatively low and stable.

3.2. Effect of nano-diamond on mechanical properties

Figure 8 uncovers the relationship between the tensile stress and tensile strain of six types of extruded ND/ZK60 magnesium matrix composites, which mainly reflects the elastic and plastic deformation process of ND/ZK60.

The figure shows that when the strain ratio reaches 4% of the total length (displacement ratio), the composites yield and then produce plastic deformation. The tensile strength of the 0.04 μm reaches 384.85MPa and the elongation reached 14.6%, while the tensile strength of the 0.5 μm was the lowest in spite of the better elongation of it (16.2%).

Table 1 shows the elastic modulus (EM), yield strength (YS), tensile strength (TS) and elongation (EL) of ND/ZK60 with different particle sizes. According to the table, YS and TS show a trend of increasing first and decreasing afterwards. Taking tensile strength as an example, 0.04 > 0.1 > 0.2 > 0.25 > 0.025 > 0.5, the tensile strength of 0.04 μm is 117% of 0.5 μm, while the yield strength of 0.04 μm is 136% of 0.5 μm. The elastic modulus of 0.04 μm particle size reached 9.9GPa. At the same time, there was little difference in other particle sizes. In addition, 0.2 μm ND/ZK60 has the worst plasticity and the lowest elongation, while 0.5 μm ND/ZK60 has the highest elongation, the worst tensile and yield strength. It can be seen that the well performance of plastic elongation is at the cost of reducing the strength of it. Among them, 0.04 μm material has more outstanding comprehensive performance. When the particle size of reinforcement phase increases, the strength of composite material will decrease [9].
3.3. Temperature dependence of damping capacity

The temperature damping curves of the ND/ZK60 magnesium matrix composites at different frequencies are presented in Figure 9. It can be seen from the figure that, at room temperature, the frequency is proportional to the damping value, while the loss coefficient $\eta = \tan\phi$ is positively correlated with temperature within a certain temperature range. Finally, $\tan\phi$ is inversely proportional to the frequency, and the damping value of composite materials with 0.025 $\mu$m and 0.1 $\mu$m particle size begins to decrease. The damping value can be divided into two regions: below 225 °C, all particle sizes increase with no significant difference among each other; above 225 °C, the damping value increases rapidly with the temperature rising and the gap among the sizes widens gradually.

The three stages are divided by temperature: from 25 °C to 100 °C, this part of the curve presents almost as a horizontal straight line, of which reasons are as follows: the energy generated by vibration is insufficient to make dislocation difficult to dispense; the dislocation line is difficult to bow out of motion. As a result, the curve characteristics are independent of temperature and frequency and other factors, belonging to resonance damping [10].

In the temperature range of 100 °C to 250 °C, $\tan\phi$ increased linearly with temperature, but fluctuated slightly at approximately 200 °C, and the $P_1$ internal friction peak appeared within this temperature range. In magnesium alloys, twinning and slip are two significant plastic deformation modes. As the temperature increases, the atomic thermal motion also increases, while the stress of the dislocation line breaking away from the pin point decreases. At the same time, the dislocation of the weak pin point continues to decrease, and the threshold required for slip decreases, that is, the critical resolved shear stress(CRSS); when the minimum

Figure 6. SEM images of Six particle sizes of ND/ZK60 magnesium matrix composites. (a): 0.025 $\mu$m, (b): 0.04 $\mu$m, (c): 0.1 $\mu$m, (d): 0.2 $\mu$m, (e): 0.25 $\mu$m, (f): 0.5 $\mu$m.
Figure 7. TEM images of 0.025 μm ND/ZK60 magnesium matrix composites.

Figure 8. Diagram of tensile stress and strain of ND/ZK60 magnesium matrix composites with different particle sizes.

Table 1. Mechanical properties of ND/ZK60 magnesium matrix composites with different particle sizes.

| Particle size (μm) | Elasticity modulus (MPa) | Yield strength (MPa) | Tensile strength (MPa) | Elongation (%) |
|-------------------|--------------------------|----------------------|------------------------|----------------|
| 0.025             | 8.62                     | 320.85               | 342.54                 | 14.2           |
| 0.04              | 9.88                     | 388.04               | 384.85                 | 14.6           |
| 0.1               | 8.50                     | 372.94               | 373.39                 | 12.9           |
| 0.2               | 8.24                     | 362.93               | 365.17                 | 11.9           |
| 0.25              | 8.44                     | 332.49               | 345.86                 | 14.4           |
| 0.5               | 8.58                     | 285.39               | 327.96                 | 16.2           |
threshold is reached, the slip system on the base plane will be thermally activated, and slip preferentially occurs on the \{0 0 0 1\} dense row plane and the \{1 1 2 0\} dense row direction, and the internal friction continues to increase \cite{11-13}. Therefore, the P1 peak is the internal friction peak of dislocation caused by the initiation of the base plane slip, meanwhile, the dominant mechanism is dislocation.

Internal friction continues to increase between 250 °C and 325 °C, with a P2 internal friction peak around 300 °C. According to Granto-Lucke theory of dislocation pinning model \cite{14, 15}, the change of damping value in this temperature range is still related to the dislocation. The continuous rise of temperature leads to the ‘avalanche’ dispinning of the dislocation line, where dislocation will ‘bow out’ between weak/strong pinning points, resulting in internal friction \cite{16}. However, the effect of the dislocation damping mechanism has been weakened.

Hu. et al found that grain boundary slip (GBS) occurs in magnesium alloys at 250 °C, which induces a large amount of internal friction. Stronger than dislocation damping, grain boundary damping is one of the sources of high-temperature damping \cite{14, 17}, which can also cause large plastic deformation. Fine-grained alloys are prone to GBS regardless of low-temperature or high-temperature plastic deformation. In this study, although the grain size is small, yet the influence of grain boundaries cannot be ignored, and the damping performance of fine grain alloys is bound to be affected by GBS \cite{18}.

According to a study by Wu \cite{19, 20}, the damping mechanism of Grp/AZ91 and SiCp/Grp/AZ91 composites is the inherent graphite grain damping and dislocation damping mechanism. The grain boundary

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**Figure 9.** Damping temperature curves of ND/ZK60 magnesium matrix composites made of ND with different particle sizes. (a): 0.025 μm, (b): 0.04 μm, (c): 0.1 μm, (d): 0.2 μm, (e): 0.25 μm, (f): 0.5 μm.
slip and interface slip are the dominant damping mechanisms above 250 °C. Therefore, it is necessary to investigate whether GBS occurs at temperatures higher than 250 °C or not.

Figure 10 shows the P2 peak temperature at different frequencies for the six particle sizes. When the frequency increases, the peak temperature moves to a higher level and the damping value tan ϕ peak height decreases.

The activation energy of grain boundary relaxation at peak P2 was calculated by Arrhenius [21] formula, in which the Arrhenius relation is \( \tau^{-1} = \tau_0 e^{-H/kT} \). Among the factors of relation, \( \tau_0 \) is the frequency factor, H is the activation energy, and K is Boltzmann constant [22]. The peak temperature is \( T_p \) and the frequency is introduced. When the peak temperature was \( T_p \), \( \omega^2 = 1 \), introducing \( f \) then attaining \( \omega = 2\pi f \).

\[
\ln(2\pi f) = -\ln \tau_0 - \frac{H}{k}(1/T_p)
\]

Figure 11 is the \( \ln(2\pi f) - 1/T_p \) diagram. It can be seen from the figure that \( \ln(2\pi f) - 1/T_p \) fits the linear relationship properly, and the slope of the line is \( H/k \). Thus, the grain boundary activation energy is shown in table 2, which shows that GBS exists in the damping mechanism when the temperature is higher than 250 °C.
Based on figure 11 and table 2, what can be seen is that the existence of the lower high-temperature activation energy means a lower energy barrier to be overcome. Under the same circumstance, the dislocation movement is easier and starts earlier; thus, the material has a higher damping upper limit [23].

The emergence of P2 damping peak is owing to the fact that the substrate ZK60 begins to soften with an increase in temperature, and the dislocation is detached from the strong pinning point. The decrease in CRSS required for crystal plane slip triggers non-basal plane slip. With the dislocation entanglements being reduced, the movable dislocation density is increasing, and the internal friction is increasing as well [24]. Non-basal plane slip and grain boundary slip occur as the temperature rises, and the lower the activation energy of the grain boundary. The earlier the grain boundary slip is involved, the better the damping performance [25]. At approximately 300 °C, the grain boundary slip of composites is limited, and the damping performance at high temperatures is improved owing to interface slip intervention. Among them, nanodiamond magnesium matrix composites with 0.04 μm particle size have the best damping performance, the earliest GBS intervention time and the lowest grain boundary relaxation activation energy; thus, the damping internal friction peak is the highest.

The P1 peak is not as obvious as the P2 peak. On the one hand, because the composite material is refined by the second-phase MgZn2 and ND-enhanced phase, the grains are smaller and the grain has more boundaries, which improves the strength but inhibits the dislocation movement and reduces internal friction. However, owing to the limited slip system of a-dislocations, the internal friction is limited successively. The activation of non-base plane slip and the involvement of grain boundary damping eminently increase the internal friction, and this process is related to the change of temperature.

### 3.4. Effect of nanodiamond particle sizes on damping properties

Both wrought magnesium alloy and as-cast magnesium alloy exhibit high damping at room temperature. Table 3 shows the damping values of some metals and alloys at room temperature. A damping value of 0.01 is the threshold of high damping [26].

Figure 12 shows the damping values tan ϕ of six ND/ZK60 magnesium matrix composites with different particle sizes at different frequencies under the room temperature conditions, where f is the frequency, Hz is the dimension, d is the particle diameter and dimension (μm). As can be seen from the table, the average damping value of room temperature is 0.04 μm ND/ZK60, which reaches 0.031; the lowest is 0.025 μm ND/ZK60, which reaches 0.022. 0.04 μm is 141% of 0.025 μm, while 0.1 μm declines greatly with an average of 0.025 μm tan ϕ being basically flat, and the damping value of other particle sizes tan ϕ decreases with an increase in the nanodiamond particle size.

At room temperature (0.5 Hz) the tan ϕ of the 0.025 μm composite is the lowest, while 0.04 μm composite is the highest, reaching to 2.45 × 10^{-2}, which is 156% of the 0.025 μm composite. With an increase in frequency, the internal friction increases at room temperature, such as 0.1 μm with poor damping performance, and tan ϕ also improves by 79.4%. Apart from this, the damping and mechanical properties of 0.025 μm were poor. On the basis of the SEM figure, what can be concluded is that the main reason is that the content of MgO in the composite material is higher than that of the second one, and the 0.025 μm diamond cannot effectively nail dislocation. Hence, the damping property at room temperature is low. Judged from figure 4(c), there are more MgO precipitates in 0.1 μm than the second precipitates. Combined with the influence of its mechanical properties, work hardening may occur, which increases the strength at the expense of damping performance.

Figure 13 shows the temperature damping curves of nanodiamond magnesium matrix composites with different particle sizes. The abscissa is temperature, the ordinate is Q^{-1} = η = tan ϕ, f = 0.5 Hz, 1 Hz, 5 Hz, 10 Hz. The unit of particle size is μm.

### Table 2. Grain boundary energy of different particle diameter of nano-diamond.

| Particle size (μm) | 0.025 | 0.04 | 0.1 | 0.2 | 0.25 | 0.5 |
|-------------------|-------|------|-----|-----|------|-----|
| Grain boundary energy (eV) | 5.4 eV | 3.79 eV | 5.16 eV | 4.99 eV | 5.25 eV | 5.17 eV |

### Table 3. Damping classes for metals and alloys.

| Level of damping | S.D.C(%) | Q^{-1} (10^{-3}) | Metal and alloy               |
|------------------|----------|------------------|-------------------------------|
| Middle level     | 3.5      | 5.6              | Pure Al, Cu                  |
| High level       | 50       | 79.6             | Deformed pure Mg, Mg alloy    |
|                  | 60       | 95.50            | Cast pure Mg, Mg alloy KIXI-F |

**Figure 11** and **table 2**, what can be concluded is that the main reason is that the content of MgO in the composite material is higher than that of the second one, and the 0.025 μm diamond cannot effectively nail dislocation. Hence, the damping property at room temperature is low. Judged from figure 4(c), there are more MgO precipitates in 0.1 μm than the second precipitates. Combined with the influence of its mechanical properties, work hardening may occur, which increases the strength at the expense of damping performance.

**Figure 13**. shows the temperature damping curves of nanodiamond magnesium matrix composites with different particle sizes. The abscissa is temperature, the ordinate is Q^{-1} = η = tan ϕ, f = 0.5 Hz, 1 Hz, 5 Hz, 10 Hz. The unit of particle size is μm.
Taking figure 13(c) as an example, the frequency is 5 Hz, at approximately 325 °C, 0.04 μm tanφ = 1.4 × 10^{-4}, while the damping value of 0.25, 0.5, 0.2 μm magnesium matrix composite is approximately 1.31 × 10^{-1}. At this temperature, 0.1 and 0.025 μm tanφ has started to decrease to about 0.1, while the damping value tanφ of other particle sizes is still increasing when the temperature is higher than 325 °C.

Based on tanφ comparison of the four frequencies, the laws of the overall curve are: the higher the frequency is, the greater the curve distortion is; despite the damping advantage of 0.04 μm in gradual loss, the overall curve will continue to grow at high temperatures. Taking 0.2 μm ND/ZK60 as an example, P2 peak damping value tanφ (0.5 Hz) = 0.172, tanφ (1 Hz) = 0.142, tanφ (5 Hz) = 0.121, tanφ (10 Hz) = 0.105, with decreases of
17.4%, 14.7% and 13.2% respectively. When the vibration frequency reaches 5 Hz or 10 Hz, the damping value $\tan\phi$ decreases by approximately 300 °C and then gradually rises. The reason is that when the frequency is high, dislocation motion and point defects cannot keep up with the vibration frequency, and the inverse relationship between frequency and damping value is presented. Whereas, when the temperature exceeds 300 °C, growth continues because the diamond has a high melting point and thermal stability, and the melting point of ZK60 relative to that of diamond becomes much lower with the coefficient of thermal expansion varying greatly [10, 23, 27]. It will form a high density movable dislocation. As temperatures rise, softening matrix, and the two had relatively strong interface binding force began to decline, the grain boundary around the interface is distorted and the relative slip loss is higher at the incoherent interface. When an external fixed load is applied, the internal friction will increase significantly, thus improving the damping performance of ND/ZK60 [23, 28].

Different orientations of nanodiamond in composites principally influence the interface relations, internal stress of the matrix and distribution of pinning materials [29]. The interface formed by diamond is anisotropic, and the orientation of the diamond is evidently distinct from that of the matrix under an applied load. Damper vibration, stress points to produce stress concentration, the higher frequency is, the more serious stress concentration phenomenon will be. When the temperature rises, the nanodiamond interface and the second-phase MgZn$_2$ interface softening [30], stress relaxation occurs around the point and slippage occurs as well, thus increasing internal friction. Because the MgZn$_2$ interface is semi-coherent with the matrix, the effect of increasing the slip rate is not as good as that of the non-coherent interface of nanodiamond. For the particle size of 0.04 $\mu$m, the second phase and nanodiamond mainly have better grain refinement and maintain higher strength. When temperature is above 200 °C, it is more effective for dislocation pinning, grain boundary slip intervention occurs sooner, and interface slip promotes greater damping capacity. The reason for the rapid decline of 0.025 $\mu$m and 0.1 $\mu$m above 300 °C is that the magnesium alloy relies on dislocation as the source of internal friction. Under the action of temperature and strain, a maximum value of damping internal friction is achieved, and then the index decreases with an increase in temperature or strain [27]. As the temperature continued to increase, it forms a negative correlation with interface binding force. At this point, the binding force becomes increasingly smaller, and the slip amount reaches the maximum. The sliding friction force to be overcome for the same slip amount becomes smaller and smaller, and the internal friction becomes smaller and smaller. At the same time, atoms are rearranged at high temperature, the dislocation density is greatly reduced, and the dislocation damping is weakened; thus, the damping value drops rapidly [28, 31].

4. Conclusion

In this experiment, what has been investigated is the effect of nanodiamond particles on the damping properties of magnesium matrix composites. The main conclusions are summarized as the follows.

(1) The damping performance of the ND/ZK60 composites was related to the size and distribution of the reinforcement phase. Reinforcement-phase nanodiamond (ND) can improve the mechanical properties of the composites. At room temperature, nanodiamond can pin dislocation lines, hinder dislocation movement and reduce the damping performance. The disparities in the thermal expansion coefficient and melting point between the reinforced phase and the matrix in high-temperature environment results in thermal mismatch of residual stress at the interface, causing plastic rheology at the interface and a significant increase in interface slip. A non-coherent interface is formed between the nanodiamond and matrix, which exceedingly improves the damping performance at high temperatures. In addition, a suitable nanodiamond particle size can enhance the mechanical properties and damping properties simultaneously.

(2) ND/ZK60 composites have a strong dependence on temperature, and the main mechanisms are dislocation damping, grain boundary damping and interface damping, which can interact with each other. At approximately 100 °C, it mainly depends on the occurrence of the basal plane slip and non-basal plane slip with the increase in temperature. At approximately 300 °C, grain boundary slip occurs, and the lower the activation energy of the grain boundary. The earlier the grain boundary slip is involved, the better is the damping performance. Above 350 °C, the grain boundary slip is limited, and the interface slip causes a continuous increase in the damping performance at high temperatures. The activation energy of the 0.04 $\mu$m is 3.79 eV.

(3) Because flocculent MgO hinders dislocation expansion, and the dislocation damping mechanism gradually weakens when the dislocation internal friction reaches maximum value at high temperature and stress loading, the particle sizes of the ND/ZK60 composite materials (0.025 $\mu$m and 0.1 $\mu$m) decreased significantly after reaching the P$_2$ internal friction peak. After the matrix being softened, the interfacial
bonding force will be weakened and the internal friction of interfacial slip will decrease sharply because MgO was difficult to intervene, and interfacial slip was the main mechanism.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Data access statement

Any data that support the findings of this study are included within the article.

Conflict of interest statement

The authors have declared that no competing interests exist.

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