Simultaneously enhanced mechanical and damping properties of Mg–Zn–Y alloys reinforced with LPSO phase

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Abstract. The microstructure, mechanical properties and damping capacities of Mg-Zn-Y alloys were investigated and compared systematically. The results showed that strength and damping of the alloy were increasing markedly with the increase of the volume fraction of long period stacking ordered (LPSO) phase (8%, 16%, 32%, 64%, respectively) on the whole. The corporate effect of LPSO phase and solid solution atoms was beneficial to the strengths. The Mg-1.36Zn-2.28Y can be classified as high damping metals (Q<sub>1</sub> ≧ 0.01) at strain amplitudes surpassing 1×10<sup>-3</sup>. With increasing of the LPSO phase, the critical strain amplitudes of alloys gradually decreased so that alloys can break away from pinning points more easily, thus, achieving a more superior damping performance. In addition, the strain amplitude-independent damping and strain amplitude-dependent damping of the Mg–Zn–Y alloys both increased. The damping capacities of the alloys cannot be explained by the Granato–Lücke theory exclusively.

1. Introduction
Magnesium alloys with low density, high strength, anti-dynamic impact load capacity, electromagnetic radiation shielding ability are widely used in aerospace, rail and 3C products [1-4]. However, with the rapid development of modern society, more and more sophisticated equipments, complex and diverse work environment, putting forward more urgent requirements for reducing energy consumption, vibration and noise. Thus, developing the lightweight and structure-function integration alloy (High-strength and high-damping alloy) will be the focus. However, the current research and development of structure-function integration magnesium alloy is very scarce. Most of the research are aimed at the mechanics or single function characteristics of magnesium alloys [5,6], because it is not easy obtain an alloy with good mechanical property and high damping capacity simultaneously. For instance, merchant high-strength Mg alloys, currently represented by the AZ and ZK series, do not have excellent damping capacities [7-10], and the high-damping Mg–Zr alloy does not have enough strength for engineering applications [11].

Fortunately, in our previous work, it was found that the damping and strength of the alloy at low strain gradually increased after the introduction of LPSO phase into the Mg-Cu-Mn-Zn-Y alloy [12]. This provides a new way for preparing high strength and high damping alloys. Simultaneously, study have been reported that Mg-Zn-Y alloy, producing by rapid solidification of powder metallurgy, has a very superior mechanical property [13]. Therefore, introducing the LPSO phase into the Mg-Zn-Y alloy is possible to prepare a structural-functional alloy with superior strength and damping property.

In this paper, the effect of LPSO structure on the mechanical property and damping capacity are expected to be researched by introducing LPSO phase into a new Mg-Zn-Y alloy. The LPSO structure is obtained by adding Zn and Y in the same atomic proportions into the alloys. The microstructure, mechanical property and damping capacity of these alloys are discussed and compared synthetically.
The present investigation hopes to contribute to the lightweight material designs of magnesium alloy for anti-vibration and noise-reduction applications.

2. Experimental procedure

The materials used in this study were the as-cast Mg–Zn–Y magnesium alloys with varying Zn and Y contents. The chemical compositions of these alloys were determined by X-ray fluorescence (XRF) and are listed in Table 1. Mg-Zn-Y alloys were prepared by melting ultra-high purity Mg, pure Zn and Mg-30wt.%Y master alloy in an electric resistance furnace. All these master alloys were kept at 750°C for an hour, and then the impurities in it were removed. After maintained for 30 minutes, the metal solution was poured in a mould, which were pre-heated at 300°C for 2 hours. In order to prevent the oxidation, a larger flow of gas was used in the above process.

The phase compositions were by measured by a Rigaku D/MAX2500PC X-ray diffractometer (XRD) with a copper target at a 10–90˚ scanning angle and 1.5˚/min scanning speed. Microstructure of the specimens was measured by using an Olympus optical microscope and a TESCAN VEGA 3 LMH scanning electron microscope (SEM) equipped with EDS (energy dispersive X-ray spectrometry). Tensile testing was carried out on a Shimadzu CMT-5105 material tester at a stretching rate of 1mm/min at room temperature. Damping capacity was determined by loss tangent $Q^{-1} = \tan \phi$, which $\phi$ is the lag angle between the applied strain and the response stress. The damping capacity was tested on an internal consumption meter MFP-1000 in a torsion mode. The machined dimension of the damping test specimen was 35 mm ×Φ2 mm using an electric spark cutter. Measurements were made at strain amplitudes ($\varepsilon$) ranging from $1 \times 10^{-5}$ to $2 \times 10^{-3}$ at room temperature with a vibration frequency (f) of 1 Hz to determine the strain-dependent damping capacity.

Table 1. Chemical composition and LPSO phase volume fraction of the as-cast Mg–Zn–Y alloys

| Nominal Alloys | Chemical Composition (wt%) | Y/Zn Ratio | Volume Fraction of LPSO Phase (%) |
|---------------|---------------------------|------------|----------------------------------|
| Alloy 1       | Bal. 1.36 Zn 2.28 Y 3/2   |            | 8                                |
| Alloy 2       | Bal. 2.35 Zn 5.08 Y 3/2   |            | 16                               |
| Alloy 3       | Bal. 4.23 Zn 8.31 Y 3/2   |            | 32                               |
| Alloy 4       | Bal. 8.37 Zn 18.13 Y 3/2  |            | 64                               |

3. Results and discussion

3.1. Microstructure of the As-cast Mg-Zn-Y alloys

Figure 1. Microstructures of the as-cast Mg-Zn-Y alloys: (a) Alloy 1; (b) Alloy 2; (c) Alloy 3; (d) Alloy 4.

Figure 2. XRD patterns of as-cast Mg-Zn-Y alloys.

Figure 1 shows the OM images of the microstructures of the as-cast Mg-Zn-Y alloys. The microstructures of these as-cast Mg-Zn-Y alloys are very variable. With the increase of alloying
elements, dendrites gradually refined, small equiaxed crystal appeared, phases gradually increased, and finally a large number of strip second phase. During this period, great amount of white particulates appear at the grain boundaries, especially in the alloy 4.

In order to reveal the phase ingredient, the crystallographic analysis was carried out by the XRD. Figure 2 shows the XRD patterns of the studied alloys. It is observed from Fig. 2 that all the experimental alloys are mainly composed of α-Mg and Mg₁₂YZn phases, which is well coincided with the previous results reported by Wang et al.[14]. It implies that the second phase is entirely a LPSO phase with increasing content of Zn and Y elements.

![Figure 2. XRD patterns of the studied alloys.](image)

Table 2. EDS results of the compositions

| Points | Composition(at.%) |
|--------|------------------|
|        | Mg   | Zn | Y   |
| A      | 98.99 | -- | 1.01 |
| B      | 88.20 | 5.49 | 6.31 |
| C      | 16.60 | 2.47 | 80.93 |

Figure 3 illustrates the SEM microstructure of the as-cast Mg–Zn–Y alloys. These alloys exhibit a typical dendrite microstructure, which mainly comprise α-Mg dendrites and intermetallic compounds precipitating along the grain boundary. With the increase of Zn and Y contents, the overall morphologies changed greatly. The white areas gradually increased, the black areas decreased gradually, and the small white-bright particles distributed in the magnesium matrix increased by degrees. At the same time, the morphology of the alloys also has undergone great changes. In Fig. 3 (a), the white phase is less dispersed and distributed on the grain boundaries of the dendrites. When comes to Fig. 3 (b) and Fig. 3 (c), the white phase is connected into a piece of mesh, which is distributed throughout the region. And the entire organization is divided into continuous white mesh and black island-like region or chicken claw-like region. Surprisingly, an elongated strip organization is found in the local white phase. As shown in Fig. 3 (d), with the further increase of Zn and Y, the white phase of the alloy occupies in most of the region, the black phase is divided into small pieces, and dispersed in the entire organization. Similarly, elongated strips or rod-like structures distributed in different directions are also found in the white phase. According to the principle of scanning backscattering, the larger the atomic coefficient is, the higher the brightness is. Therefore, it can be deduced that the white areas in the figures are mainly composed of Zn and Y elements with relatively large atomic coefficients, and they are likely to be Mg₁₂YZn phase. Those black or dark colors region, which may mainly consist of Mg elements, are likely to be α-Mg phase.

In order to verify the above inference, we carried out EDS energy spectrum analysis of the alloy 4, and the EDS results of the compositions of the corresponding positions in Fig. 2 are shown in Table 2. It can be concluded that almost all the Zn and Y atoms are concentrated on the precipitates, no Zn element was found in the magnesium matrix. 98.99% Mg atoms and 1.01% Y atoms were found in point A, this implies that the black area is α-Mg matrix, in which a small amount of Y atoms are dissolved. Mg, Zn and Y three elements are found in point B, and the atom ratio of Y to Zn is 6.31/5.49=1.15, which is very close to the Y/Zn atom ratio in the Mg₁₂YZn LPSO. Obviously, it can
be concluded that the second phase is the Mg12YZn LPSO phase. This means that the gray phase with continuous network distribution is the LPSO phase. And there are also Mg, Zn and Y three elements in point C, and the contents of Mg, Zn and Y atoms are 16.60%, 2.47%, 80.93%, respectively. Where Y atom is much more than Mg and Zn, which is likely to be the Y atoms enriched in the magnesium and LPSO phases. In short, these are consistent with the results of XRD, where the phase compositions in alloy 4 are identified as α-Mg and LPSO-phase.

3.2. Mechanical properties of the As-cast Mg-Zn-Y alloys

![Figure 4](image-url)  
**Figure 4.** Tensile stress-strain curves of as-cast Mg-Zn-Y alloys.

![Figure 5](image-url)  
**Figure 5.** Relationship between the UTS and the volume fraction of LPSO phase.

| Table 3. Mechanical properties of as-cast Mg-Zn-Y alloys |
|---|---|---|---|
| Alloy No. | UTS/MPa | YS/MPa | Elongation/% |
| 1 | 113 | 51 | 5.4 |
| 2 | 117 | 53 | 2.8 |
| 3 | 130 | 60 | 2.1 |
| 4 | 143 | 48 | 1.4 |

Figure 4 illustrates the stress-strain curves of the as-cast Mg-Zn-Y alloys. And the values of the mechanical properties are listed in Table 3, relationship between the UTS and the volume fraction of LPSO phase are shown in Fig. 5. As a whole, the LPSO phase is beneficial to the improvement of the strength of the alloy, but not to the improvement of the elongation. It can be seen that the ultimate tensile strengths (UTS, σ0) range from 113MPa to 143MPa, and the yield tensile strengths (YTS, σy) vary between 48MPa and 60MPa. Alloy 1 showed the most excellent plasticity, but worst in tensile strength, while alloy 4 is just the opposite.

As we all know, the strength of alloy is often affected by the secondary phase, solid atoms, grain size and texture. As we mentioned above, we found that the grain size changed little, and new phase is not discovered. Since the alloy is obtained by a conventional manufacturing method, so no significant texture is produced. At the same time, the EDS results show that the alloy contains only a small amount of solid solution atoms (Zn and Y), so the second phase enhancement will be the main factor. The precipitation strengthening effect of LPSO phase is conducive to the improvement of strength. However, as the content of LPSO phase increases, the elongation of the alloys decline gradually. This may because while the LPSO phase acts as a strengthening phase to enhance the alloy strength, its reticular formation around the grain boundary is not conducive to the plastic deformation of the alloy. Thus not easy to coordinate the plastic deformation between the grain and the second phase, but easily lead to uneven stress distribution and local stress concentration, resulting in brittle fracture material, which exacerbated the plasticity.

3.3. Damping capacities of the As-cast Mg-Zn-Y alloys

The strain amplitude dependence of damping capacities at 1 Hz and room temperature of as-cast Mg-Zn-Y alloys are shown in Fig. 6. As we can see, the strain amplitude increases from 1×10^{-3} to 2×10^{-3}. It is obvious that, from the whole graph, the damping capacity of the alloys increase with the
strain amplitude. It can be seen that in the small strain amplitude, the damping capacity value of every sample is small and varies little with the strain amplitude. While the strain attains a certain critical value, the damping capacity initiates to increase rapidly with the increase of strain amplitude. Obviously, there is a close relationship between the size of the final damping value and the critical strain amplitude (Which is mainly determined by the binding energy between the dislocation and the solute atoms, which should relate to the solute concentration [11]).

![Figure 6. Damping-strain amplitude curves of Mg-Zn-Y alloys.](image)

By calculating the average strain amplitude value at the inflection point of the curve, the corresponding critical strain amplitude of alloys are $9.58 \times 10^{-4}$, $7.57 \times 10^{-4}$, $3.7 \times 10^{-4}$, $3.43 \times 10^{-4}$, respectively. As shown in Fig.7(a), with the increasing content of the LPSO phase, the critical strain amplitudes of alloys gradually decrease so that alloy can break away pinning points easier, having more time to perform high energy dissipation, therefore, it will tend to show higher damping properties at high strain amplitudes. Figure.7(b) shows the relationship between the damping capacities and LPSO content of the alloys under high strain amplitude ($\varepsilon=10^{-3}$) and low strain amplitude ($\varepsilon=10^{-4}$), respectively. We find that the damping properties at the low and high strain amplitudes have the same trend. That is, with the increase of the content of LPSO phase, the growth rate at low strain is lower than that of high strain. Low strain amplitude damping capacity increased from 0.0045 to 0.0054, an increase of 20%; while high strain amplitude damping capacity increased from 0.01 to 0.047, an increase of 370%.

In general, the damping values of the four alloys are almost the same at low strain amplitudes, but the alloys with more LPSO phase have lower critical strain amplitude, which may lead to more time for energy dissipation. As a result, exhibits more excellent damping performance at high strain amplitude. Obviously, we can conclude that LPSO phase has a great effect on the damping properties of the alloys. However, it is not clear that why these alloys has such excellent damping property.
The classic “Granato–Lücke” theory is widely used to decipher the dislocation damping mechanism of Mg and its alloys[9,15–17]. However, some papers have pointed out that the alloy containing LPSO phase does not meet the G-L dislocation theory [12,18]. This means that the high damping properties of these alloys do not originate from dislocation motion, there may be other damping mechanism. As we know, this alloy just contain LPSO phase and Mg matrix. Owing to their different thermal expansion coefficients, they may reduce the amount of entangled dislocations in the alloy during the solidification. Meanwhile, there is a large difference between the hardness of the two (nearly 100HV [19]), resulting in a great friction between the two factors, thus, consuming more energy and exhibiting a high damping performance. These deductions can well explain that the damping capacity increases with LPSO phase. Therefore, this new mechanism may provide a new way to prepare high-damping alloy, but further studies will need to provide more sufficient evidence. As mentioned above, the alloy containing more LPSO phase also has a good mechanical property, so it may provide a new idea for the preparation of structural and functional integration materials.

4. Conclusions
(1) The main phase composition for these 4 alloys consist of α-Mg and LPSO phase. With the increase of LPSO phase, grain size refined and its morphology also undergone a very big change.

(2) With the increase of LPSO phase, the critical strain amplitudes of alloys gradually decrease so that alloys can separate pinning points easier, behaving better in both low strain amplitude level and high strain amplitude level. The LPSO phase is conducive to damping capacities on the whole.

(3) Both the damping capacities and mechanical properties increase with the content of LPSO phase at the same time, which breaks the contradiction that they cannot be simultaneously improved.

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