Effect of Zn Content and Solution Treatment on Damping Capacities of Mg–Zn Casting Alloys

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The effects of Zn content and solution treatment on the damping capacities of Mg–(0–6)%Zn casting alloys were investigated. In the as-cast state, increasing Zn content led to an increase in the volume fraction of the MgZn phase, and to the deterioration of the damping levels, both in the strain-amplitude-independent and strain-amplitude-dependent regions. The microstructural evaluation indicated that the increased Zn concentration in the α-(Mg) matrix and increased number of MgZn particles are responsible for the deterioration of the damping in the strain-amplitude-independent and strain-amplitude-dependent regions, respectively. The solution-treated Mg–6%Zn alloy exhibited better strain-amplitude-dependent damping than the as-cast one, but the tendency was reversed in the strain-amplitude-independent region. The dissolution of the MgZn phase and the correspondingly increased Zn concentration in the α-(Mg) matrix after the solution treatment can explain the reversed damping behaviors in the strain-amplitude-dependent and strain-amplitude-independent regions, respectively.

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1. Introduction

In recent years, Mg and its alloys have attracted increasing attention due to their potential as biodegradable implant materials for load-bearing orthopedic applications.1–3) Mg is a non-toxic element and essential to the human metabolism,4) and compared with other metallic biomaterials, it has lower density (1.74 g/cm³) and compared with other metallic biomaterials, it has lower density (1.74 g/cm³) and mechanical properties (elastic modulus, compressive yield strength and fracture toughness) that are more similar to those of natural bone.5) However, most of Mg alloys are susceptible to corrosion, especially in the physiological important PH region of 7.4–7.6 and high chloride environment.5)

Zn is a essential nutritional element for human beings and shows appropriate non-toxicity for biomedical applications unlike Al and RE (rare earth).2,7) When Mg is alloyed with Zn, its corrosion resistance and strength are improved. Cai et al.8) investigated the tensile properties and corrosion behavior of Mg–(0–7)%Zn binary alloys and reported that the best combination of mechanical and anti-corrosion properties is realized with 5%Zn alloy in the as-cast state. They also suggested that the Zn content should be precisely controlled to promote both the mechanical properties and corrosion resistance of Mg alloys for biomedical applications. Moreover, heat treatment can also affect the corrosion resistance of Mg–Zn alloys. Song et al.9) investigated the effect of heat treatment on corrosion behavior of Mg–5%Zn alloy and reported that the solution-treated (T4) sample without secondary phases showed the best corrosion resistance whereas the aging-treated (T6) one with the largest volume fraction of secondary phases had the weakest resistance. Among the fundamental properties of Mg alloys to be used as biodegradable implant materials, corrosion resistance is undoubtedly the principal factor influencing their practical application, but to suppress bone damage before biodegradation by reducing vibrations and maintaining the mechanical integrity during the healing process, the damping capacity should also be regarded as a significant parameter to assess their suitability for fabricating biomedical devices. In spite of numerous studies8–12) on the mechanical properties and corrosion behaviors of Mg–Zn-based alloys, little information is available on their damping capacities with respect to Zn content and heat treatment. The present work reports on the influences of Zn content and solution treatment on the damping capacities of Mg–(0–6)%Zn alloys.

2. Experimental

Mg–Zn binary alloys having 2, 4, and 6% of Zn (mass%) were prepared by melting 99.9% pure Mg and 99.99% Zn under (SF₆ + CO₂) protective gas environment and casting them into a steel mold. Pure Mg was also considered as a reference material. The chemical compositions of the experimental alloys were determined by inductively coupled plasma (ICP) analysis, and the results are listed in Table 1. From the ingots, various specimens for microstructural characterization and damping measurements were prepared by machining. Some of the Mg–6%Zn specimens were solution-treated at 420°C for 24 h, followed by water quenching at room temperature. The damping capacities were measured at room temperature by using a dynamic mechanical analyzer (DMA, TA Q-800) in the strain-amplitude range of 1 × 10⁻⁶ to 2 × 10⁻³, vibrating in a single cantilever mode (frequency: 1 Hz). The dimensions of the damping test specimens were 35 × 12 × 1.5 mm³.

<table>
<thead>
<tr>
<th>Composition</th>
<th>Zn (%)</th>
<th>Fe (%)</th>
<th>Ni (%)</th>
<th>Mg (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Mg</td>
<td>0.002</td>
<td>0.003</td>
<td>0.003</td>
<td>Bal.</td>
</tr>
<tr>
<td>Mg–2%Zn</td>
<td>1.9</td>
<td>0.003</td>
<td>0.006</td>
<td>Bal.</td>
</tr>
<tr>
<td>Mg–4%Zn</td>
<td>3.8</td>
<td>0.004</td>
<td>0.005</td>
<td>Bal.</td>
</tr>
<tr>
<td>Mg–6%Zn</td>
<td>5.9</td>
<td>0.003</td>
<td>0.005</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

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damping capacity was evaluated in terms of the loss tangent \((\tan \phi)\), where \(\phi\) is the phase-lag angle between applied strain and responding stress. The microstructures were characterized by means of scanning electron microscopy (SEM, FEI QUANTA-200F) including energy dispersive X-ray spectroscopy (EDS, AMETEK PV72-60030F) and X-ray diffraction (XRD, Bruker-AXS D8 Discover) using Cu-K\(\alpha\) radiation.

3. Results and Discussion

Low- and high-magnification SEM images of the Mg–(2–6)%Zn alloys are shown in Fig. 1. In the as-cast state, the Mg–Zn alloys consist of the dendritic primary \(\alpha\)-(Mg) matrix with Mg–Zn precipitates and Zn-rich areas along the dendritic cell boundaries. With increasing Zn content, the microstructure becomes finer, and the size and amount of the Mg–Zn precipitates increased. The XRD patterns of the Mg–(2–6)%Zn alloys (not shown in this article) indicated that the Mg–Zn precipitates are MgZn phase. It can be seen in Fig. 1 that the MgZn particles have divorced shape in the Mg–2%Zn alloy, whereas eutectic \((\alpha\)-(Mg) + MgZn) phases with lamellar morphologies are found in the alloys with Zn content above 4%. In a previous work, Lu et al.\(^{10}\) investigated the as-cast microstructure of the Mg–3%Zn alloy and reported that the eutectic particles in the microstructures are composed of \(\alpha\)-(Mg) and the MgZn intermetallic compound having a rhombohedral crystal structure with lattice constants of \(a = 2.6\,\text{nm}\) and \(c = 1.8\,\text{nm}\). The EDS analysis of the areas “A” in Fig. 1(d) and “B” in Fig. 1(f) indicates compositions of Mg\(_{51.3}\)Zn\(_{48.7}\) and Mg\(_{62.1}\)Zn\(_{37.9}\) (at%), respectively. The larger amount of Mg element in the eutectic particle can be ascribed to the Mg phase coexisting with the MgZn phase. The Zn concentration in the \(\alpha\)-(Mg) matrix and volume fraction of the MgZn phase in the Mg–(2–6)%Zn alloys, determined by EDS and image analysis, respectively, are plotted in Fig. 2. As the Zn content increases, the Zn concentration in the \(\alpha\)-(Mg) matrix and volume fraction of MgZn precipitates increase simultaneously.

Figure 3 shows the changes in damping capacity \((\tan \phi)\) with strain amplitude for pure Mg and Mg–(2–6)%Zn alloys; the inset shows a magnified view of the curves in the strain-amplitude-independent region below \(1 \times 10^{-5}\). The damping capacity in response to the variation of the strain amplitude can be divided into two regions: the strain-amplitude-independent damping at low strain and the strain-amplitude-dependent damping at higher strain. It is clear from Fig. 3 that all Mg–Zn alloys exhibit lower damping capacities than pure Mg does and that the damping capacity deteriorates with increasing Zn content. The changes in damping capacity with strain amplitude for the Mg–6%Zn alloy in the as-cast and solution-treated states are presented in Fig. 4. The complete dissolution of the MgZn phase after the solution treatment can be identified from the microstructure.
shown in the inset. It is obvious that the solution-treated alloy has a higher damping capacity in the strain-amplitude-dependent region above $10^{-3}$ than the as-cast alloy, but the reverse tendency is observed in the strain-amplitude-independent region.

The damping mechanism of Mg and its alloys can be explained by the Granato–Lücke (G–L) model. At small stress, dislocation loops pinned down by weak pinning points bow out and continue to do so until the breakaway stress is reached. This process can contribute to the strain-amplitude-independent damping ($\delta_o$). At the breakaway stress, a large increase in the dislocation strain occurs without further stress increase. The loss caused by dislocation segments pinned by strong pinning points produces strain-amplitude-dependent damping ($\delta_H$). $\delta_o$ arises from the loss caused by forced vibrations of dislocation segments pinned by weak pinning points, such as solute atoms, while $\delta_H$ results from the loss caused by dislocation segments pinned by strong pinning points, such as precipitates and aggregates. According to the G–L theory, the total damping capacity ($\delta$) can be described as follows:

$$\delta = \delta_o + \delta_H$$

$$\delta_o \sim \rho L d$$

$$\delta_H(\varepsilon) = (C_1 / \varepsilon) \exp(-C_2 / \varepsilon)$$

$$C_1 = (\rho F_B L_N^2)/(6b E L_d)$$

$$C_2 = F_B/(b E L_d)$$

where $\rho$ and $L_d$ are the dislocation density and average distance between weak pinning points, respectively, and $F_B$, $E$, $L_N$, and $b$ are the binding force between dislocations and weak pinning points, the elastic modulus, the average distance between strong pinning points, and the Burgers vector, respectively.

From eq. (2), $\delta_o$ depends largely on $L_d$. As the Zn content increases in the Mg–Zn alloys, the concentration of Zn solutes in the Mg matrix increases, as seen in Fig. 2, which eventually decreases the $L_d$ value. Therefore, the lower $\delta_o$ values at higher Zn content presented in Fig. 3 are readily explained by the lower $L_d$ values. Meanwhile, the lower $\delta_H$ values at higher Zn content can be interpreted as the result of the decreased $L_N$ values. The number density of the MgZn precipitates that act as strong pinning points for dislocations, plays a critical role in determining $\delta_H$ because the $C_1$ parameter is governed by $L_N$ according to eqs. (3) and (4). When the Mg–Zn alloy is solution-treated, the MgZn particles are dissolved and the Zn concentration in the Mg matrix increases. This eventually results in the increase in $L_N$ and decrease in $L_d$. Thus, the increased $\delta_H$ and decreased $\delta_o$ values of the solution-treated Mg–6%Zn alloy, compared to those of the as-cast sample shown in Fig. 4, can be readily explained by the higher $L_N$ and lower $L_d$ values, respectively.

Figure 5 shows the G–L plots of the as-cast Mg–(0–6)%Zn alloys and the solution-treated Mg–6%Zn alloy. The $\tan \phi$ values were converted to $\delta_H$ by using the relation $\delta = \pi \tan \phi$. A linear relationship is established between $\ln(\delta_H \times \varepsilon)$ and $1/\varepsilon$, demonstrating that the damping behavior of pure Mg and Mg–Zn alloys are closely related to the dislocation damping mechanism. In Fig. 5, $\ln(C_1)$ and $C_2$ are used to calculate $\delta_H$.
\( C_2 \) correspond to the Y-axis intercept and the slope, respectively, and the calculated \( C_1 \) and \( C_2 \) values are listed in Table 2. The \( C_1 \) value decreases with increasing Zn content in the as-cast state. Because the \( C_1 \) value is controlled by \( L_N \) and \( \delta_H \) is dependent on \( C_1 \), this result confirms that the increased number density of MgZn precipitates is responsible for the lower \( \delta_H \) value. In the case of \( C_2 \), its value increases with increasing Zn content. This explains the decreased \( L_d \) value, in accordance with eq. (4), and demonstrates that the increasing concentration of Zn solutes in the \( \alpha-(Mg) \) matrix contributes to the decrease in \( \delta_0 \) in the Mg–Zn alloys. When the Mg–6%Zn alloy is solution-treated, it has a remarkably higher \( C_1 \) value than the as-cast alloy. This result strongly supports the role of the number density of intermetallic particles for the \( \delta_H \) value. The \( C_2 \) value of the solution-treated specimen is also higher than that found in the as-cast state. This demonstrates that the increased Zn concentration after the solution treatment contributes to the further decrease in \( L_d \) and \( \delta_0 \).

### 4. Conclusion

The objective of this paper is to investigate the effects of Zn content and solution treatment on the damping capacities of Mg–(0–6)%Zn casting alloys. With increasing Zn content, the amount of MgZn compound particles increases, while the damping levels become lower, both in the strain-amplitude-dependent (high strain) and strain-amplitude-independent (low strain) regions. The microstructural evaluation indicates that the higher Zn concentration in the \( \alpha-(Mg) \) matrix and the increased number density of MgZn compound particles are responsible for the deterioration of the damping in the strain-amplitude-independent and strain-amplitude-dependent regions, respectively. After solution treatment, the Mg–6%Zn alloy exhibits better strain-amplitude-dependent damping but lower strain-amplitude-independent damping, compared to the as-cast alloy. This result can be explained by the dissolution of MgZn particles and the corresponding increased Zn concentration in the \( \alpha-(Mg) \) matrix.

### REFERENCES