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ARTICLE

Mechanical and Damping Properties of Porous Mg97Zn1Y2 Composites

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Abstract: Porous material is a new type of lightweight structure-functional material with high damping performance, low density, light weight, and other characteristics, making it useful in many applications. Mg97Zn1Y2 with long-period stacking ordered phase (LPSO phase) as a matrix, $MgCO_3$ as foaming agent and SiC as tackifier was used to prepare magnesium-based porous materials by melt-foaming method. The mechanical properties and damping properties of the porous Mg97Zn1Y2 were studied by OM, SEM, XRD and DMA technology. Results show that the porous Mg97Zn1Y2 composites are mainly composed of magnesium matrix (α-Mg), LPSO phase and SiC phase. When the strain amplitude is small, the damping value of porous Mg97Zn1Y2 composites is obviously better than that of Mg97Zn1Y2 alloy, and the damping properties are improved as porosity is increased. However, increased porosity decreases the compression properties of porous Mg97Zn1Y2 composites. In addition to the dislocation damping, interface damping, and grain boundary damping of the Mg97Zn1Y2 alloy, “gas phase” damping is found to affect the damping properties of the porous Mg97Zn1Y2 composites jointly.

Key words: porous materials; mechanical properties; damping properties; damping mechanism

With the continuous development of modern industry and transport frameworks, vibration and noise have emerged as major public hazards, critically endangering human health and machine operation. Therefore, it is of exigent significance to reduce vibration and noise and to enhance the man-machine working environment. In this context, magnesium alloy, which have excellent damping characteristics and low density, is a promising candidate material. In particular, the damping attenuation coefficient of pure magnesium is considerably higher than that of cast iron and aluminum alloys[1-4]. With the increasing demand for lightweight, high-strength, and high damping structural materials in the aviation, aerospace, construction, automobile, and other industries, magnesium alloy is likely to become a key development direction in the future. However, the dislocation damping mechanism of magnesium alloys leads to a certain tradeoff between mechanical and damping properties, which restricts the development and application of magnesium and magnesium alloys[5-8]. To satisfy the development requirements of the aerospace domain and modern industrial applications, the realization of novel high-damping materials is desirable[9].

Porous materials, which are novel lightweight structure-functional materials, have been developed based on traditional dense metals. Foam metals, such as iron, copper, aluminum and nickel foams have been successfully prepared[10-13]. Due to the large number of defects (macropores and microdefects) in porous materials[14], porous magnesium exhibits a higher damping performance than bulk magnesium alloy. In this study, magnesium-based porous composites were prepared using Mg97Zn1Y2 with a long period stacking ordered (LPSO) phase as the matrix, $MgCO_3$ as the foaming agent, and SiC as the tackifier. Furthermore, the mechanical and damping properties of the designed porous composites were examined.

1 Experiment

The starting materials were as follows. Matrix alloy was

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pure Mg (purity 99.99%), pure Zn (purity 99.9%), and Mg-Y (25wt% Y) master alloy; tackifier was SiC ceramic particles (purity 99.95%) that were ultrasonically cleaned via alcohol and dried in a drying oven at room temperature; foaming agent was $MgCO_3$ powder (purity 99.95%). In general, the principle of preparing porous materials by foaming $MgCO_3$ is as follows: when the temperature rises to a certain extent, $MgCO_3$ is heated and decomposes, and CO_2 gas overflows, through the following reaction:

$$MgCO_3(s) \rightarrow MgO(s) + CO_2(g)\uparrow \quad (1)$$

According to Ref.[15], when the temperature is lower than 450 °C, $MgCO_3$ does not decompose. When the temperature is between 450 and 580 °C, part of $MgCO_3$ decomposes. When the temperature is higher than 580 °C, the decomposition rate of $MgCO_3$ rapidly increases. When the temperature reaches approximately 700 °C, $MgCO_3$ is completely decomposed.

The porous Mg97Zn1Y2 composite was prepared through the melt foaming method, which is a simple process for preparing materials with high quality and large porous ratio[16-19]. The preparation of porous Mg97Zn1Y2 composites by the melt foaming method involves the following processes.

Melting and casting of porous composites: pure Mg, pure Zn and Mg-Y master alloys were weighed according to the designed alloy composition. Pure Mg was placed in a crucible preheated to 300~350 °C and inserted in the resistance furnace; the temperature was increased to 720 °C and maintained for 10~15 min to ensure that the pure Mg was completely melted, and the surface residue was removed. Subsequently, the Mg-Y master alloy was added, and the crucible was placed back in the furnace cavity to continue heating. The temperature was maintained at 720 °C for 10~15 min to ensure that the Mg-Y alloy was completely melted. Then, the slag was removed, pure Zn was added, and the crucible was placed back in the furnace and heated to 720 °C; this temperature was maintained for 10~15 min to ensure the complete melting of pure Zn. Subsequently, the surface residue was removed and the temperature was maintained for 5 min. The tackifier SiC (1wt%) was added, and the mechanical stirring paddle was simultaneously operated for 45 s at a stirring speed of 800 r/min. After stirring, the temperature was maintained at 720 °C for 2 min. Thereafter, the foaming agent $MgCO_3$ (1.2wt%, 1.5wt%, and 2.0wt%) was added, and the mechanical stirring paddle was simultaneously operated for 2 min at a stirring speed of 1000 r/min. The heat was preserved for 2 min under the power-on condition, the surface residue was removed, and the material was cast in the steel mold preheated to 200~300 °C.

Porosity refers to the ratio of the volume of pores in the material to the volume of the material in the natural state, usually expressed as a percentage. At the same time, porosity is also an important technical index to measure the quality and performance of porous material. The calculation formula of porosity is as follows:

$$\theta = \left(1 - \frac{M}{\rho_s V_T}\right) \times 100\% \quad (2)$$

where θ is porosity, M is mass of sample, ρ_s is density of dense solids in porous material (g/cm^3), and V_T is the apparent total volume of porous material (cm^3)

The mass of sample can be weighed by electronic balance, and the volume can be measured by drainage method. The whole process was operated at room temperature and relative humidity to ensure the accuracy of the measurement results.

2 Results and Discussion

2.1 Microstructure of porous Mg97Zn1Y2 composites

Fig.1 shows the microstructures of the porous Mg97Zn1Y2 composites. As shown in Fig. 2, with the increase in the content of foaming agent $MgCO_3$, the porosity and pore size increase. Changing the mass fraction of $MgCO_3$ mainly affects the amount of gas generated in the thermal insulation foaming process. When the content of $MgCO_3$ is low, less gas is generated by decomposition, the decomposition pressure is not enough to provide the power for bubble growth, the bubble structure is unstable, and some bubbles even disappear spontaneously. Finally, the porous Mg97Zn1Y2 composite has low porosity and small pore diameter. With the further increase of $MgCO_3$ content, the gas generated by decomposition increases, the pressure is large, and more bubbles grow. Therefore, the porosity and pore diameter of porous Mg97Zn1Y2 composites increase[20]. However, their distribution is not uniform because it is difficult to ensure the uniform distribution of CO_2 decomposed from $MgCO_3$. This phenomenon leads to an increase in the number voids in the sample, lack of bubble layer, and other defects, and the alloy structure far from the voids does not change significantly. Fig.3 shows the SEM image of porous Mg97Zn1Y2 composites.

2.2 Phase of porous Mg97Zn1Y2 composites

Fig. 4 shows the results of XRD analysis of the porous Mg97Zn1Y2 composites. The patterns indicate that the addition of the foaming agent and tackifier does not substantially change the phase composition of the Mg97Zn1Y2 alloy. The porous Mg97Zn1Y2 composite is mainly composed of α-Mg, the LPSO phase, and the tackifier SiC phase.

2.3 Mechanical properties of porous Mg97Zn1Y2 composites

The compressive stress-strain curves of the porous Mg97Zn1Y2 composites are shown in Fig. 5. It can be seen that the compressive strength of the composite decreases with the increase of porosity. The quasi-static stress-strain curves of foam magnesium mainly consist of three stages, namely, linear elastic stage, yielding platform stage and densification stage. At the beginning of compression, the stress is small, the stress-strain relationship is basically linear, and the deformation at this stage is small. When the stress is cancelled, the deformation can be restored without macro cracks. When the stress increases and reaches the yield strength of the foam magnesium, the stress increase becomes slower as the strain increases, and the stress-strain curve begins to increase slowly, and the curve enters the yield plateau area. At this stage, because of the stress concentration,

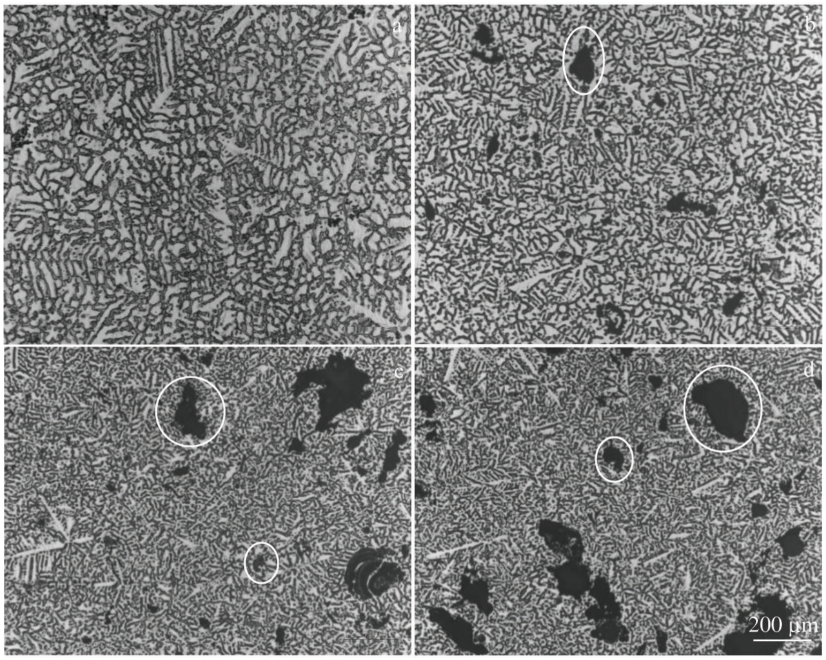

Fig.1 OM morphologies of porous Mg97Zn1Y2: (a) Mg97Zn1Y2, (b) $MgCO_3$-1.2wt%/Mg97Zn1Y2, (c) $MgCO_3$-2.0wt%/Mg97Zn1Y2, and (d) $MgCO_3$-2.5wt%/Mg97Zn1Y2 composites

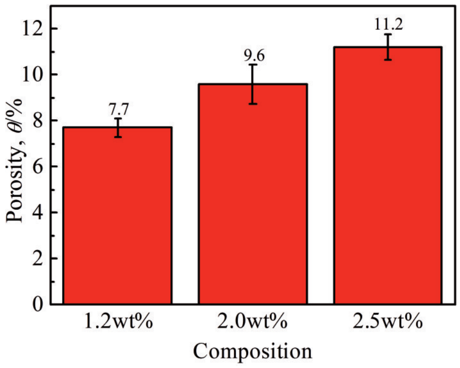

Fig.2 Variation of porosity for Mg97Zn1Y2 composites with foaming agent content of $MgCO_3$

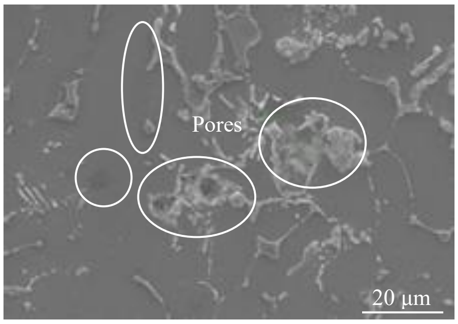

Fig.3 SEM image of porous Mg97Zn1Y2 composites

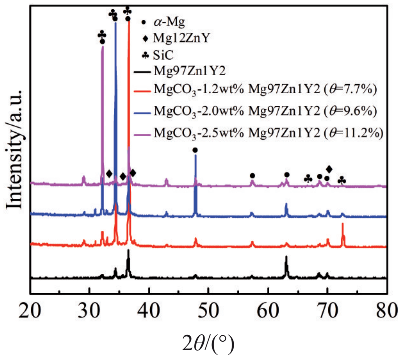

Fig.4 XRD patterns of porous Mg97Zn1Y2 composites

the internal defects of the composites lead to crack initiation. With the increase and expansion of cracks, the pore edge, pore wall, and other weak points undergo bending, tearing and fracture, and other forms of irreversible plastic deformation. This plastic deformation may lead to new defects in the open foam magnesium. In this scenario, a layer-by-layer collapse occurs and the pores are gradually compacted and the foam magnesium enters the densification stage[21,22]. The compressive properties of foam magnesium are affected by many factors, including relative density, average pore size, pore structure (shape or defect), test temperature and load type (static or dynamic). With the decrease of porosity, the relative density of foam magnesium decreases, and the Young's modulus, compressive strength and plateau stress of foam magnesium also decrease[23,24].

The fracture morphology of porous Mg97Zn1Y2 composites is shown in Fig. 6. It can be seen from the stress-strain curves that the porous composites are brittle fractures. Moreover, the compression fracture morphology indicates that with the increase in the $MgCO_3$ content, the fractures are evener and more clear. As shown in Fig. 6c, the fractures

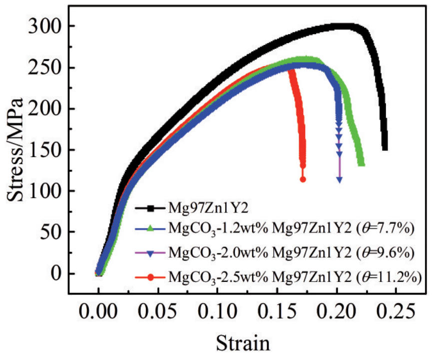

Fig.5 Compression stress-strain curves of porous Mg97Zn1Y2

exhibit a river-like pattern, corresponding to cleavage and brittle fracture.

2.4 Damping properties of porous Mg97Zn1Y2 composites

Magnesium and magnesium alloys are typical dislocation-type damping materials. The presence of many dislocations in the matrix is the main reason for the high-damping characteristics of these materials. The Granato-Lücke dislocation theory, referred to as the G-L model, is widely used to explain the mechanism of magnesium alloys[25,26]. The damping (Q^{-1})-strain amplitude curves of porous Mg97Zn1Y2 composites are shown in Fig. 7a. The trend of the curve is consistent, and the curve can be divided into two stages that are independent of and dependent on the damping strain amplitude. When the strain amplitude is small, the damping of the porous Mg97Zn1Y2 composites is considerably higher than that of the Mg97Zn1Y2 alloy, and the damping properties are enhanced with the increase in the porosity. As shown in Fig. 7b, when the strain amplitude is 4×10^{-4}, the highest damping value of the composite material is 0.017 22 when the porosity is 11.2%, corresponding to that of a high-damping material. When the strain amplitude is high, the interface begins to slip, the dislocation movement is hindered, and dislocation proliferation occurs, which enhances the damping performance. According to the phase analysis, LPSO and SiC phases remain in the matrix, the interface between LPSO phase and matrix is weak, and the interface exhibits relative micro-slip under the action of stress[27]. This phenomenon leads to the conversion of mechanical energy into other forms of energy, thereby increasing the damping. However, with the increase in the SiC particles, the interface between the SiC particles and matrix is strengthened, and the interface as a strong pinning point reduces the length of the dislocation lines between the adjacent strong pinning points. Therefore, the damping properties of the composite are slightly inferior to those of the Mg97Zn1Y2 alloy in the curve section with a strain amplitude dependence. In addition, with the increase in the porosity, Mg97Zn1Y2 alloy phase and attached oxide, the interface areas between the Mg97Zn1Y2 alloy phase and gas phase and attached oxide and gas phase are increased. In other words, the internal friction of interface sliding increases, and stress concentration is more likely to occur in the skeleton. The increase in the internal friction may increase the damping value. However, as the porosity continues to increase, the number of secondary phases in the matrix and interface between the precipitated phase and matrix decreases. When the porosity is 7.7%, the interface in the composite helps to enhance the damping properties. As the porosity continues to

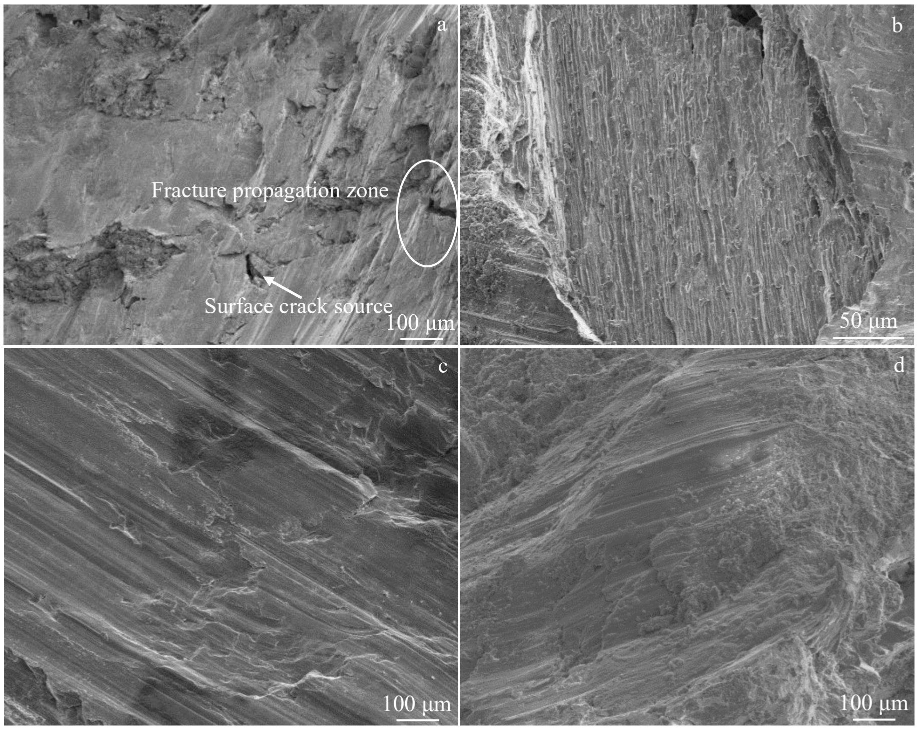

Fig.6 Fracture morphologies of porous Mg97Zn1Y2: (a) Mg97Zn1Y2, (b) MgCO$_3$-1.2wt%/Mg97Zn1Y2, (c) MgCO$_3$-2.0wt%/Mg97Zn1Y2, and (d) MgCO$_3$-2.5wt%/Mg97Zn1Y2

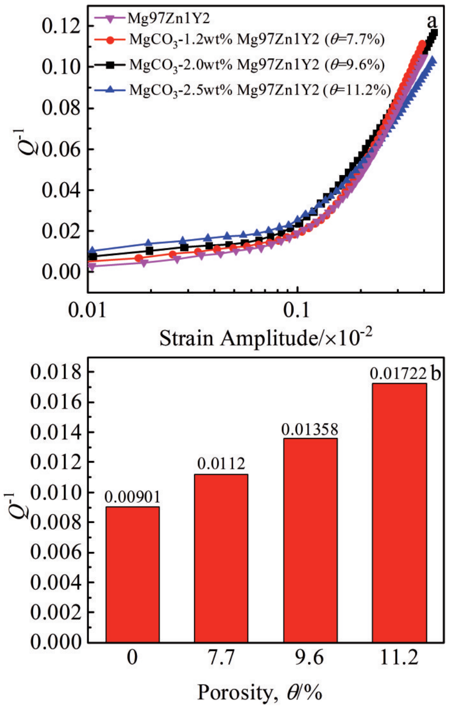

Fig.7 Variation of damping (Q^{-1}) with strain amplitude (a) and porosity (b) of porous Mg97Zn1Y2 composite

increase, the secondary phase in the matrix, interface between the precipitated phase and matrix, number of grain boundaries and damping properties deteriorate.

The microstructure of the porous Mg97Zn1Y2 alloy involves pores, which reduces the compactness and mechanical properties of the material. However, the damping properties of porous Mg97Zn1Y2 alloy are considerably enhanced[28]. Although pores exist in the Mg97Zn1Y2 alloy, the porosity is not extremely high due to the limitation of the preparation technology and equipment; therefore, intrinsic damping (Mg97Zn1Y2 alloy), interface damping, and grain boundary damping occur in the matrix. The damping properties are enhanced owing to the dislocation damping and gas phase damping as well as the presence of the SiC phase, LPSO phase, pore wall, and magnesium matrix. Notably, in addition to the abovementioned three damping mechanisms, gas phase damping occurs in the case of porous composites. The gas phase in the composite increases the interface area between the matrix and air and that between the oxide and matrix alloy. This phenomenon may cause slipping of the interface of the porous material under certain conditions, increase internal friction, and enhance damping properties. However, the increase in the interface area may disrupt the dislocations in the matrix, thereby reducing the number of dislocations, changing the morphology of the dislocations, reducing the mobility of the dislocations, and deteriorating the damping properties.

3 Conclusions

1) As the amount of foaming agent is increased, the porosity of Mg97Zn1Y2 increases. The porous Mg97Zn1Y2 composite is mainly composed of magnesium matrix (α-Mg), LPSO phase and SiC phase.

2) As the porosity increases, the compressive properties of porous Mg97Zn1Y2 composites significantly decrease, and a river-like pattern appears on the fracture surface due to cleavage fracture and brittle fracture.

3) When the strain amplitude is small, the damping value of the porous Mg97Zn1Y2 composite is significantly better than that of the Mg97Zn1Y2 alloy, and the damping properties are improved as the porosity increases. In addition to the dislocation damping, interface damping, and grain boundary damping of the Mg97Zn1Y2 alloy, “gas phase” damping is found to affect the damping properties of the porous Mg97Zn1Y2 composites jointly.

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多孔 Mg97Zn1Y2 材料的力学性能与阻尼性能

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摘　要：多孔材料是一种新型轻质的结构-功能材料，具有较高的阻尼性能，同时兼具密度小、质量轻等特点，使其具有广阔的应用价值。基于此，选取含有长周期特殊结构相（LPSO 相）的 Mg97Zn1Y2 为基体，以 $MgCO_3$ 为发泡剂，SiC 为增粘剂，通过熔体发泡法制备出镁基多孔材料，通过 OM、SEM、TEM、XRD 及 DMA 等技术手段，研究多孔 Mg97Zn1Y2 材料的力学性能、阻尼性能等。结果表明，多孔 Mg97Zn1Y2 材料主要由镁基体（*α*-Mg）、LPSO 相和 SiC 相组成，当应变幅值较小时，多孔 Mg97Zn1Y2 复合材料的阻尼值明显优于 Mg97Zn1Y2 合金，随着孔隙率的增加，阻尼性能得到改善。孔隙率的增加降低了多孔 Mg97Zn1Y2 复合材料的抗压缩性能。此外，除了 Mg97Zn1Y2 合金本身的位错阻尼、界面阻尼和晶界阻尼之外，还有“气相”阻尼，共同影响着多孔 Mg97Zn1Y2 材料的阻尼性能。

关键词：多孔材料；力学性能；阻尼性能；阻尼机制

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