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Mechanical properties and damping capacity of magnesium matrix composites

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Abstract

Magnesium matrix composites reinforced by TiC particulates was prepared using in situ synthesis method. The mechanical properties and damping capacity of the composites was examined. The experimental results revealed that the TiC particulates play an important role on mechanical properties and damping capacity of the composites. In our study, compared to AZ91 magnesium alloy, damping capacity and tensile strength of the composites improve. The mechanical characterization is explained with the strengthening mechanisms as grain size and Orowan bowing. The damping characterization is explained with dislocation motion, twinning, grain boundary slip and interface slip.

Keywords: A. Metal–matrix composites (MMCs); B. Mechanical properties; Physical properties

1. Introduction

The beginning of 1990s has marked the renaissance of magnesium as a structural material, the demand mainly coming from automotive industry owing to environmental concerns, increasing safety and comfort levels. Magnesium alloy can conform to the trend owing to its high specific strength and specific stiffness, good machining ability, high damping capacity and fine size stabilization [1,2]. However, magnesium alloys reach their limit at about 200 °C, above which magnesium matrix composites (Mg-MMCs) have to be developed. Particulate reinforced Mg-MMCs might actually achieve the above expectation. Zhang et al. [3] researched the mechanical properties and damping capacity of magnesium alloy composites. Their results confirmed that the elastic modulus increased largely, but the elongation decreased with the increase of the volume fraction of the reinforcements. Seshan et al. [4] synthesized two magnesium alloys reinforced with silicon carbide particulates. The results discovered that an increase in particulate reinforcement content was observed to decrease ultimate tensile strength and ductility of the composite. Among those studies, the MMCs were ex situ synthesized. Compared to ex situ synthesis technique, in situ synthesis method is a new technique to prepare metal matrix composites owing to many advantages, e.g., fine reinforcements, clean interface between matrix and reinforcement and good mechanical characterization [5,6]. The size of in situ reinforcements is smaller than that of the ex situ reinforcements, which may result some interesting effect of reinforcements on materials properties and damping capacity.

Remelting and dilution (RD) technique is one of in situ synthesis methods. RD technique consists of two steps, firstly, master alloy that contains reinforcements is prepared; secondly, master alloy is diluted into metal melt to

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synthesize metal matrix composites. In the present study, Mg-MMCs reinforced by TiC particulates were synthesized using RD technique. And the mechanical properties and damping capacity of Mg-MMCs were researched.

2. Experimental procedure

In our study, pure magnesium was used as the base materials, and aluminum, titanium and graphite powder (purity are up 99.5% and size are less than 75 μm) were used as the base materials of master alloy. The powder mixture consisting of 50 wt.%Al, 36.4 wt.%Ti and 13.6 wt.%C was mixed by a ball mill. After had been mixed, the mixed powder was pressed into columned block (Φ30 mm × 50 mm) under 15 MPa pressure. The mixing and pressing process was achieved under argon atmosphere protection. Then, the blocks reacted under high temperature under argon atmosphere protection to prepare master alloy.

After pure magnesium has been molten, it was superheated to 750 °C under $SF_6 + CO_2$ gas atmosphere protection in a iron crucible. Master alloy was put into the magnesium melt according to 8 wt.%TiC in the composites. The magnesium melt was stirred by two blade steel stirrer with the speed of 200 rpm to facilitate the incorporation and uniform distribution of TiC particulates in the metallic melt. Finally, magnesium melt was poured into an iron sample mould to synthesize 8 wt.%TiC/AZ91.

Philips S-52 SEM and Olympus PME3 metallography microscope were applied on samples to determine the grain size of materials and the size and distribution of TiC particulates. Mechanical properties were examined on Zwick T1-FRO20 electric materials tester. Damping characterization of 8 wt.%TiC/AZ91 composites and AZ91 magnesium alloy was tested on Mark IV dynamic mechanical thermal analyzer with three-point bending mode. The size of the machined samples is 40 mm × 5 mm × 1.5 mm.

3. Results and discussion

3.1. The composition of materials

EDX analysis of 8 wt.%TiC/AZ91 composites was conducted on polish samples. The results of EDX analysis revealed that titanium is 6.43 wt.%, graphite is 1.58 wt.%, and aluminum is 8.36 wt.% in 8 wt.%TiC/AZ91 composites (as shown Fig. 1). It can be calculated that there is about 8.01 wt.%TiC particulates in the composites for element titanium is being by mean of TiC mainly. It is about 3.37 vol.%TiC particulates in the composites by mathematic calculation, which is consilient with numerical estimate about Fig. 3. There is 8.36 wt.% element aluminum in the composites, which is consilient with that of AZ91 magnesium alloy (as shown in Table 1).

3.2. Mechanical characterization

Mechanical characterization of 8 wt.%TiC/AZ91 and AZ91 magnesium alloy was listed in Table 2. Compared to AZ91 alloy, material strength of 8 wt.%TiC/AZ91 improves. Contrarily, plasticity of 8 wt.%TiC/AZ91 decreases.

The yield strength and ultimate tensile strength (UTS) of materials can be estimated by considering the strengthening mechanisms by grain size and Orowan bowing [7]. Addition of TiC particulates results to grain refinement due to more nucleation form the melt. Therefore the grain size of composites is smaller than that of AZ91 alloy (as shown in Fig. 2). According to image analysis on Olympus PME3 metallography microscope, the grain size of composites has been calculated out (as shown in Table 2). For grain strengthening, it is considered as the Hall–Petch equation [8]:

$$\sigma = \sigma_0 + KD^{-1/2} \quad (1)$$

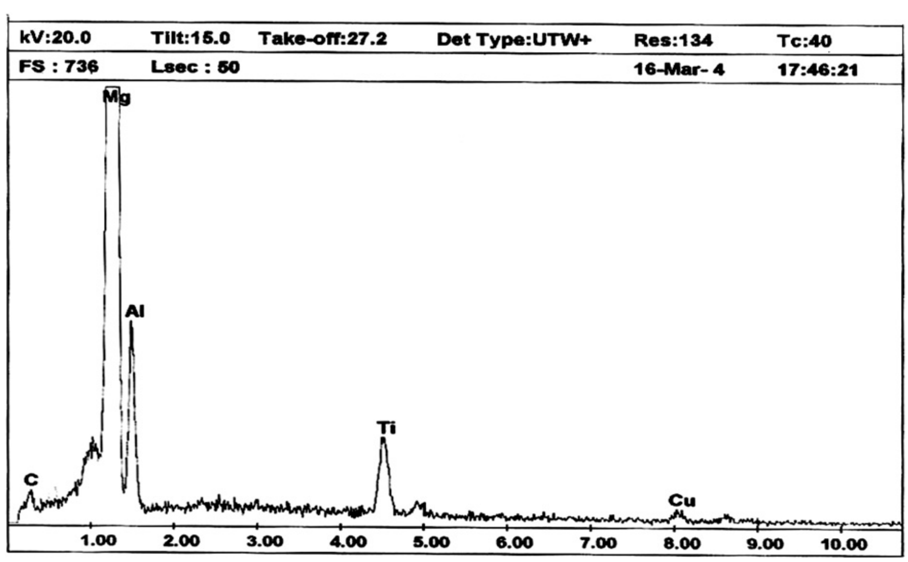

Fig. 1. EDX analysis of the 8 wt.%TiC/AZ91 composites.

Table 1
The composition of AZ91 magnesium alloy

Element	Al	Zn	Mn	Si	Cu	Fe	Mg
Weight fraction (%)	7.5–9.5	0.2–0.8	0.15–0.5	⩽0.25	⩽0.15	⩽0.05	remainder

Table 2
Mechanical properties of 8 wt.%TiC/AZ91 and AZ91 magnesium alloy

Material	Volume content (%)	Tensile module (GPa)	Grain size (μm)	Yield stress (MPa)	Theoretic yield stress (MPa)	UTS (MPa)	Elongation (%)
AZ91 alloy	0	45 ± 0.5	62 ± 2	95 ± 5	115.56	198 ± 5	2.5 ± 0.5
8 wt.%TiC/AZ91	3.10	49.1 ± 0.5	12 ± 2	115 ± 5	160.83	235 ± 5	1.0 ± 0.5

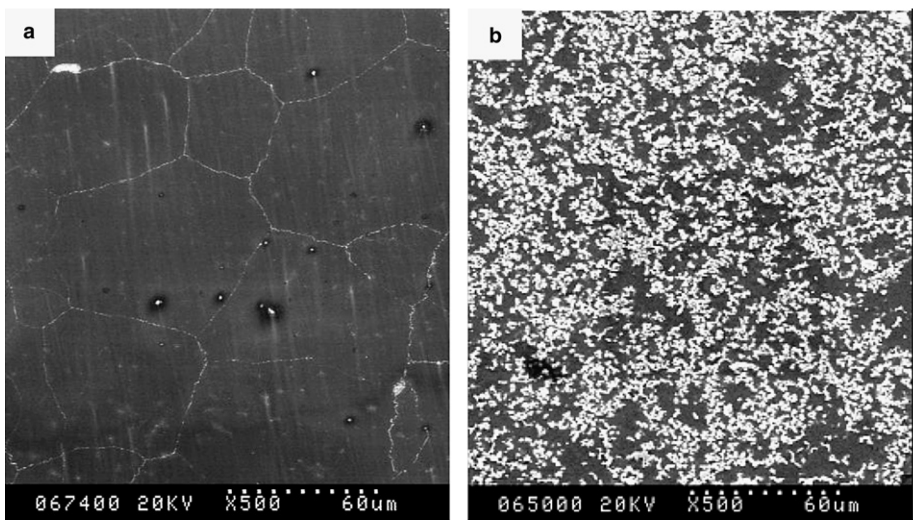

Fig. 2. SEM photograph of materials (a) AZ91 magnesium alloy; (b) 8 wt.%TiC/AZ91 composites.

where σ is the yield stress of materials, D is average grain diameter, σ_0 is the yield stress of single crystal materials, and K is constants. In our study, σ_0 is 80 MPa; K is 280. According to Hall–Petch equation, the theoretic yield stress of materials can be calculated out (as shown in Table 2). So the improvement of yield strength may be attributed to the strengthening of TiC particles originally existed in the matrix.

According to previous literatures [9], the strength of the metal alloy is related to the particulate–dislocation interaction by means of the Orowan bowing mechanism. Residual dislocation loops are left around each particle after a dislocation passes the particles. The Orowan bypassing of particles by dislocations can increase the material's strength. If the particles are assumed to be equiaxed, then the strength increment ($\Delta\sigma$) is estimated to be [10]:

$$\Delta\sigma = 2Gb/L \tag{2}$$

$$L = 0.6d(2\pi/V_p)^{1/2} \tag{3}$$

where G is tensile module, L is the interparticle spacing, b is the Burger's vector, V_p is the volume fractions, and d is the grain diameter of reinforcements. In our research, G and V_p are shown in Table 1; b is 0.32094 nm; and d is average 0.6 μm. AZ91 magnesium alloy as the base materials, the theoretic strength increments are 61.5 corresponding to 8 wt.%TiC/AZ91. For the casting defect, such as gas cavity and shrinkage porosity, the experimental strength increment is far smaller than the theoretic strength increment.

Poor ductility of 8 wt.%TiC/AZ91 can be attributed to the presence of brittle ceramic phase TiC in matrix, which serves as crack nucleation sites leading to the reduction in ductility under tensile loading conditions.

3.3. Damping characterization

Damping characterization revealed that damping capacity of 8 wt.%TiC/AZ91 and AZ91 magnesium alloy is dependent on strain amplitude (as shown in Fig. 3). Damping capacity of materials increase when the strain amplitude increase, but there is a damping peak in damping–strain curve of materials when strain amplitude is about at 1.50E−6 (as shown in Fig. 3). Compared to AZ91 alloy, damping capacity of the composites is higher, and the damping peak of the composites presents at low strain amplitude. Damping capacity of AZ91 alloy and

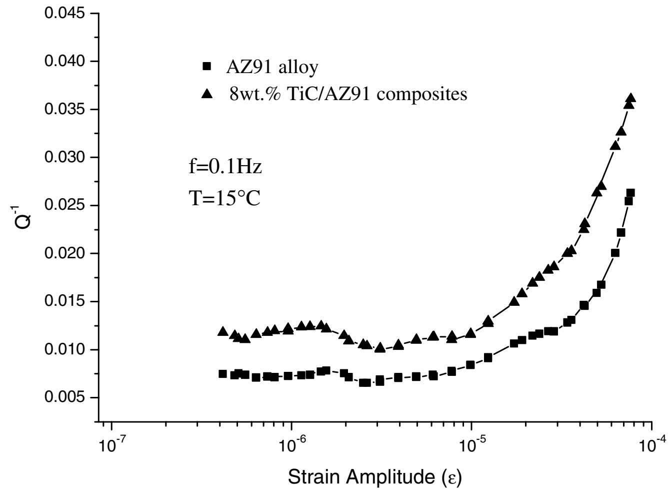

Fig. 3. Damping capacity of materials corresponding to strain amplitude.

8 wt.%TiC/AZ91 is intensively dependent on testing temperature. They increase quickly as testing temperature ascend. Moreover, it is observed that the appearance of damping peak around 140 °C or 250 °C, respectively (as shown in Fig. 4). Compared to AZ91 alloy, damping–temperature peak of the composites appears at low temperature.

According to Granato–Lücke mechanism [11,12], in metal matrix, dislocation is pinned by the strong pinning and the weak pinning (as shown in Fig. 5(a)). At low strain amplitude, dislocation string L_i (L_1, L_2 and L_3) vibrates to and fro to dissipate energy (as shown in Fig. 5(b) and (c)). In the region, the damping capacity of these composites is only weakly dependent on strain amplitude. They improve slowly when strain amplitude increase (as shown in Fig. 3). When the applied cyclic load increases, dislocation string breaks away the weak pinning, and the unpinning of dislocation occurs (as shown in Fig. 5(d)–(f)). So the breakaway damping capacity generates. And damping capacity

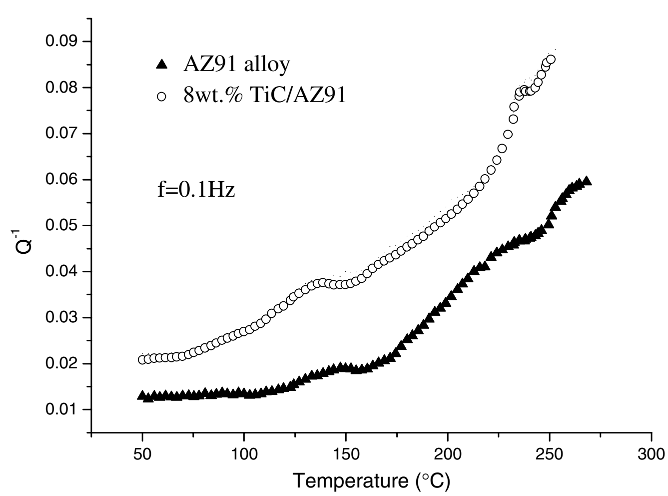

Fig. 4. Damping capacity of materials corresponding to testing temperature.

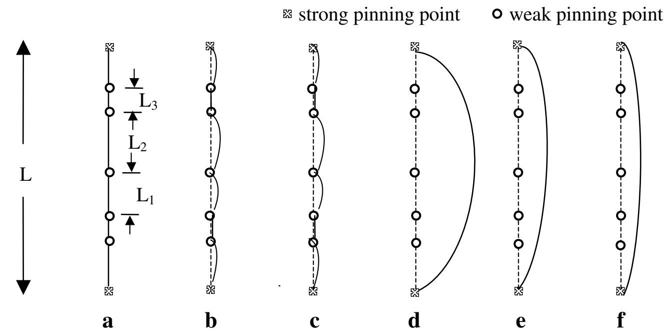

Fig. 5. The damping mechanism according to dislocation movement.

of these composites increases quickly at the strain amplitude up 1E−5 (as shown in Fig. 3). In addition, the unpinning process of dislocations also generates when testing temperature increase. The presence of the damping peak at about 140 °C is contributed to the avalanche effect of anchoring of dislocation.

Metal matrix composites reinforced by particulate will cause high residual stresses around the particulates because of the distant discrepancy of thermal expansion coefficient between magnesium and reinforcements, which are responsible for the generation of high dislocation density in matrix (as shown in Fig. 6). The dislocation density is given as following [13]:

$$\rho = \frac{9.6\Delta\alpha\Delta T V_p}{bd} \tag{4}$$

where $\Delta\alpha$ is the difference of thermal expansion coefficient between matrix alloy and reinforcements, ΔT is difference between working temperature and final temperature, b is the burger's vector, V_p is the volume fractions, and d is the grain diameter of reinforcements. In our study, $\Delta\alpha$ is 20.5×10^{-6} K^{-1}, ΔT is 280 K, b is 0.32094 nm, d is average 0.6 μm, and V_p is listed in Table 2. So the dislocation density of composites is 8.87×10^{10} mm^{-2} corresponding to 8 wt.%TiC/AZ91 composites. With the increasing of TiC particulates, the dislocation densities of composites improve (as shown in Fig. 6). According to Granato–Lücke mechanism, damping capacity of materials can be described as follows [11,12]:

$$Q^{-1} = Q_f^{-1} + Q_\varepsilon^{-1} \tag{5}$$

$$Q_\varepsilon^{-1} = C_1 \frac{\rho b^2}{\varepsilon_0} \exp\left(-\frac{C_2}{\varepsilon_0}\right) \tag{6}$$

$$Q_f^{-1} = \frac{C_3 \rho f^2}{b^2} \tag{7}$$

where Q_f^{-1} is the strain amplitude independent component, and the component Q_ε^{-1} is depends on the strain amplitude and it is determined usually by dislocation vibrations. C_1, C_2, C_3 is numerical factor, ρ is the dislocation density, b is the Burger's vector, ε_0 is the strain amplitude, and f is the vibration frequency. According to the Eqs. (4)–(7), damping capacity of materials is relative to dislocation

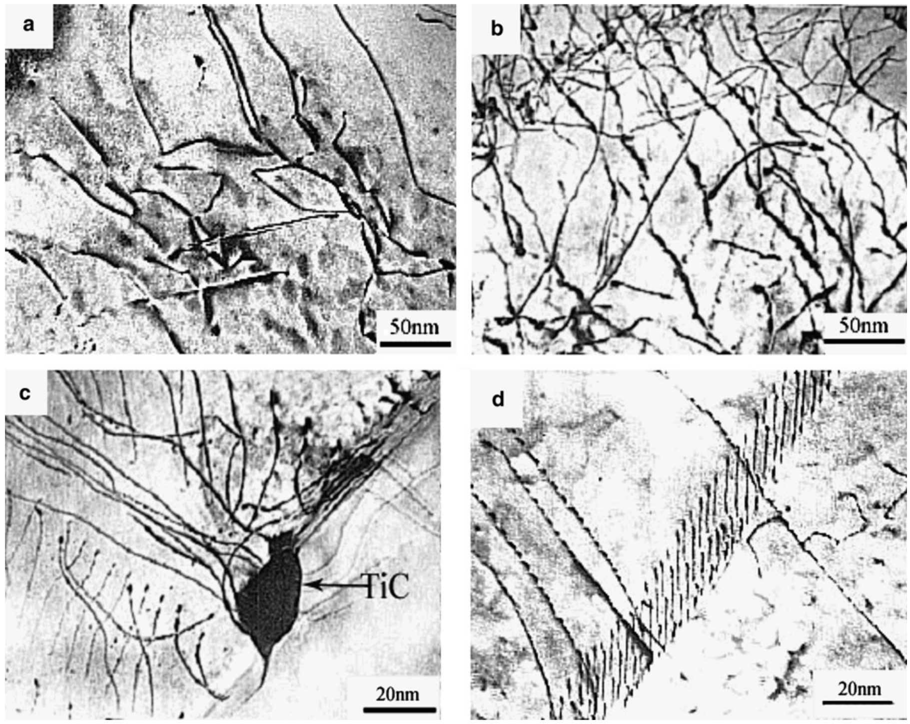

Fig. 6. The dislocation arrangement in materials (a) AZ91 magnesium alloy; (b), (c) and (d) 8 wt.%TiC/AZ91 composites.

density. They improve when dislocation density increase. So damping capacity of 10 wt.%TiC/AZ91 is higher than that of AZ91 alloy.

Simultaneously, the crossing and interaction of dislocation occur when dislocation moves. The dislocation motion leads to the tangle of dislocation, so the effective length of sympathetic vibration dislocations becomes short. Correspondingly, damping capacity of materials decrease after a specific strain value, so there is a damping–strain peak at about 1.50E−6 in damping–strain curve of 8 wt.%TiC/AZ91 (as shown in Fig. 3). It is easy to generate the tangle of dislocation in 8 wt.%TiC/AZ91 that have high dislocation density. The presence of damping–strain peak is discovered firstly in 8 wt.%TiC/AZ91 composites.

In metal materials, the damping capacity is also contributed to the generation and motion of compound twin [14]. The compound twin moves in metal materials due to the movability of them when the materials undergo stress, which results to the relaxation of stress and energy dissipation. So the damping capacity generates. In 8 wt.%TiC/AZ91 composites, it is revealed the presence of compound twin, as shown in Fig. 7. So the damping mechanism in 8 wt.%TiC/AZ91 composites can also be attributed to the generation and motion of compound twin.

It has been suggested that the grain boundary and the interface between the reinforcement and matrix play an important role on the damping behavior of composite materials. When interface or grain boundary slip at high temperature, much energy dissipates (as shown in Fig. 8).

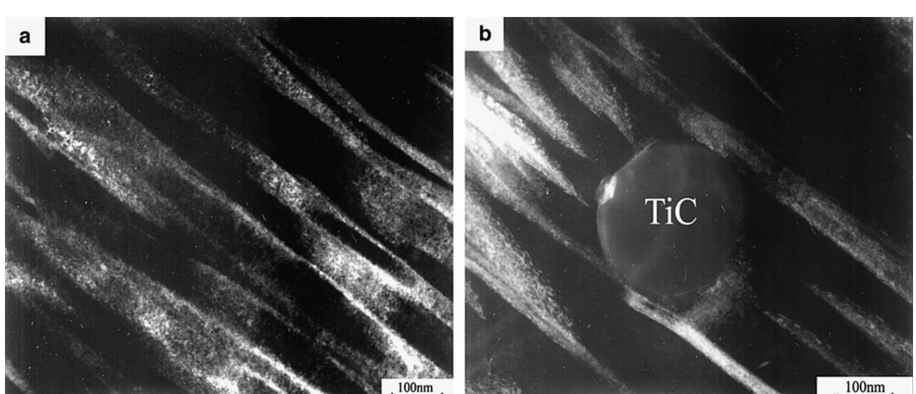

Fig. 7. TEM images of compound twin in 8 wt.%TiC/AZ91 composites.

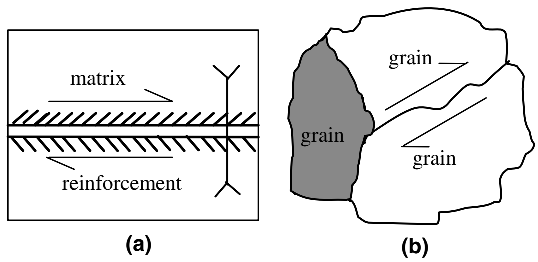

Fig. 8. The damping mechanism of (a) interface slip and (b) grain boundary slip.

A theory regarding the contribution of the grain boundary and interface to damping has been offered by Schoeck [15,16]. Assuming a viscous boundary at high temperature, the contribution to damping is approximately given by:

$$Q^{-1} \approx [4.5(1-\gamma)V_f]/[\pi^2(2-\gamma)] \quad (8)$$

where γ is Poisson's ratio and V_f is volume fraction of reinforcements. This value is consistent with the observed results of damping capacity at elevated temperatures. So much energy dissipates between the movable grain boundary and interfaces of the composites. The presence of damping at around 250 °C was observed in 8 wt.%TiC/AZ91 (as shown in Fig. 4). The damping peak is contributed to the motion of grain boundary and interfaces. With the addition of TiC particulates, the grain boundary and interfaces of 8 wt.%TiC/AZ91 improve, and the damping capacity of 8 wt.%TiC/AZ91 increases (as shown in Fig. 4).

4. Conclusion

Magnesium matrix composites reinforced with TiC particulates was successful prepared using in situ synthesis method. Compared to AZ91 alloy, mechanical properties of 8 wt.%TiC/AZ91 improve. Addition of TiC particulates results to grain refinement and high dislocation density in composites, which is contributed to the improvement of mechanical properties of 8 wt.%TiC/AZ91. Damping capacity of AZ91 alloy and 8 wt.%TiC/AZ91 is dependent on strain amplitude, temperature. With the increasing of strain, temperature, damping capacity of the composites improve. And it is discovered the presence of damping–strain peak and damping–temperature peak in damping curves. The damping capacity of 8 wt.%TiC/AZ91 is higher than that of AZ91 alloy due to the addition of TiC particulates. The damping characterization was explained with dislocation motion, twinning, grain boundary slip and interfaces slip.

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