Available online at www.sciencedirect.com
ScienceDirect
Trans. Nonferrous Met. Soc. China 28(2018) 1928−1937
Transactions of Nonferrous Metals Society of China
www.tnmsc.cn

Mechanism of improving strength and damping properties of powder-extruded Al/Zn composite after diffusion annealing

Zhi-hao ZHANG[1,2], Fei XIAO[1], You-wei WANG[1], Yan-bin JIANG[1,2]

1. Institute for Advanced Materials and Technology, University of Science and Technology Beijing, Beijing 100083, China;
2. Key Laboratory for Advanced Materials Processing (Ministry of Education), University of Science and Technology Beijing, Beijing 100083, China

Received 22 March 2018; accepted 13 June 2018

Abstract: In order to develop high strength, high damping and low density Al matrix composites, the Al/Zn composite bar samples with Zn mass fraction of 10%−40% were prepared by powder extrusion. The tensile strength and damping properties of the samples are improved by controlling both the Zn/Al diffusion degree and the precipitation of the interfacial phases. The results show that the tensile strength of the samples with Zn mass fraction of 10%−30% increases with the increases of both the Zn content and annealing temperature. When the Zn mass fraction increases to 40%, the tensile strength of the sample remains basically unchanged or decreases slightly, and the plasticity decreases gradually. Alloying of Al matrix and the formation of Zn/Al interface layer are mainly responsible for improving the strength of the annealed samples. The damping properties increase with the increases of both the Zn content and annealing temperature. The Zn/Al eutectoid lamella eliminates the detrimental effects on damping properties due to both alloying of the Al matrix and reduction of pure Zn in the Al matrix. The Al−30%Zn sample annealed at 350 °C for 0.5 h has good comprehensive properties, including the tensile strength of 330 MPa, the elongation to failure of 10% and the room-temperature damping properties (tan θ) of 0.025.

Key words: aluminum matrix composites; fiber reinforcement; mechanical properties; damping properties

1 Introduction

Damping property of the material refers to the ability to dissipate elastic strain energy. The application of high damping materials in mechanical parts can reduce the use of energy absorbing devices or shock absorbing structures in mechanical systems, which can simplify the system structure and save cost [1].

Although the polymeric materials (such as rubber and plastic) have a high damping property [2], narrow temperature range (generally less than 150 °C) and low stiffness restrict their wide application as structural part. Damping alloy not only has good mechanical properties, but also has a wide range of service temperature, which is more favorable for extending the service conditions of structural parts. The commonly used damping alloys include Zn−Al [3], Ni−Ti [4], Mn−Cu [5] alloys, etc. Developing Zn−Al alloy becomes a research hotspot in the field of high damping metallic materials because of its light weight, easy forming, heat treatment and other advantages. At present, some Zn−Al alloys with high damping property were developed [6−9], such as Zn−0.3Al, Zn−12Al, Zn−27Al and Zn−22Al. Especially, Zn−22Al alloy has been successfully applied in some high-rise buildings [10], but its density is relatively high (~6.16 g/cm^3) due to its high Zn content.

Some researchers used Al as matrix and added high damping second phase to obtain light high-damping materials. For example, ZHENG et al [11] prepared $Li_{6.75}La_3Zr_{1.75}Nb_{0.25}O_{12}$ particle-reinforced Al-based composites by accumulative roll bonding to improve damping property by using damping peaks of $Li_{6.75}La_3Zr_{1.75}Nb_{0.25}O_{12}$ ceramic particles near 300 K. HU et al [12] prepared SiC/TiNi$_f$/Al Al-based composites by pressure infiltration, and used high damping TiNi fiber [13] to improve the damping properties. The methods mentioned above increased the damping

Foundation item: Project (2016YFB0300901) supported by the National Key Research and Development Program of China
Corresponding author: Yan-bin JIANG; Tel/Fax: +86-10-62332253; E-mail: jiangyanbin@tsinghua.org.cn
DOI: 10.1016/S1003-6326(18)64838-1

properties of Al-based composites effectively. However, Al-based composites have low damping property because of the poor intrinsic damping property of Al. The loss factor tan θ at room temperature (tan $\theta \approx \Delta W/W$, where ΔW is the energy loss in a cycle of forced vibration, W is the work done by external force in a cycle of forced vibration, and θ is the phase angle of strain behind stress) is less than 0.01. Meanwhile, the strength of Al-based composites is relatively low and usually less than 200 MPa.

The Zn−Al alloy with the main component of Zn has a relatively high strength and high damping property (tan θ is usually greater than 0.04), but the density is also high (about 6.0 g/cm^3). The Al-based composite has advantages in lightweight; however, its damping property is not as good as that of Zn−Al alloys because of the low intrinsic damping property and the inability to improve damping property by increasing the sliding phase boundary by precipitation [14]. Al/Zn composites with the main component of Al combine the advantages of Zn−Al alloy and Al-based composite in both performance and density. It is expected to produce Al-based composites with high strength, high damping and low density, through controlling the diffusion of Al and Zn during annealing to form solid-solution strengthening for improving the strength and controlling precipitation of the Zn/Al interface layer for enhancing the damping property.

In this work, the Al/Zn composites with the main component of Al were prepared by the combination of powder extrusion and diffusion annealing. The effects of diffusion annealing on the mechanical and damping properties of the Al/Zn extruded samples with different Zn contents were studied. The mechanisms of improving the mechanical properties and damping properties of Al/Zn composite samples after annealing were discussed.

2 Experimental

The raw materials were pure Al powder (99.7% in purity, 48 μm) and pure Zn powder (99.7% in purity, 48 μm), and the mass fraction of the Zn powder was 10%−40%. According to our previous experimental method [15], with anhydrous ethanol as the liquid medium, the mixed Al and Zn powders were stirred by ultrasonic stirring for 0.5 h. The mixed powders were dried at 100 °C for 5 h, and then pressed under a pressure of 550 MPa at 320 °C in cylindrical steel die with a diameter of 40 mm. The compacts were hot extruded into rods at 320 °C with an extrusion ratio of 16:1. Subsequently, the extruded bars were annealed in a temperature range of 290−350 °C for 0.5 h followed by natural-air cooling.

The strength and ductility of the composites were measured by tensile testing methods. The tensile property of the cylindrical samples with a diameter of 3 mm and a gauge length of 15 mm were tested on MTS810 universal testing machine at a cross head speed of 1 mm/min. The microstructure and fracture morphology of the composites were analyzed with a FEI Quanta 450 field emission scanning electron microscope (SEM) equipped with an energy dispersive spectroscopy (EDS). The damping property of the Zn/Al samples with the dimensions of 40 mm × 8 mm × 1 mm was tested by dynamic thermomechanical analyzer Q800, and the damping property was evaluated by tan θ. The measurement method was three-point bending, the heating rate was 5 °C/min and the temperature range was 25−250 °C.

3 Results

3.1 Microstructure of Al/Zn composite

Figure 1 shows the microstructures of the transverse and longitudinal sections of the as-extruded Al/Zn composite sample with Zn mass fraction of 20%, where the white zone is Zn and the black zone is Al matrix under the backscattered electron imaging mode. Figure 1(a) shows the distribution of Zn in the cross section of the bar, and the Zn is uniformly distributed in the Al matrix. From the longitudinal section of the extruded bar in Fig. 1(b), a large number of Zn is elongated along the extrusion direction. The larger plastic deformation of the

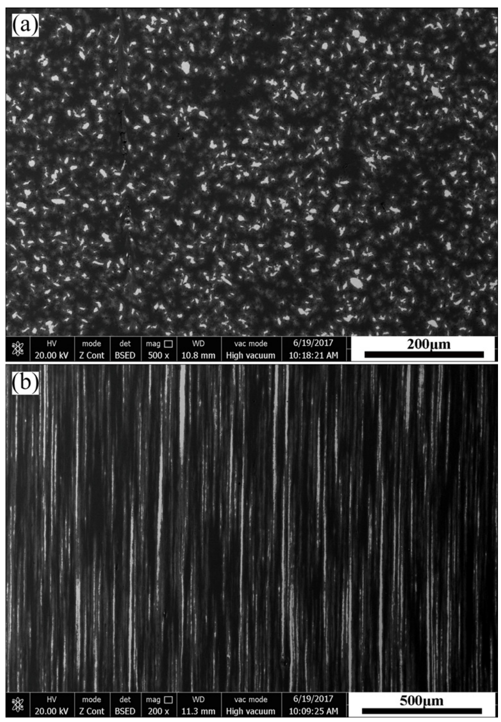


Fig. 1 Microstructures of as-extruded Al−20%Zn sample under backscattered electron imaging mode: (a) Cross section; (b) Longitudinal section

Zn during extrusion can engender more fresh contact interface with the matrix, which is beneficial to enhancing the interfacial bonding strength.

Figure 2 shows the microstructures of the Al−20%Zn samples annealed at different temperatures, where the bright color is Zn and Zn/Al diffusion interface layer and the black back is Al matrix. The samples exhibit various morphologies after annealing at different annealing temperatures. When the sample is annealed at 290 °C for 0.5 h, the Zn/Al diffusion interface layer appears around the pure Zn fibers. As the annealing temperature rises to 320 °C, the thickness of the Zn/Al diffusion interface layer increases significantly. After annealing at 350 °C for 0.5 h, most of the pure Zn fibers in the sample are replaced by Zn/Al diffusion layer, and only a small number of pure Zn remains in the core of the fiber.

The effect of the annealing temperature on the microstructure of the Al/Zn samples is achieved by the influence of the annealing temperature on diffusion rate of the Al and Zn. The variation of the Zn content mainly changes the density degree of the Zn fiber in the Al matrix, but has small effect on the microstructure of the Zn fiber.

3.2 Mechanical properties of Al/Zn composites

The engineering stress−engineering strain curves of the as-extruded and annealed Al−20%Zn samples are shown in Fig. 3. It is indicated that the tensile strength of the as-extruded sample is relatively low, ~190 MPa. After annealing at 290−350 °C for 0.5 h, the tensile strength increases with an increase of the annealing temperature, and reaches 270 MPa at 350 °C. The plasticity of the samples decreases with an increase of the annealing temperature, and the elongation to failure reduces from 19% of the as-extruded sample to 9% of the annealed sample (350 °C, 0.5 h).

Figure 4 shows the mechanical properties of the as-extruded and annealed Al/Zn samples with different Zn contents. For the as-extruded samples, when the Zn content is less than 30%, the strength of the samples increases with an increase of the Zn content. When the Zn content is more than 30%, increasing the Zn content has a small effect on the tensile strength of the samples. The strength of the as-extruded samples with different Zn contents is improved by diffusion annealing. For the samples with the Zn content of 0−30%, the strength of the annealed samples increases with an increase of the Zn content. For the samples with more than 30% Zn, there is a limited increase or even a downward trend in the tensile strength of the annealed samples. Diffusion annealing improves the strength of the Al/Zn samples but reduces the plasticity of the samples at the same time. The plasticity of the samples decreases with an increase of the annealing temperature. With the Zn content increasing from 10% to 20%, the plasticity of the annealed samples decreases apparently. When the Zn content is more than 20%, the plasticity of the samples under the same annealing condition remains basically unchanged.

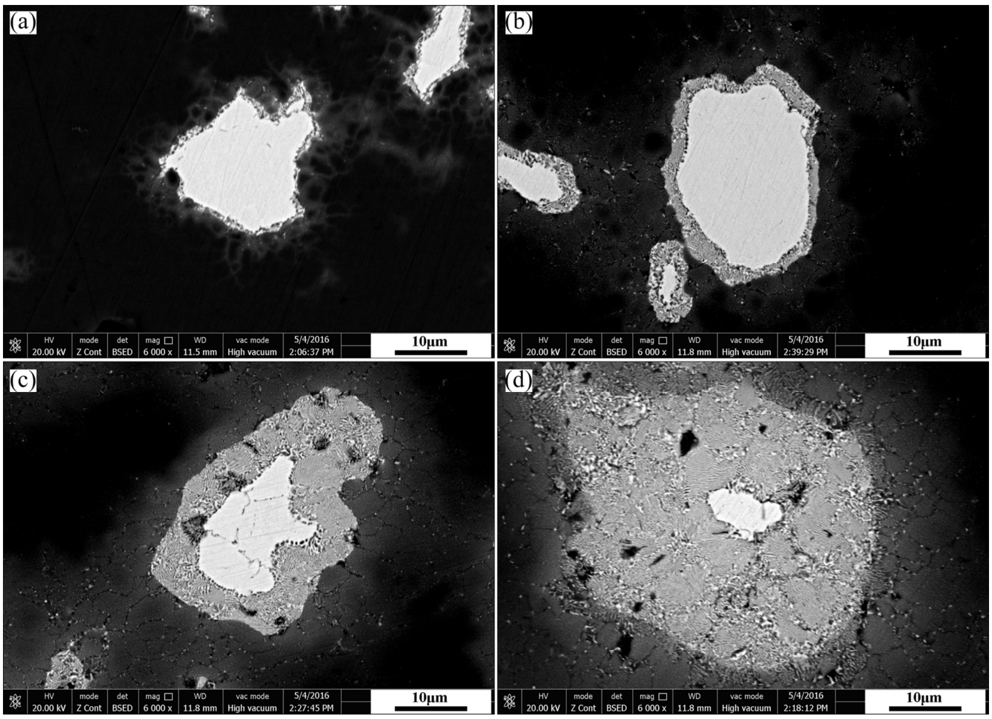


Fig. 2 Effect of annealing temperature on microstructure of Al−20% Zn sample: (a) As-extruded; (b) Annealing at 290 °C for 0.5 h; (c) Annealing at 320 °C for 0.5 h; (d) Annealing at 350 °C for 0.5 h

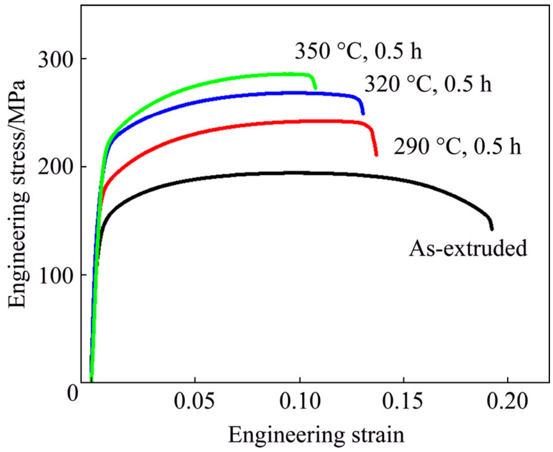


Fig. 3 Engineering stress−engineering strain curves of Al−20%Zn samples annealed at different temperatures

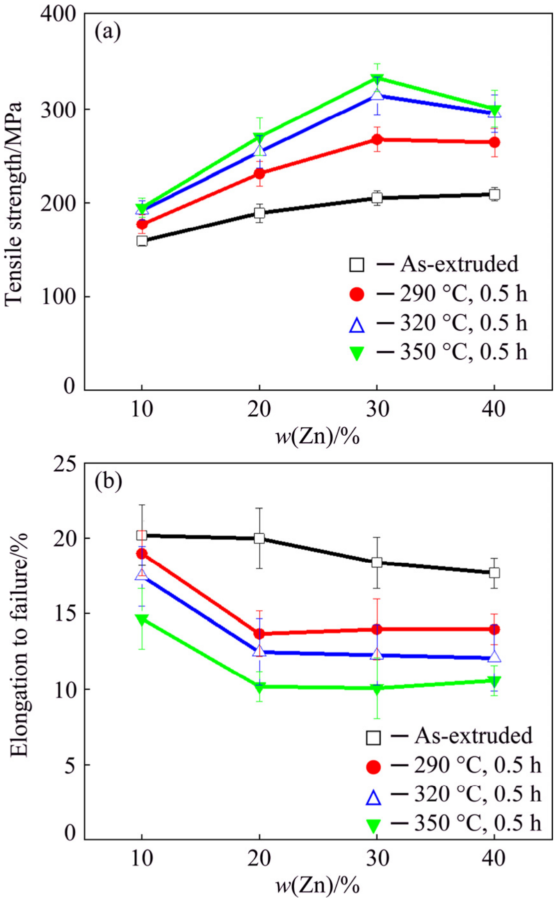


Fig. 4 Mechanical properties of as-extruded and annealed Al/Zn samples with various Zn contents: (a) Tensile strength; (b) Elongation to failure

The fracture morphologies of the as-extruded and annealed Al−20%Zn samples are shown in Fig. 5. A large number of dimples are observed on the fracture surface of the as-extruded sample, indicating that ductile fracture takes place in the as-extruded sample. Compared with the as-extruded samples, the diameter and depth of the dimples of the annealed samples decrease obviously, indicating the decrease in the plasticity of the annealed samples. Such behaviors further confirm the result in Fig. 3 that the plasticity of the samples decreases with the increase of the annealing temperature.

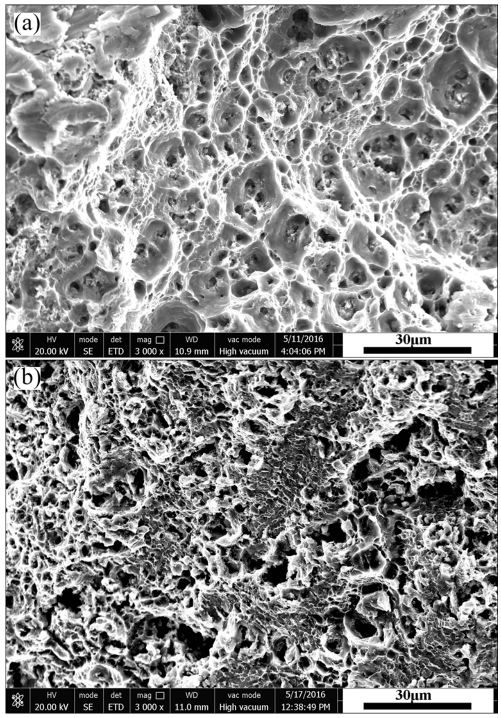


Fig. 5 Fracture morphologies of Al−20%Zn samples: (a) As-extruded; (b) Annealed at 350 °C for 0.5 h

3.3 Damping properties of Al/Zn composites

The damping properties of the as-extruded and annealed Al/Zn composite samples with different Zn contents are shown in Fig. 6. Figure 6(a) shows that the damping property of the as-extruded Al/Zn samples increases with the increase of Zn content, which indicates that increasing Zn content can improve the damping property of the as-extruded Al/Zn samples. In addition, the damping properties of the as-extruded Al/Zn samples increase with the increase of test temperature.

Figure 6(b) shows that the damping properties of the annealed samples at 320 °C for 0.5 h increase with the increases of Zn content and the test temperature, which is consistent with that of the as-extruded samples.

Figure 7 shows the variation of the damping properties of the Al−30%Zn samples with the annealing temperature. After annealing at 290−350 °C, the damping properties of the samples increase with an increase of the annealing temperature. The damping property of the sample annealed at 290 °C for 0.5 h is lower than that of the as-extruded sample. The damping property of the sample annealed at 320 °C is close to that

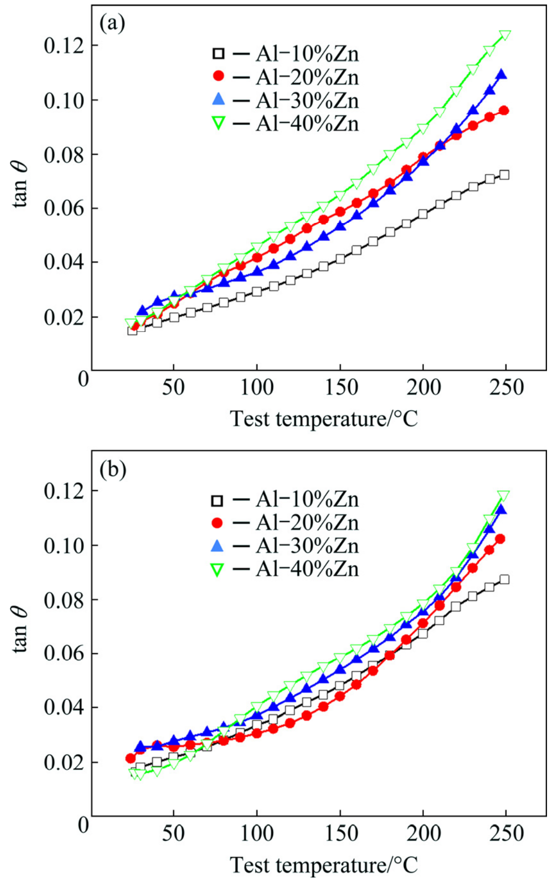


Fig. 6 Effect of Zn content on damping properties of Al/Zn samples: (a) As-extruded; (b) Annealed at 320 °C for 0.5 h (f=1 Hz)

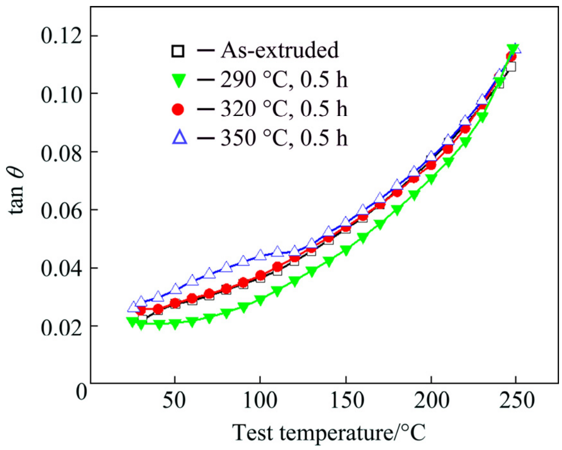


Fig. 7 Effect of annealing temperature on damping properties of Al−30%Zn samples

of the as-extruded sample. The damping property of the sample annealed at 350 °C increases.

In fact, damping property of the Al/Zn samples is affected by the test temperature as well as the test frequency. Figure 8 shows the incline of damping property with the increase of the test frequency. When the frequency is less than 10 Hz, the damping effect decreases with the increase of the test frequency. When the test frequency is more than 10 Hz, the decrease extent of the damping property reduces with the increase of the frequency. This implies that the Al/Zn composite has good damping properties at high temperature as well as at high frequency.

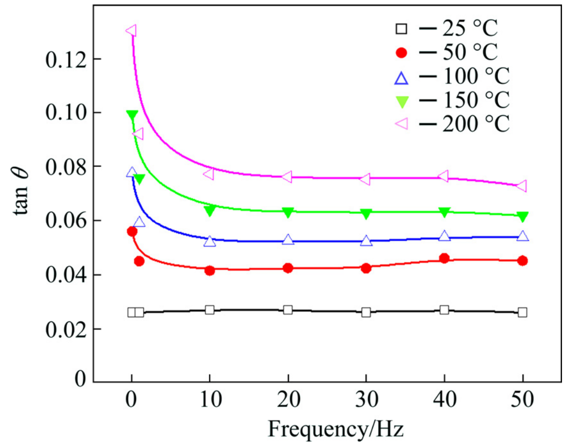


Fig. 8 Effects of test frequency and temperature on damping property of Al−30%Zn sample annealed at 350 °C for 0.5 h

4 Discussion

4.1 Strengthening mechanism of Al/Zn composites

Figure 9 shows the hardness changes of the Al matrix with the annealing temperature. The hardness of the Al matrix increases with an increase of the annealing temperature, which is consistent with the tensile strength change of the samples with the annealing temperature (Fig. 3 and Fig. 4). This implies that the increase of the strength of the samples is related to the strengthening of the Al matrix. With increasing the annealing temperature, the diffusion coefficient of Al and Zn atoms increases exponentially, and thus the thickness of the Zn/Al diffusion interface layer also (Fig. 2), which induces the increase of hardness. It is indicated that the strength of the sample may be affected by the Zn/Al diffusion

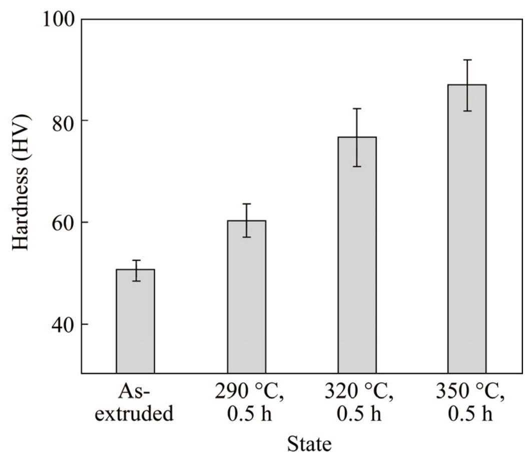
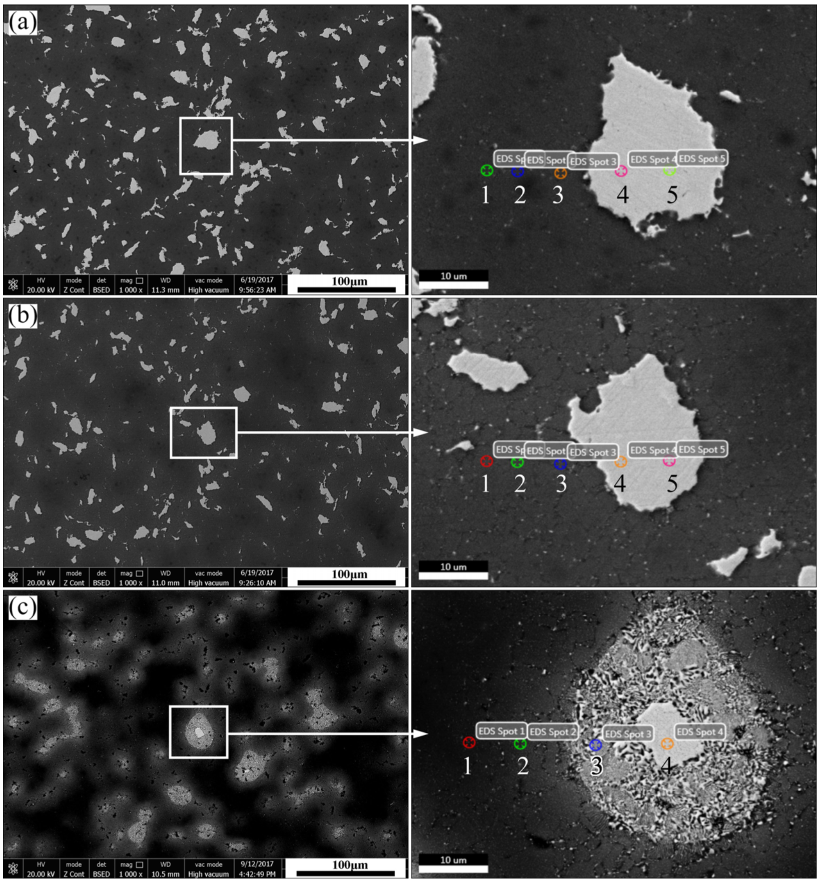


Fig. 9 Hardness of Al matrix in as-extruded and annealed Al−30%Zn samples

interface layer. To investigate the effects of Al matrix strengthening and Zn/Al diffusion interface layer on the strength of the samples, low temperature annealing experiments at 230 and 260 °C (lower than the Zn−Al eutectoid temperature of 277 °C) were carried out because annealing below 277 °C can strengthen the Al matrix (Fig. 9) instead of forming apparent Zn/Al diffusion interface layer (Figs. 10(a) and (b)).

Figure 11 shows the tensile stress−strain curves of the Al−30%Zn samples after long-time annealing at low temperatures (230 and 260 °C). For comparison, the curves of the samples annealed at 350 and 320 °C for 0.5 h were also given. The strength of the sample annealed at 260 °C for 4 h is equivalent to that of the sample annealed at 350 °C for 0.5 h, ~330 MPa. The strength (~280 MPa) of the sample annealed at 230 °C for 8 h is larger than that (~200 MPa) of the as-extruded sample. It is indicated that both short-time annealing at high temperature and long-time annealing at low temperature can improve the strength of the Al/Zn samples. The results of the EDS analysis in Fig. 10 show that after diffusion annealing, alloying of the Al/Zn samples induces the local region of Al−Zn alloy which has large strength due to solid solution strengthening, and provides the strength higher than 350 MPa, which is much higher than that (~100 MPa) of pure Al [16−18]. This implies that alloying of the Al matrix plays an important role in improving the strength of the Al/Zn samples.

If alloying of the Al matrix is the sole factor of the strength enhancement, the strength of the Al/Zn sample should increase with the increase of its hardness. However, the results show that the hardness of the matrix in the sample annealed at 320 °C for 0.5 h is HV 76.6, close to that (~HV 78.5) of the sample annealed at 230 °C for 8 h. The strength of the sample annealed at 320 °C for 0.5 h is 300 MPa and higher than that (~280 MPa) of the sample annealed at 230 °C for 8 h (Fig. 11). Meanwhile, the hardness of the Al matrix in the sample annealed at 350 °C for 0.5 h is HV 86.9 (Fig. 9) and lower than that (~HV 97.8) of the sample annealed at 260 °C for 4 h, but the strengths of the two samples are very close (Fig. 11). Therefore, besides the alloying of the Al matrix, there are other factors affecting the strength of the sample. The apparent diffusion interface layer is formed in the sample annealed at 350 °C for 0.5 h (Fig. 10(c)), while no obvious diffusion interface layer is formed in the sample annealed at



Spot	w(Al)/%	w(Zn)/%
1	84.29	15.71
2	84.89	15.11
3	82.11	17.89
4	1.74	98.26
5	1.85	98.15

Spot	w(Al)/%	w(Zn)/%
1	76.21	23.79
2	75.50	24.50
3	75.58	24.42
4	1.72	98.28
5	1.29	98.71

Spot	w(Al)/%	w(Zn)/%
1	77.89	22.11
2	74.79	25.21
3	28.71	71.29
4	1.94	98.06

Fig. 10 Effects of short-time annealing at high temperature and long-time annealing at low temperature on microstructure of Al−30%Zn samples (air cooling): (a) Annealing at 230 °C for 8 h; (b) Annealing at 260 °C for 4 h; (c) Annealing at 350 °C for 0.5 h

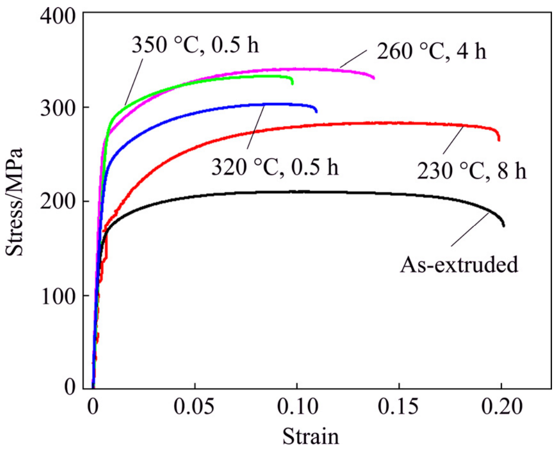


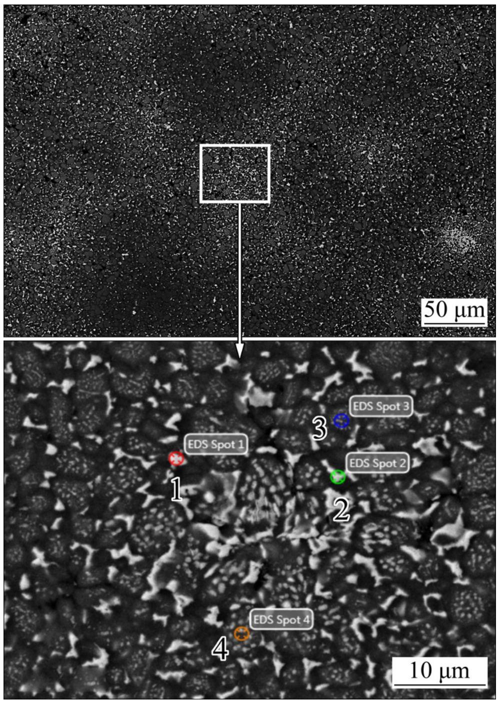
Fig. 11 Effects of short-time annealing at high temperature and long-time annealing at low temperature on tensile properties of Al−30%Zn samples

260 °C for 4 h (Figs. 10(a) and (b)). Since the strength of the Zn/Al diffusion interface layer is higher than that of the pure Zn (150 MPa) [19] and can effectively impede dislocation movement in the samples, it can be deduced that the diffusion interface layer formed during high temperature annealing is another factor in improving the strength of the Al/Zn composite.

4.2 Damping mechanism of Al/Zn composites

Due to the high intrinsic damping property of pure Zn [7], the Al/Zn sample with high pure Zn content should have high damping property theoretically. Accordingly, with an increase of the annealing temperature, the pure Zn content in the samples decreases, which reduces the damping property of the samples. Compared with the sample annealed at 290 °C for 0.5 h, however, the damping property of the sample annealed at 350 °C for 0.5 h increases (Fig. 7). The damping mechanism of the Al/Zn samples is further analyzed.

After annealing at 350 °C for 0.5 h followed by furnace cooling, the Al/Zn sample consists of the alloyed Al matrix and precipitated Zn-rich phase, and no apparent Zn/Al diffusion interface layer is found in Fig. 12. Figure 13 shows that the damping properties of the samples with the Zn/Al diffusion interface layer (air cooling) are higher than those of the samples without the Zn/Al diffusion interface layer (furnace cooling). This implies that the Zn/Al diffusion interface layer induces good damping properties, which can offset the decrease of damping due to both reduction of pure Zn and alloying of the Al matrix. Meanwhile, such behaviors can be responsible for the phenomenon that the damping properties of the sample decrease first and then rise in Fig. 7, because a thin Zn/Al diffusion interface layer which is formed in the sample annealed at 290 °C for 0.5 h (Fig. 2) is not enough to offset the damping loss caused by both the Al matrix alloying and the reduction of pure Zn.



Spot	*w*(Al)/%	*w*(Zn)/%
1	20.49	79.51
2	31.04	68.96
3	64.32	35.68
4	64.91	35.09

Fig. 12 Microstructures of Al−30%Zn sample annealed at 350 °C for 0.5 h followed by furnace cooling

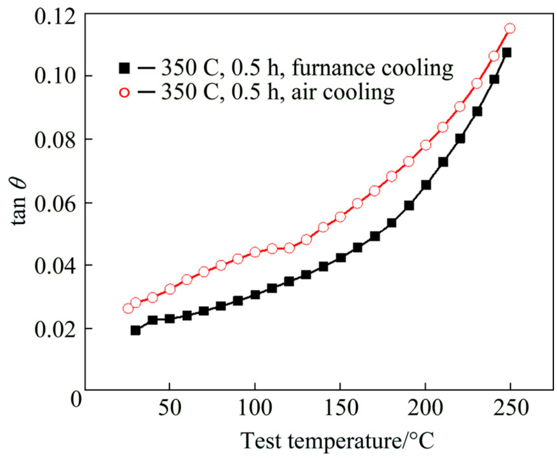
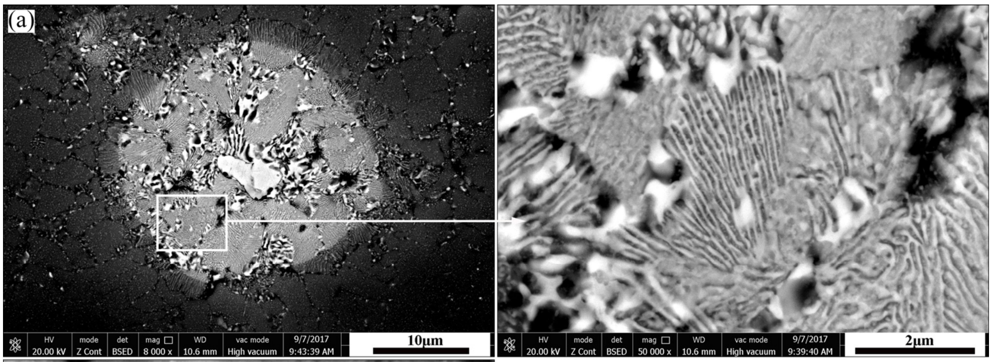
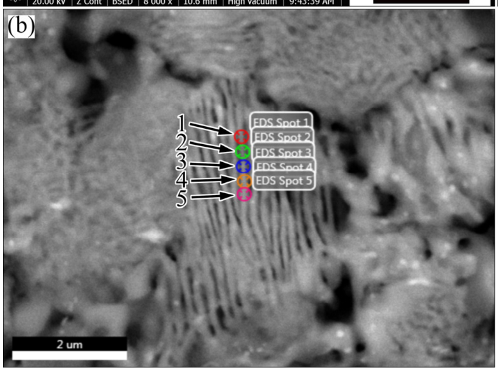


Fig. 13 Effect of cooling rate on damping properties of Al−30%Zn samples

From Fig. 14(a), the Zn/Al diffusion interface layer has lamellar structure and the thickness of the lamellae is 100−200 nm. The backscattered electron image of Fig. 14 displays that the lamella is composed of two phases. The EDS analysis in Fig. 14(b) shows that the retained lamella is composed of Al-rich phase, indicating that the lamella has eutectoid microstructure due to the presence of eutectic reactions during the cooling of the Zn/Al solid solution. When the annealing temperature is below 277 °C, Al and Zn precipitate from the solid solution. Therefore, the Zn/Al diffusion interface layer is a eutectoid layer which consists of an Al-rich phase and a Zn-rich phase. Since the interphase slip of lamellar structure or grain boundary is the main damping mechanism of Zn/Al alloy, η/α and η/η phase boundaries are easier to slip than α/α phase in the process of deformation [20−23]. Therefore, a large number of Zn/Al eutectoid layers which easily slide to each other in the Zn/Al diffusion interface layer are mainly responsible for obtaining good damping properties.

In this work, the damping property at room temperature of the as-extruded Al/Zn composite is higher (tan θ>0.015), but its strength is relatively low (<200 MPa). By diffusion annealing, the tensile strength of the as-extruded sample is improved obviously and tan θ remains at a relatively high level of 0.02. Especially, the tensile strength of the 30% Zn/Al sample after annealing at 350 °C for 0.5 h is ~330 MPa, and tan θ reaches 0.025. Table 1 gives the damping and





Spot	w(Al)/%	w(Zn)/%
1	82.09	17.91
2	81.72	18.28
3	80.66	19.34
4	82.02	17.98

Fig. 14 Microstructures of Al−30%Zn sample annealed at 350 for 0.5 h: (a) Before metallographic etching; (b) After metallographic etching

Table 1 Preparation method, damping at room temperature (f=1 Hz) and mechanical properties of some Al−Zn alloys and Al-based composites

Material	Method	UTS/MPa	Elongation/%	tan θ	Reference
Zn−22Al	Casting	~206	~2.3	~0.04	[24]
Zn−22Al	Casting + Refined by 0.3wt%Al−5Ti−1B+0.1wt%Zr	234	3.3	0.05	[24]
Zn−27Al	Casting	~203	~9	~0.025	[6]
Zn−22Al	Casting + Warm rolling	−	−	0.05	[8]
Zn−22Al−0.55Sc−0.26Zr	Casting + Warm rolling	−	−	0.08	[8]
Al−35Zn	Casting + Hot rolling	400	9	0.014	[25]
20vol%$NiTi_f$/1060Al	Pressure infiltration	~260	~16	~0.005	[7]
50vol%C_f/Al	Pressure infiltration	−	−	0.014	[26]
10wt%$BaTiO_3$/Al	Powder extrusion	~140	~20	~0.008	[27]
10wt%$Li_{6.75}La_3Zr_{1.75}Nb_{0.25}O_{12}$/Al	Accumulative roll bonding	~132	~10	~0.007	[11]
Al−30%Zn	Powder extrusion + Diffusion annealing	~330	~10	~0.025	Present work

mechanical properties of some Al-based composites, Zn−Al alloys and Al−Zn alloys. The material in Table 1 can be divided into two groups. One group is Zn−Al casting alloy whose damping property tan θ can be improved to ~0.05 generally by adding refiner or applying large deformation of the casting microstructure to increase the number of grain boundary. The other group is Al-based composite whose damping property can be improved by adding a phase with high damping, but the damping property is still at a low level and tan θ is generally less than 0.01.

The density of the Al−30%Zn sample is 3.32 g/cm^3, and after annealing at 350 °C for 0.5 h the specific strength (tensile strength/density) is ~9.93×10^4 N·m/kg. The specific strength of the Zn−27Al alloy with equivalent damping property is ~3.4×10^4 N·m/kg, and the specific strength of other Al-based composites is (3.0−7.5)×10^4 N·m/kg. By comparative analysis, the damping property of the Al/Zn composite is lower than that of typical cast damping alloy (Zn−22Al), but its damping property is much higher than that of other Al-based composites, with good mechanical properties.

5 Conclusions

1) The tensile strength of the Al/Zn composites with Zn content of 10%−30% (mass fraction) increases with the increases of both Zn content and annealing temperature. When the Zn content increases to 40%, the tensile strength of the sample remains basically unchanged or slightly decreases, while the plasticity decreases gradually. Compared with the as-extruded sample, the tensile strength of the Al−30%Zn sample annealed at 350 °C for 0.5 h is increased by 65%. The alloying of the Al matrix and the formation of the Zn/Al diffusion interface are mainly responsible for improving the strength of the annealed sample.

2) The damping properties of the samples increase with the increases of both the Zn content and the annealing temperature. The Zn/Al eutectoid layer offsets the detrimental influences of both the alloying of Al matrix and the decrease of pure Zn on the damping properties of the annealed samples, which is one of the main reasons for the high damping properties of the annealed samples.

3) The Al−30%Zn sample annealed at 350 °C for 0.5 h has good comprehensive properties. The tensile strength, the elongation to failure and the room temperature damping property (tan θ) under frequency of 1 Hz are 330 MPa, 10% and 0.025, respectively. The specific strength is ~9.93×10^4 N·m/kg, which is much larger than that (3.4×10^4 N·m/kg) of Zn−27Al alloy with similar damping property.

References

[1] TANAKA T, MAKII K, UEDA H, KUSHIBE A, KOHZU M, HIGASHI K. Study on practical application of a new seismic damper using a Zn−Al alloy with a nanocrystalline microstructure [J]. International Journal of Mechanical Sciences, 2003, 45(10): 1599−1612.

[2] DUC F, BOURBAN P E, PLUMMER C J G, MANSON J A E. Damping of thermoset and thermoplastic flax fiber composites [J]. Composites Part A: Applied Science & Manufacturing, 2014, 64(21): 115−123.

[3] OTANI T, HOSHINO K, KUROSAWA T. Damping capacity and Mechanical properties of Zn−Al alloy castings [J]. Le Journal De Physique Colloques, 1981, 42(C5): 935−940.

[4] HU X, ZHENG Y F, TONG Y X, CHEN F, TIAN B, ZHOU H M, LI L. High damping capacity in a wide temperature range of a compositionally graded TiNi alloy prepared by electroplating and diffusion annealing [J]. Materials Science & Engineering A, 2014, 623: 1−3.

[5] FUKUHARA M, YIN F, OHSAWA Y, TAKAMORI S. High-damping properties of Mn−Cu sintered alloys [J]. Materials Science & Engineering A, 2006, 442(2): 439−443.

[6] GIRISH B M, PRAKASH K R, SATISH B M, JAIN P K, PRABHAKAR P. An investigation into the effects of graphite particles on the damping behavior of ZA-27 alloy composite material [J]. Materials & Design, 2011, 32(2): 1050−1056.

[7] DEMIRTAS M, ATLI K C, YANAR H, PURCEK G. Enhancing the damping behavior of dilute Zn−0.3Al alloy by equal channel angular pressing [J]. Metallurgical & Materials Transactions A, 2017, 48(6): 2868−2876.

[8] LUO B H, BAI Z H, XIE Y Q. The effects of trace Sc and Zr on microstructure and internal friction of Zn−Al eutectoid alloy [J]. Materials Science & Engineering A, 2004, 370(2): 172−176.

[9] WEI J N, WANG D Y, XIE W J, LUO J L, HAN F S. Effects of macroscopic graphite particulates on the damping behavior of Zn−Al eutectoid alloy [J]. Applied Mechanics & Materials, 2007, 366(2): 134−136.

[10] UEDA H, OKADA T, KATO M. A study of superplastic Zn−Al alloy seismic device [J]. Transactions of the Japan Society of Mechanical Engineers C, 2002, 68: 2332−2338.

[11] ZHENG W, GAO Y X, WANG X P, LU H, ZENG L F, FANG Q F. High strength and damping capacity of LLZNO/Al composites fabricated by accumulative roll bonding [J]. Materials Science & Engineering A, 2017, 689: 306−312.

[12] HU J, WU G H, ZHANG Q, GOU H S. Mechanical properties and damping capacity of SiCp/TiNif/Al composite with different volume fraction of SiC particle [J]. Composites Part B: Engineering, 2014, 66(4): 400−406.

[13] CAI W, LU X L, ZHAO L C. Damping behavior of TiNi-based shape memory alloys [J]. Materials Science & Engineering A, 2005, 394(2): 78−82.

[14] DEMIRTAS M, PURCEK G, YANAR H, ZHANG Z J, ZHANG Z F. Improvement of high strain rate and room temperature superplasticity in Zn−22Al alloy by two-step equal-channel angular pressing [J]. Materials Science & Engineering A, 2015, 620(1): 233−240.

[15] WANG Y W, ZHANG Z H, XIAO F . Effect of powder ratio and annealing temperature on mechanical properties of Cu/Al composites with core-shell structure [J]. Materials Science & Engineering A, 2017, 705: 160−168.

[16] ZHANG Y M, YANG L J, ZENG X D, ZHENG B Z, SONG Z L. The mechanism of anneal-hardening phenomenon in extruded Zn−Al alloys [J]. Materials & Design, 2013, 50(50): 223−229.

[17] SHIN S S, LIM K M, PARK I M. Characteristics and microstructure of newly designed Al−Zn-based alloys for the die-casting process [J]. Journal of Alloys & Compounds, 2016, 671: 517−526.
[18] LIU Y, LI H Y, JIANG H F, LU X C. Effects of heat treatment on microstructure and mechanical properties of ZA27 alloy [J]. Transactions of Nonferrous Metals Society of China, 2013, 23(3): 642−649.
[19] SRINIVASARAO B, ZHILYAEV A P, LANGDON T G, PEREZ-PRADO M T. On the relation between the microstructure and the mechanical behavior of pure Zn processed by high pressure torsion [J]. Materials Science & Engineering A, 2013, 562(2): 196−202.
[20] SHIAT P, VASTAVA R B, LANGDON T G. An evaluation of the roles of intercrystalline and interphase boundary sliding in two-phase superplastic alloys [J]. Acta Metallurgica, 1982, 30(1): 285−296.
[21] KUMA P, XU C, LANGDON T G. The significance of grain boundary sliding in the superplastic Zn−22% Al alloy after processing by ECAP [J]. Materials Science & Engineering A, 2005, 410(12): 447−450.
[22] NAZIRI H, PEARCE R, BROWN M H, HALE K F. Microstructural-mechanism relationship in the zinc/aluminium eutectoid superplastic alloy [J]. Acta Metallurgica, 1975, 23(4): 489−496.
[23] NOVIKOV I I, PORTNOY V K, TERENTIEVA T E. Analysis of superplastic deformation mechanisms in Zn−22%Al alloy on the basis of electron microscopy topographic investigations [J]. Acta Metallurgica, 1977, 25(10): 1139−1149.
[24] LI N, LIU X M, WANG Q Z, CUI C X, YIN F X, JI X W, JIAO Z X. Effect of combined addition of Al−Ti−B ribbon and Zr element on the microstructure, mechanical and damping properties of ZA22 alloy [J]. Materials & Design, 2017, 127: 97−105.
[25] JIANG H J, LIU C Y, MA Z Y, ZHANG X, YU L, MA M Z, LIU R P. Fabrication of Al−35Zn alloys with excellent damping capacity and mechanical properties [J]. Journal of Alloys & Compounds, 2017, 722: 138−144.
[26] GU J H, ZHANG X N, GU M Y, LIU Z Y, ZHANG G D. The damping capacity of aluminum matrix composites reinforced with coated carbon fibers [J]. Materials Letters, 2004, 58(25): 3170−3174.
[27] FAN G L, LI Z Q, ZHANG D. Damping capacity of $BaTiO_3$/Al composites fabricated by hot extrusion [J]. Transactions of Nonferrous Metals Society of China, 2012, 22(10): 2512−2516.

粉末挤压 Al/Zn 复合材料扩散退火后的强度和阻尼性能提高机制

张志豪 [1,2]，肖 飞 [1]，王有为 [1]，姜雁斌 [1,2]

1. 北京科技大学 新材料技术研究院，北京 100083；
2. 北京科技大学 材料先进制备技术教育部重点实验室，北京 100083

摘　要：以开发高强、高阻尼、低密度 Al 基复合材料为目的，采用粉末挤压方法制备 Zn 含量(质量分数)为 10%~40%的 Al/Zn 复合棒材试样，通过退火条件控制 Zn/Al 的扩散程度及界面层的析出形貌，从而提高复合试样的强度和阻尼性能。结果表明，Zn 含量 10%~30%试样的抗拉强度随 Zn 含量的增加和退火温度的提高而逐渐增大；Zn 含量继续增大至 40%时，试样的抗拉强度基本不变或略有下降，而塑性则随之逐渐下降；Al 基体的合金化和所形成的 Zn/Al 扩散界面层是退火试样强度提高的主要原因。随着 Zn 含量的增加和退火温度的升高，试样的阻尼性能逐渐增大，Zn/Al 共析片层部分抵消退火后试样中 Al 基体的合金化和纯 Zn 的减少对阻尼性能带来的不利影响，是退火试样具有高阻尼性能的主要原因。Al−30%Zn 复合棒材试样经 350 °C 退火 0.5 h 具有良好的综合性能：室温抗拉强度为 330 MPa，断后伸长率为 10%，阻尼性能 tan θ 为 0.025。

关键词：铝基复合材料；纤维增强；力学性能；阻尼性能

(Edited by Bing YANG)