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Internal friction peak and damping mechanism in high damping aluminium alloy laminate①

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[Abstract] A new aluminium alloy laminate characterized by high damping, corrosion resistance and weldablity was developed. The laminate designed for required aforesaid functions was actually a composite material, which was made of two anti-corrosive layers (Al), two damping layers (ZnAl alloy) and one reinforcing layer (AlMg alloy) by hot rolling. The damping characteristics were studied and it was found that there was an internal friction peak at about 50 ℃ on internal fraction vs temperature curve for the laminate. For this reason, the activation energy of the peak was calculated. The origin and damping mechanism for this peak was researched by means of SEM, TEM, X-ray and DSC. It is considered that the peak is caused by the interaction between dislocations and point defects in damping layers (AlZn alloy). i. e. by the movement of dislocations dragging point defects under the action of thermal-activation. The laminate is remained at room temperature for a long time, it will weaken or even disappear with the restoration of the crystal microstructure and the reduction of the dislocation density in the ZnAl alloy layers. The mechanism of the peak is in conformity with that of the dislocation-induced damping.

[Key words] aluminium alloy; laminate composite; damping; internal friction
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1 INTRODUCTION

Aluminium alloys with high damping capacity were found in several alloy systems, such as AlSi, AlFe and AlNi[1~3]. High damping capacity of these alloys were obtained usually by strong cold process (deformation amount ε is larger than 90%). Such a large plastic deformation caused by this process made the plasticity and the toughness of these alloys worse, so that Al system alloys with high damping capacity for engineering uses were difficult to develop. ZnAl alloys, however, can obtain high damping capacity by heat treatment or mild cold process[4~6]. Azushima et al[7] and LI et al[8] reported that a sandwich structural material consisting of two steel layers and one SPZ (ZnAl22 alloy) layer was developed, which possessed high damping capacity at 300 ℃. The author developed a laminate composite material, consisting of multi-layer metals and alloys, which possessed multi-functions of high damping, anti-corrosion and weldability[9,10]. The author found that there was an internal friction peak in the laminate composite[11,12], and it would weaken or even disappear with time. This paper studied the origin and mechanism for the peak, which would be certainly helpful to further exploring the improvement or stabilization of the damping capacity of the laminate.

2 PREPARATION OF LAMINATE

The laminate had symmetric configuration, consisting of two pure Al layers, two ZnAl alloy layers and one AlMg alloy layer. It was made through the following processing:

A sandwich billet piled up by those materials, held at 360 ℃ for 1 h followed by hot rolling (ε= 80%) → held at 350 ℃ for 1 h → quenched at 18 ℃ → rolled at room temperature (ε= 60%), and then made into laminate. The layer thicknesses of Al, ZnAl and AlMg account for 2 × 4%, 2 × 17%, and 58% of the overall thickness of the laminate respectively.

In addition, each of those materials constructing the laminate was also processed respectively by the same deformation processing and heat treated as mentioned above for comparison.

3 EXPERIMENTAL ANALYSES AND CALCULATION

3.1 Characteristic curves of Q^{-1} vs t and internal friction peak

Samples with dimensions of 48 mm × 3 mm × 1 mm were taken from a laminate aged at atmospheric temperature for 2 months and 1 year, respectively, and measured for determining the relationship of internal friction (Q^{-1}) vs temperature (t) at a strain magnitude of 5×10^{-5}, using a multifunctional internal friction measuring instrument made by the Research Institute of Solid State Physics of the Academy of Sciences of China. For the laminate aged for 2 months at room temperature, the curves of Q^{-1}– t

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shown in Fig. 1 reveal that there is an internal friction peak appearing at 30 ℃ to 70 ℃. But when the samples were aged for 1 year at room temperature, the internal friction peak almost disappears, as shown in Fig. 2. Accordingly, there should be a damping mechanism to act in the process of the internal friction peak appearing or disappearing in the laminate.

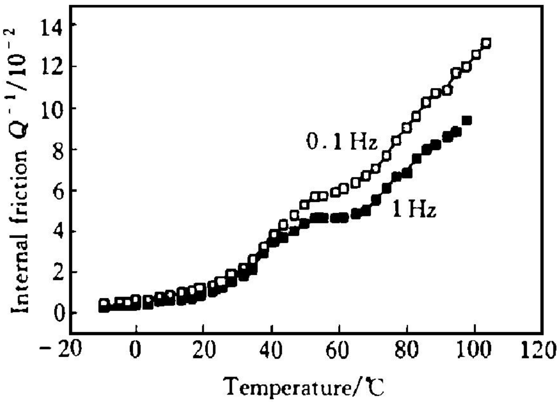

Fig. 1 Characteristics of $Q^{-1}- t$ for laminate aged at room temperature for 2 months

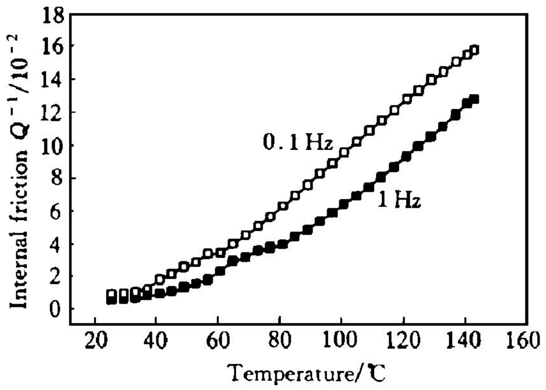

Fig. 2 Characteristics of $Q^{-1}- t$ for laminate aged at room temperature for 1 year

3.2 Internal friction for component layers and inter-layers in laminate

The internal friction in the laminate should result from the overall effects of the component layers and the interfaces between the component layers. The relationships of $Q^{-1}- t$ at 1 Hz for Al and AlMg are shown in Fig. 3, which indicates that Q^{-1} increases with increasing temperature and there is no any internal friction peak appearing at 30 ℃ to 70 ℃. Bonding between the component layers in the laminate (i. e. Al/ZnAl, ZnAl/AlMg) is metallurgical. From the SEM picture showing the interface between ZnAl and AlMg, in Fig. 4, it can be seen that there is diffusion of Mg atoms to ZnAl and that of Zn atoms to AlMg at the interface of ZnAl/AlMg. Similarly, there is also the diffusion of Al atoms to ZnAl and that of Zn atoms to Al on Al/ZnAl interface. These processes of diffusions have been completed during the hot rolling. The diffusion atoms will form some solid solutions respectively in the corresponding diffusion layers. The interfacial condition will no more change with the protraction of aging time at room temperature, and these interfaces have little effect on the internal friction of the laminate and will not lead to any internal friction peak. However, the curves of $Q^{-1}- t$ for ZnAl eutectoid alloy aged at room temperature for 90 days and about 1 year, respectively, in Fig. 5, show that there is an internal friction peak appearing at 30 ℃ to 70 ℃. And the peak will weaken or even disappear with the protraction of aging time at room temperature. In view of the above, it can be concluded that the internal friction peak appearing at 30 ℃ to

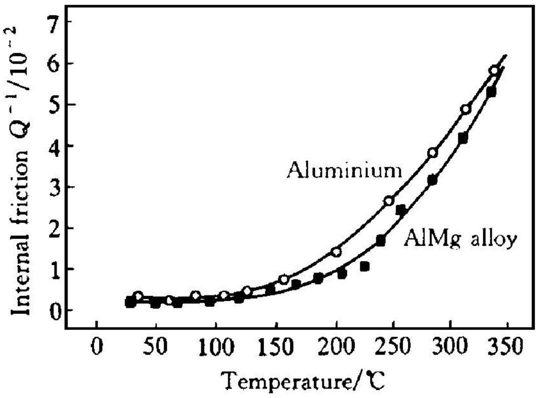

Fig. 3 Characteristics of $Q^{-1}- t$ for aluminium and AlMg alloy

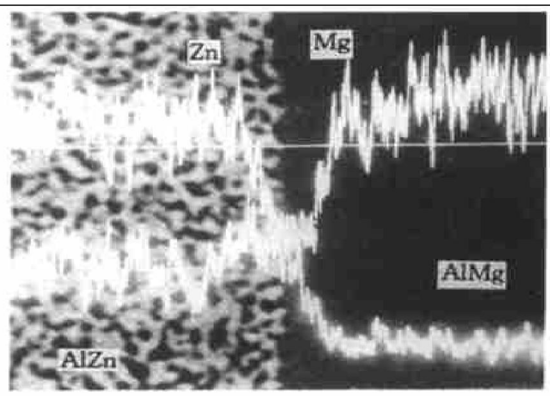

Fig. 4 SEM photograph of interface between ZnAl layer and AlMg layer

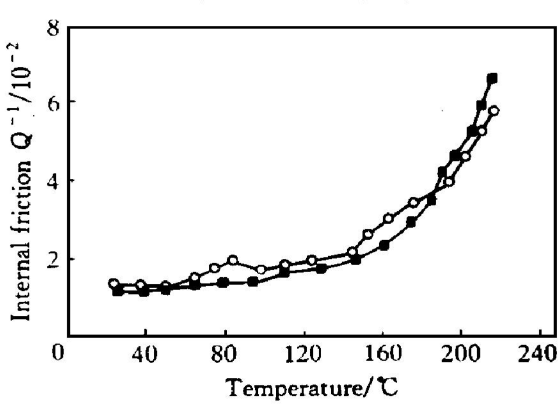

Fig. 5 Characteristics of $Q^{-1}- t$ for ZnAl alloy aged for 90 days and 1 year respectively

70 ℃ should be caused by the ZnAl eutectoid alloy layer in the laminate.

3.3 Calculation of activation energy of internal friction peak in laminate

Under the action of the thermal-activation, the relationship of Q^{-1} vs t should follow an exponential law listed as follows, which is called as the background internal friction formula[13]:

$$Q^{-1} = A\exp(-H/RT) \qquad (1)$$

where A is the constant associated with the relaxation strength ΔM, frequency ω and relaxation time τ_0; H the activation energy; R the Boltzman's constant; and t the absolute temperature. From Fig. 1 it can be seen that both parts of lower and higher temperature in the $Q^{-1}-t$ curves follow the above exponential law. The background internal friction, such as the broken lines shown in Fig. 6, can be extracted by the regression method using computer simulation. Then the curves of internal friction peak, as shown in Fig. 7, are obtained when the background internal friction is taken away from the experimental $Q^{-1}-t$ curves. Fig. 7 displays that the peak temperature shifts with the frequency. And from Fig. 7 the peak temperatures can be ascertained, which are $T_1 = 325$ K and $T_2 = 321$ K accordingly when the frequencies are $f_1 = 1$ Hz and $f_2 = 0.1$ Hz respectively. Then the activation energy of the internal friction peak can be calculated by using the following formula[13]:

$$\ln(f_2/f_1) = (H/R)(T_1^{-1} - T_2^{-1}) \qquad (2)$$

where f_1 and f_2 are the frequencies, and T_1 and T_2 are the absolute temperatures of the peaks at f_1 and f_2 respectively. When those data of the peak value ascertained from Fig. 7 are substituted into Formula (2), the activation energy H of the peak is calculated to be 475 kJ•mol^{-1}.

4 MECHANISM ANALYSIS AND DISCUSSION

There have been reports[14~19] about the research on the internal friction of AlZn eutectoid alloy.

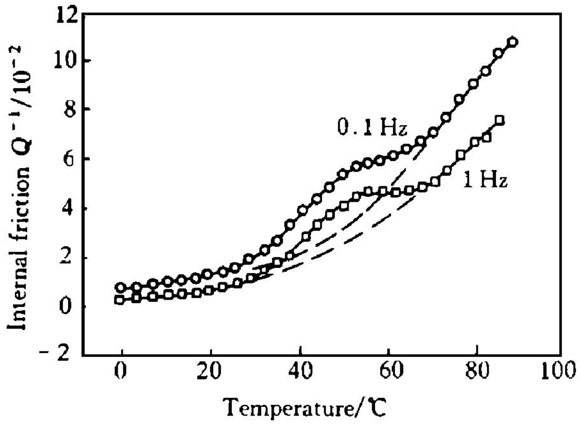

Fig. 6 Regressive curves of experimental data and background internal friction

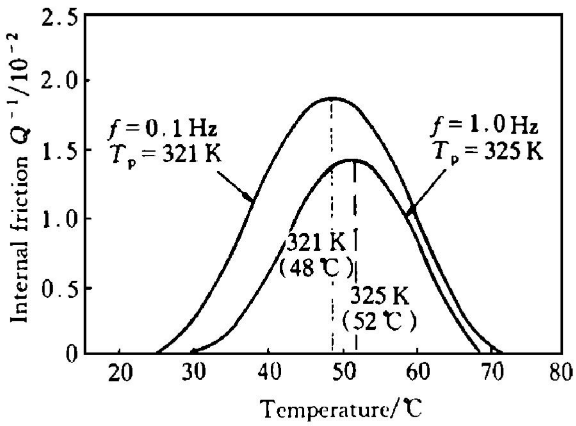

Fig. 7 Internal friction peak when background internal friction is taken away from $Q^{-1}-t$ curves

For example, Torisaka et al[14] found a series of internal friction peaks of P_α, $P_{\alpha/\beta}$ and P_β to rise at 186 ℃, 222 ℃ and 252 ℃, respectively, with activation energies of 109, 93 and 62 kJ•mol^{-1} accordingly, and through analysis the internal friction peaks were determined to be caused by the relaxation process of the grain boundaries sliding due to the diffusive flux of Al or Zn on the boundaries. Zhu and Zhang[15,16] studied the age-damping of AlZn eutectoid alloy and found two age-internal friction peaks (P_1 and P_2). They appeared in order in the alloy after quenching with the increase of aging time. It was considered that P_1 would be associated with a non-equilibrium diffusion transformation and the effect of Spinodal pre-transformation, and P_2 with the nucleation and growth of grains during a discontinuous transformation. However, the peak discussed in this paper, appearing at 30 ℃ to 70 ℃, was not mentioned in their works. The position of the internal friction peak measured by the experiment in this paper will shift with the frequency, and the calculated activation energy of the laminate is much greater than those of the above.

The result of DSC analysis shown in Fig. 8 indicates that there are no endothermic or exothermic peaks at 30 ℃ to 70 ℃ for both the laminate and the ZnAl alloy. In addition, the X-ray diffraction spectra of ZnAl quenched at 350 ℃ followed by aging at room temperature for different times are shown in Fig. 9. From Fig. 9 it can be seen that, there is the complete precipitation of the α and β phases from high temperature phase γ after aged for 1 h, followed by the slight increase in the diffraction intensity of β phase and the slight decrease in that of α phase, and then there is no anymore variation of the diffraction peak after 24 h, without new phase precipitation. Therefore, it can be affirmed that the internal friction peak at 30 ℃ to 70 ℃ in the laminate is neither caused by the relaxation process on grain boundaries or interfaces, and nor by phase transformation.

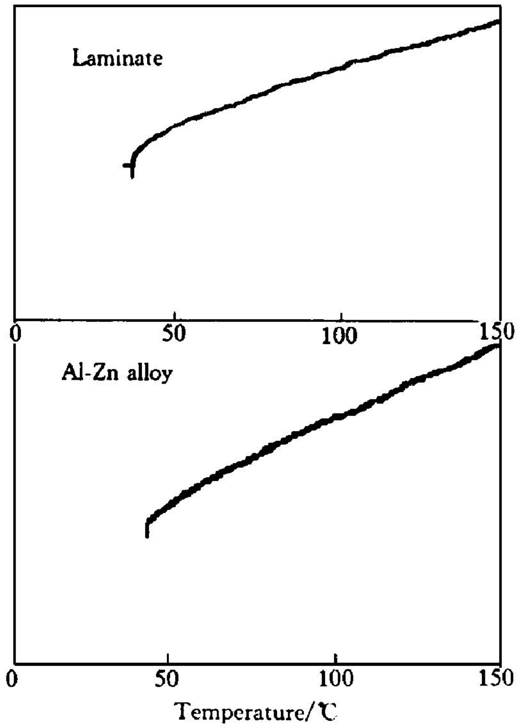

Fig. 8 Results of DSC analysis for laminate and ZnAl alloy (scan ratio of 40 K·s^{-1})

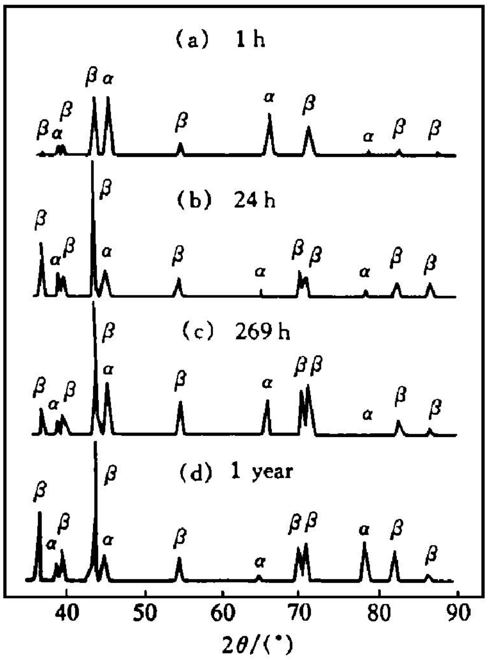

Fig. 9 X-ray diffraction spectra of ZnAl alloy aged at room temperature for different time

The variation of microstructures of ZnAl aged at room temperature for 2 months, 7 months and 1 year, respectively, analyzed by using TEM, is shown in Fig. 10, in which the black phase is α and the off-white phase is β. From the comparison among Figs. 10(a), (b) and (c), it is found that the dislocation density in grains decreases with increasing aging time. After aged for 1 year, the dislocation density in the grains decreases greatly. It can be seen that the configuration of dislocations in gains of ZnAl alloy varies with increasing aging time. This is obviously associated with the restoration and re-crystallization

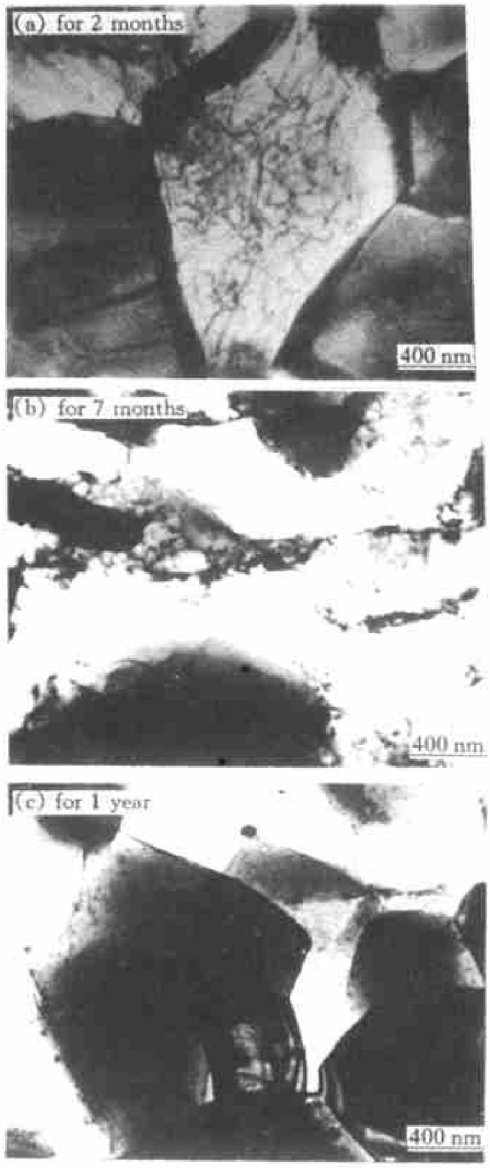

Fig. 10 TEM photographs of microstructure of ZnAl alloy aged for different times

of the microstructure of ZnAl alloy. From all those above, the mechanism for causing the internal friction peak in the laminate can be discussed as follows.

This internal friction whose peak temperature shifts with frequency as shown in Fig. 7 is clearly of relaxation mode. According to such instances as the variation of the dislocation configuration in Fig. 8 and the appearing or disappearing of internal friction peak in Fig. 1, Fig. 2 and Fig. 5, it is considered that the mechanism of the peak should be associated with the dislocations and point defects in the ZnAl alloy. These defects are brought by the process of deformation and quench. And the peak is one of relaxation mode resulting from the interaction between dislocations and point defects.

Dislocations will move when exerted by a cyclic stress. This movement will be restrained from some pinning points at or around the dislocation line. The pinning points involve the strong-pinning points (such as precipitated particles, dislocation network nodes) and the weak-pining points (such as vacancies, impurity atmosphere). Under the action of cyclic stress, dislocations will bow out in the shape of bowstring or even break away in the snowslide-like mode from the pinning points with increasing stress. The internal friction described by K-G-L mode depends on stress, i.e. on strain magnitude. However, the characteristics of the internal friction in the laminate are different from that described by K-G-L mode. That is, there is no dependence of internal friction on strain magnitude when the strain magnitude is as low as 10^{-5}. This has been confirmed by the author's experimental result[7]. The internal friction peak of the laminate will shift with the frequency, and the height of the peak will recede with the prolongation of aging time. This is not clearly the same as the internal friction peaks of the damping resonance type or of the breakaway in the snowslide-like mode described by K-G-L mode, but is a relaxation internal friction peak under thermal-activation due to the dislocation movement dragging point defects. This dislocation movement dragging the atmosphere needs to overcome a damping force, and then results in an internal friction peak. It is also due to the dislocation movement dragging impurity atmosphere that the internal friction peak as shown in Fig. 1 in the laminate is caused. With the aging time prolonging at room temperature, the crystal restoration in the microstructure of ZnAl alloy will occur, and then the dislocations in the grains will break away from some pinning points and slip to the grain boundary from the grain inside, so the dislocation density decreases greatly. As a result, the internal friction due to dragging movement will decrease, and the internal friction peak will weaken or even disappear. That is, the peak results from dislocation movement dragging impurity atmosphere under thermal activation, and obeys a dislocation-induced damping mechanism.

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