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Low Temperature Ultrasonic Attenuation in Magnesium and Magnesium Alloys

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The ultrasonic attenuation in pure Mg and Mg-Li and Mg-N alloys was studied in the temperature range from 4.2°K to 300°K. In Mg, four peaks were observed in the attenuation *vs* temperature curves. The peaks were named as P_1, P_2, P_3 and P_4 from the low temperature side. P_1 was observed at about 20°K and the origin of which was confirmed to be the interaction between sound waves and conduction electrons.

The activation energies of the relaxation processes accompanied with P_2 and P_3 were obtained as 0.009 eV and 0.09 eV, respectively. The ratio between the activation energies for P_2 and P_3 agrees well with that calculated from Seeger's theory making use of the values of the critical resolved shear stress for the basal slip and the non-basal slip. Therefore, the relaxation processes related to P_2 and P_3 are confirmed to be dislocation movements in the basal plane and in the non-basal plane, respectively.

In Mg-Li alloys, the activation energy increased for P_2 but decreased for P_3. In Mg-N alloys, the activation energy of P_2 was comparable with that of pure Mg.

The activation energy for P_4 was about 0.5 eV, and the value was considerably higher than that of the other peaks. Therefore, the origin of P_4 probably differs from that of the other peaks.

Introduction

In the variation of the internal friction with temperature in metals, a relaxation peak at a temperature corresponding to nearly a third of the Debye temperature was observed at first by Bordoni. In order to explain the origin of the peak, dislocation relaxation processes were suggested, based on the various investigations carried out mainly on face-centered cubic metals[1].

In hexagonal metals, however, only a few results have been reported on low temperature internal friction[2),3),4)]. Moreover, on the dislocation relaxation processes, impurity effect is not so clear and the study of internal friction in alloys has not been performed.

It has been experimentally shown that in magnesium the addition of nitrogen atoms gives rise to a yield point[5]. The axial ratio of magnesium is decreased by alloying with lithium atoms, and at the same time, this decrease in the ratio is associated with occurrence of the prismatic slip system beside the original basal slip[6]. The purpose of the present study is to determine the actual behavior of the Bordoni peaks in magnesium containing a known amount of nitrogen, and to investigate the interaction between dislocation and impurity atoms or point defects, and the relation between the Bordoni peaks in hexagonal metals and the slip systems.

Furthermore, the attenuation due to lattice wave-electron interaction in magnesium has been studied.

Experimental Procedure

For the ultrasonic attenuation measurements, 99.99% pure magnesium, magnesium-lithium alloy and magnesium-nitrogen alloy specimens were prepared. Magnesium-lithium alloys were melted in an argon atmosphere, and the addition of nitrogen was carried out by melting in a nitrogen atmosphere. The composition of the alloys was determined by the chemical analysis, as shown in Table 2. Each ingot was hot-forged at 500°C and shaped into rods of 1.8 cm in diameter and 1.2 cm in length. The ends of the rod were polished carefully to make suitable geometrical conditions for ultrasonic wave propagation.

The longitudinal ultrasonic attenuation coefficients were measured by the pulse-echo method between 5 and 75 Mc/s at temperatures ranging from 4.2° to 300°K. The bonding material between the specimen and the quartz crystal transducer was a high vacuum silicone grease (Dow Corning).

The electrical resistivity was measured on the same specimen by a mutual induction method.

Results of the Measurements

(1) *Pure Mg*

A typical result of the temperature variation in the attenuation of pure magnesium is shown in Fig. 1. The four peaks observed starting from the low temperature side are designated as P_1, P_2, P_3 and P_4, respectively.

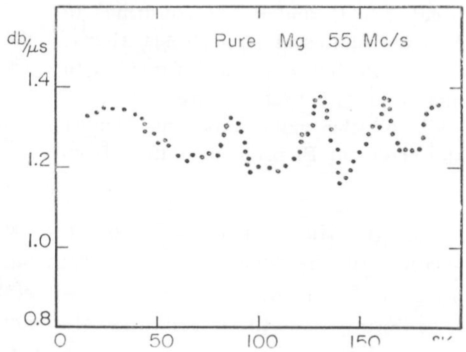

Fig. 1. Ultrasonic attenuation as a function of temperature for magnesium at 55 Mc/s.

P_1 was observed at about 20°K and the peak temperature was nearly independent of the frequency in a specimen. However, the peak height was increased in direct proportion to the square root of the frequency as shown in Table I.

The variation with temperature of the electrical resistance in the same specimen was shown in Fig. 2. A minimum was observed at about 20°K.

The height of P_2 and P_3 was reduced by annealing for 1 hour at 300°C, although the temperature of the peaks remained unchanged. Fig. 3 shows the relation between frequency f and inverted peak temperature

Table I.

Mc/s	15	25	35	45	75
T°K	14	26	20	26	22
db/μsec	1.38	1.36	1.58	1.68	1.97

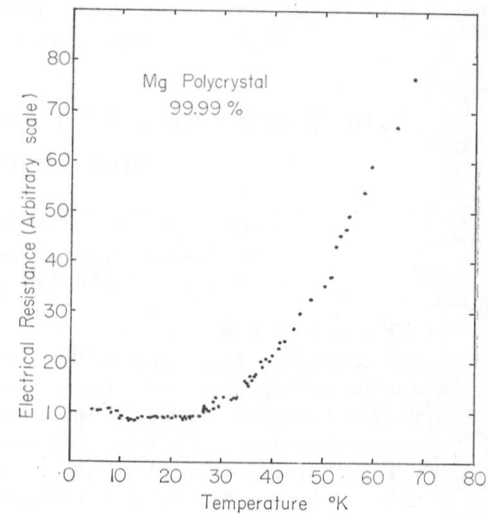

Fig. 2. The variation of the electrical resistivity with temperature in the same specimen of Mg as in Fig. 1.

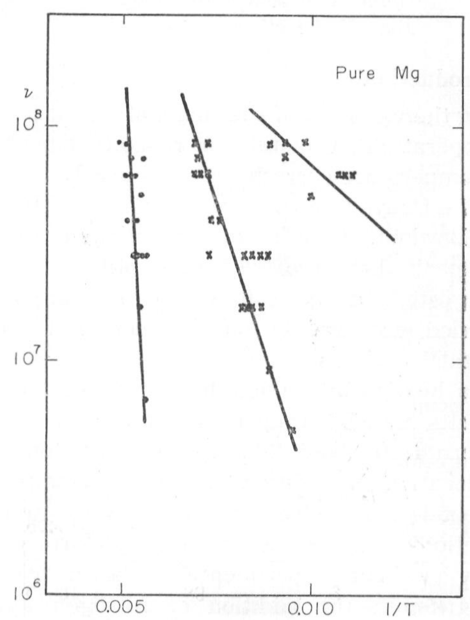

Fig. 3. Plot of the relaxation frequency against the reciprocal of the peak temperatures for magnesium.

for P_2, P_3 and P_4. Arrhenius-type relation $f=f_0 \exp(-E/kT)$ was applied on these peaks, and the activation energy E was determined from the linear relations in Fig. 3, obtaining the values listed in Table II.

Table II. Activation energy (eV)

Specimen	P_2	P_3	P_4
Pure Mg	0.009	0.09	0.42
Mg-Li 1.88%	0.018	0.10	1.31
Mg-Li 4.45%	0.015	0.07	0.92
Mg-N 0.0048%	0.010	0.23	0.36

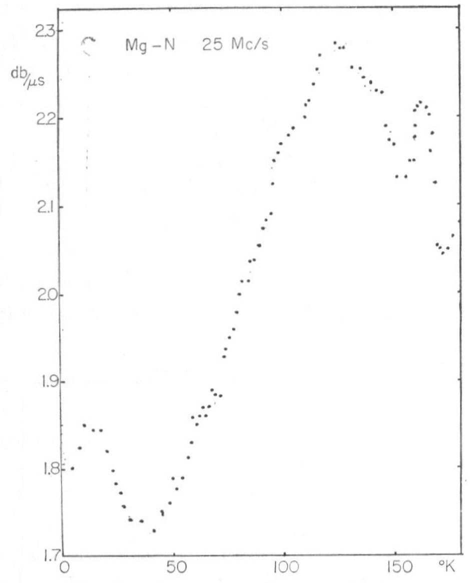

Fig. 4 Ultrasonic attenuation at low temperatures for Mg-N at 25 Mc/s.

Table III. Peak temperatures at 15 Mc/s

	P_2		P_3		P_4	
Specimen	T°K	d	T°K	d	T°K	d
Pure Mg	37	0	106.5	0	155.5	0
Mg-Li 1.88%	51	+14	99.5	−7.0	154.5	−1
Mg-Li 4.45%	50	+13	98	−8.5	150.0	−5.5
Mg-N 0.0048%	46	+ 9	116	+9.5	157.0	+1.5

(2) *Mg-N alloy*

In magnesium, alloying with nitrogen causes the increase of the peak height of P_1, the decrease of P_2, the shift of the peak temperatures to a slightly higher temperature, and the increase of the peak width of P_3. These features are shown in Fig. 4 and Table III. d is the amount of the shift of the peak temperature.

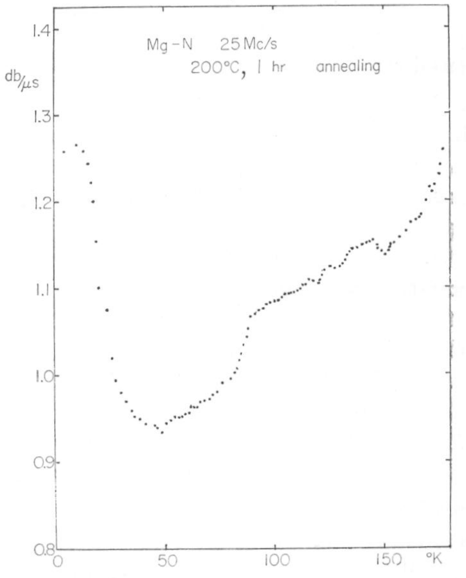

Fig. 5 Ultrasonic attenuation in Mg-N annealed for 1 hour at 200°C.

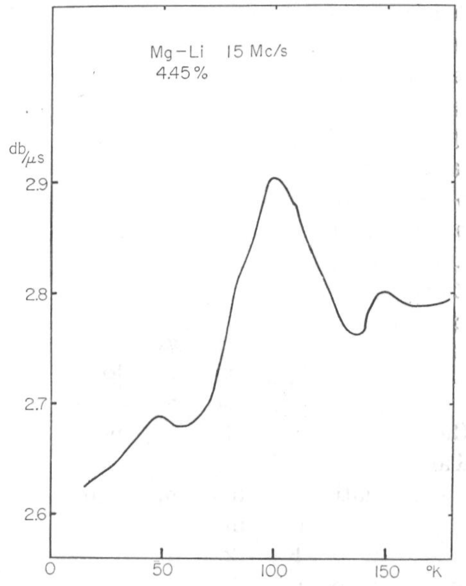

Fig. 6. Ultrasonic attenuation as a function of temperature in Mg-Li at 15 Mc/s.

After the annealing for 1 hour at 200°C, the peak height was remarkably reduced and only P_1 was observed as shown in Fig. 5.

(3) *Mg-Li alloys*

A typical curve for Mg-Li alloys is shown in Fig. 6. P_1 was not observed, P_2 shifted to the high temperature side, but P_3 and P_4 to the lower temperature side. Peak temperatures observed at 15 Mc/s are shown in Table III.

Discussion

At low temperatures where the mean free path of conduction electrons is comparable with the sound wavelength, the ultrasonic attenuation is caused by the electron-phonon interaction. According to the theory based on the electron-phonon interaction, the attenuation obtained in the present measurement varies in proportion to the electrical conductivity and to the square of the frequency. In the present experiment, these two characters are confirmed as shown in Fig. 2 and Table I. Hence P_1 corresponds to an electrical resistance minimum in magnesium.

Seeger's mechanism of dislocation relaxation[7], which was applied successfully to face-centered cubic metals, is based upon two basic parameters of dislocation; the line tension E_0 and the Peierls force τ_p. The activation energies calculated for the dislocation relaxation are roughly proportional to the square root of the product of E_0 and τ_p. E_0 is a function of the shear modulus G and the Burgers vector b, both G and b being nearly equal in magnesium for the basal slip and non-basal slip, respectively. As the critical resolved shear stress is proportional to the Peierls force[8], the activation energy is proportional to the square root of the Peierls force. In magnesium the critical resolved shear stresses for the basal slip and for the non-basal slip extraporated to 0°K are estimated as 200 g/mm² and 35 kg/mm², respectively. So the activation energy of the non-basal slip is about thirteen times larger than that of the basal slip. In Table II, the activation energy of P_3 is ten times larger than that of P_2. The coincidence of the two values is fairly good, and this confirms the fact that the relaxation processes related to P_2 and P_3 are associated with the dislocation movement in the basal plane and in the non-basal plane, respectively. The values of the Peierls force τ_p listed in Table IV are calculated from the present data by applying Seeger's theory.

Table IV.

Peak	E (eV)	τ_c(g/mm²)	τ_p(g/mm²)	Slip plane
P_2	0.009	200	90	Basal
P_3	0.09	35×10^3	5×10^3	Non-Basal

In Mg-Li alloys, the activation energies increased for P_2 but decreased for P_3 and the width of P_3 became broader than in the case of pure magnesium. The critical resolved shear stress in Mg-Li alloys increased for the basal slip and decreased for prismatic slip in contrast with pure magnesium. Hence, in the present measurements, the active non-basal slip plane is the prismatic plane.

In Mg-N alloys, the activation energy of P_2 is comparable with that of pure magnesium. This is consistent with the fact that the critical resolved shear stress for the basal plane is not affected, or may be rather slightly lowered by the addition of nitrogen to magnesium.

The peak height of P_2 in the alloy is very small compared with that in pure magnesium and the peaks P_2 and P_3 are almost eliminated by the annealing for 1 hour at 200°C. In body-centered cubic metals and Mg-N alloys a sharp yield point is observed and such a character suggests that impurity atoms lock the dislocation lines.

On the last peak P_4, the activation energy is about 0.5 eV and considerably higher than that of the other two peaks, and its origin can hardly be explained by Seeger's theory.

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