A STUDY OF THE INTERNAL FRICTION OF THE ALUMINUM-LITHIUM ALLOYS

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Abstract

The internal friction of the binary and quinary aluminum-lithium alloys has been studied. By means of the inverted torsion pendulum, the internal friction and the shear modulus of the aluminum-lithium alloys with different heat treatment and aging process have been measured in the course of ascending and descending temperatures. The frequency of vibration used was about 2 Hz and could be varied from 0.3 to 5 Hz by chang of inertia. The grain boundary internal friction peaks are observed in the two kinds of aluminum-lithium alloys (Al-Li binary alloy and Al-Li-Cu-Mg-Zr quinary alloy). Comparing with pure aluminum and some conventional aluminum alloys, the heights of the Kê peaks of the aluminum-lithium alloys are lower and the peaks are situated at a lower temperature. According to the viscous sliding model of grain boundary, these phenomena could be attributed to the grain boundary damping and pinning by the solute atoms Li and precipitates $\delta'(Al_3Li)$, $\delta(AlLi)$, $T_1(Al_2CuLi)$ and $T_2(Al_6CuLi_3)$. The evidence for grain boundary precipitation has been demonstrated by TEM observations in the present work.

I. Introduction

The internal friction technique has been used in studing the grain boundary behaviours as a very important method. Early in 1947, T.S. Kê observed an internal friction peak and a rapid drop of shear modulus (vs temperature) in polycrystalline pure aluminum which is absent in single crystal specimens.[1] These experimental results have been interpreted as the stress relaxation across (or viscous sliding along) the grain boundaries. Since then, numerous experiments which are about the grain boundary internal friction have been made in some high purity aluminum and aluminum alloys. In recent years, the internal friction technique has been used in Al-Mg, Al-Na, Al-La, Al-Y, Al-Sn and Al-Cu separately.[2-6]

It is well known that the aluminum-lithium alloys, while having lower densities and higher elastic modulus than the conventional aluminum alloys, have been used in the aerospace industry. Unfortunately, the reduction in the fracture toughness and ductility with an increase in yield strength hinders the substitution of the aluminum-lithium alloys for conventional aluminum alloys in existing aircraft designs. This deficiency seems to be due to the weakness and brittleness of the grain boundaries. Much of the work on fracture toughness has been concerned with grain boundary behaviours in the aluminum-lithium alloys, but no research work on the internal friction in these alloys.[7-9]

It is only lately that Zhou et al. observed the grain boundary internal friction peak (vs temperature) in Al-Li-Cu-Mg-Zr alloy which is the first time that anelastic measurments have been made in an aluminum-lithium alloy.[10] However, the internal friction value is very sensitive to the alloying addition. In the case of the quinary aluminum-lithium alloy (Al-Li-Cu-Mg-Zr), it is conceivable that different alloying element will be responsible for the internal friction in its own way depending on the solid solubility and precipitation state of each element in the quinary aluminum alloy. Therefore, in order to study the influence of solute Li on the grain boundary behaviours, it is necessary to measure the internal friction in the binary Al-Li alloys.

II. Experimental Procedures

The aluminum-lithium alloys studied in the present work are binary Al-Li and quinary Al-Li-Cu-Mg-Zr alloys produced by vaccum induction refining and casting in laboratory. The ingots were homogenized for 24 hours at 470°C and then extruded into the rods with diameter of 15 mm. The compositions of the binary and quinary alloys are shown in Table 1.

System	No.	Element, wt. %				
		Li	Cu	Mg	Zr	Al
binary alloy	1	1.63	-	-	-	balence
quinary alloy	2	2.07	0.98	0.29	0.14	balence
	3	2.45	0.99	0.61	0.09	balence
	4	2.73	1.00	0.46	0.05	balence

TABLE 1 COMPOSITION OF THE ALUMINUM-LITHIUM ALLOYS

The rods of the binary alloy were rolled into the sheets with thickness of 5mm. The rods of the quinary alloys and the sheets of the binary alloy were solution treated for 1 hour at 520°C and cold water quenched. The internal friction Q^{-1} and the shear modulus G´were measured on the 60 x 4 x 3 mm plate specimens in different aging conditions with a low-frequency inverted torsion pendulum. The frequency of vibration used was about 2 Hz and could be varied from 0.3 to 5 Hz by change of inertia. The Q^{-1} of any temperature can be determined through measuring the strain amplitude while the relationship is as follows:

$$Q^{-1} = \frac{1}{n\pi} \ln (A_m / A_{m+n}) \qquad (1)$$

where n and m are the times of vibration, A_m is the strain amplitude at m and A_{m+n} is the strain amplitude at m+n. The results also can be given by using the computer IBM-PC/8087 which is connected with the inverted torsion pendulum.

III. Experimental Results

Internal Friction in the Binary Al-Li Alloy

Fig. 1 illustrates the variation of the internal friction Q^{-1} and the relative shear modulus G′ of the binary Al-Li alloy with temperature. The specimens solution treated are in the natural aging condition. curves 1 and 2 were measured at ascending temperatures and curve 3 at desending. The heating or cooling rate is about 3°C/min. the frequency of vibration f is 3 Hz for curve 1 and 3; and 0.3 Hz for curve 2.

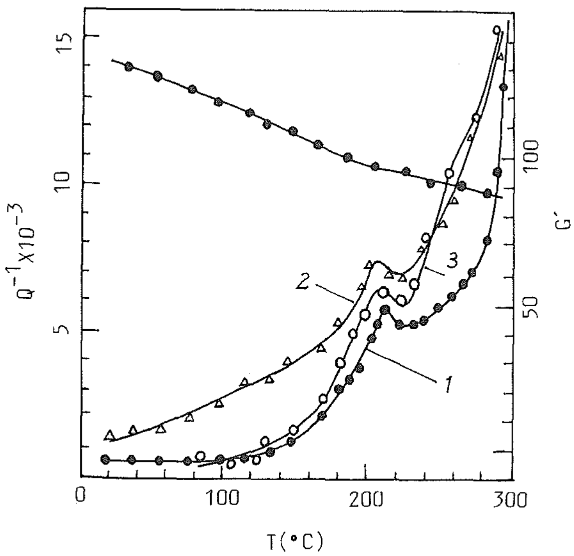


FIGURE 1. Variation of Internal Friction with Temperature in the Binary Al-Li Alloy
(1 and 2 ---- ascending temperature; 3 ---- descending temperature; 1 and 3 ---- frequency of vibration f=3Hz; 2---- frequency of vibration f=0.3 Hz)

It is seen from Fig.1 that the grain boundary internal friction peaks (GBP) appear at 210°C (curve 1 and 3) or 204°C (curve 2) separately. This means that the situated temperature of GBP is unsensitive to the measuring processing (heating or cooling), but is under the influence of frequency. However, the height of GBP in descending temperature higher than that in ascending.

Fig.2 shows the variation of the internal friction Q^{-1} of the binary Al-Li alloy with ascending temperature at the heating rate of 3°C/min in different frequency (3 Hz and 0.3 Hz). The specimens are in solution treatment and natural aging condition.

It can be seen clearly from Fig. 2 that the situated temperature of GBP changed with the frequency, at 204°C in 3 Hz and at 170°C in 0.3 Hz.

Curves 1 to 4 of Fig. 3 correspond to the cases of measuring times at first time, second time, third time, and fourth time with ascending temperature (at the heating rate of 3°C/min). The internal friction Q^{-1} was measured in the frequency of 3 Hz. The specimen was solution treated and nature aged, but each measuring processing from room temperature to 300°C corresponded to an artificial aging treatment.

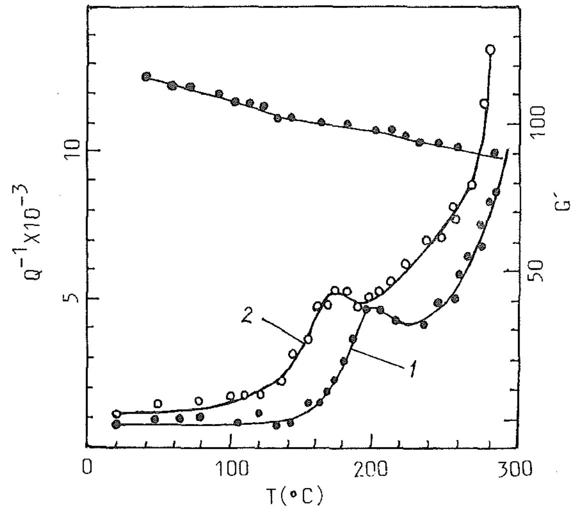


FIGURE 2. Variation of Internal Friction with Ascending Temperature in the Binary Al-Li Alloy
(1 ---- frequency f= 3 Hz; 2 ---- frequency f=0.3 Hz)

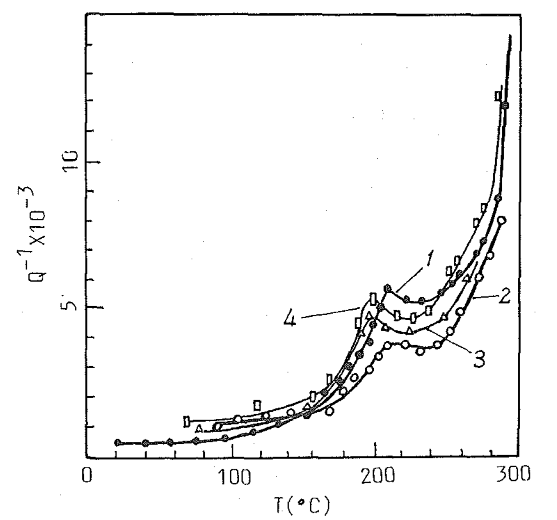


FIGURE 3. Variation of Internal Friction with Ascending Temperature in the Binary Al-Li Alloy
(at different measuring times: 1 ---- at first time; 2 ---- at second time; 3 ---- at third time; 4 ---- at fourth time)

From Gig. 3, it is seen that the height of GBPs does not change regularly, but the position of the Kê peaks shifts successively to lower temperature (from 210°C to 204°C) with increasing measuring times.

Fig. 4 illustrates the variation of internal friction with ascending temperature (at the heating rate of 3°C/min) in the binary Al-Li alloy which was solution treated at 520°C for 1 hour and then aged at 190°C for 3 hours. The measuring frequency was 3 Hz for curve 1 and 0.3 Hz for curve 2.

It is to be noted that from Fig. 4 that the background level of internal friction became higher

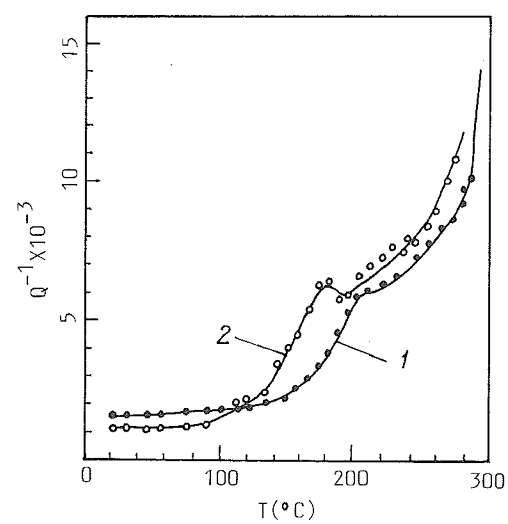


FIGURE 4. Variation of Internal Friction with Ascending Temperature in the Binary Al-Li Alloy Solution Treated at 520°C for 1 Hour and Then Aged at 190°C for 3 Hours
(1 ---- frequency f=3 Hz; 2 ---- frequency f=0.3 Hz)

in comparison with that of Fig. 3 and the GBP temperature shifted definitely to lower temperature when the frequency decreased from 3 Hz to 0.3 Hz. The situated temperature of GBP is 204°C (for 3 Hz) and 172°C (for 0.3 Hz) respectively.

Numerous experimental measurements show the following results: the background level of internal friction curves was raised with increasing aging duration at 190°C after solution treatment of 520°C/1 hr. for the binary Al-Li alloy specimens.

Internal Friction in the Quinary Al-Li-Cu-Mg-Zr Alloy

Fig. 5 illustrates the variation of the internal friction Q^{-1} of the quinary Al-Li-Cu-Mg-Zr alloy with ascending temperature. The heating rate is about 7°C/min and the measuring frequency is 1.0 Hz. The number of the specimens is No.2 (see Table 1) which were solution treated at 520°C/1 hr and then aged in nature (corresponding to curve 1) or in artificial aging 190°C/16 hrs (corresponding to curve 2) respectively.

The Kê peaks of the quinary aluminum-lithium alloy can be seen from Fig. 5. At 270°C, the GBP appeared and reached a maximum Q^{-1} of 10.5×10^{-3} for the specimen of natural aging condition. And at 200°C, the GBP reached 7.8×10^{-3} for the specimen of 190°C/16 hrs aging. The lithium content of this quinary alloy is 2.07 % (see Table 1). In order to study the influence of lithium on the internal friction, the specimen of No.3 with 2.45 % Li was taken to measure the Q^{-1} with ascending temperature (as shown in Fig. 6).

Comparing the curves with each other in Fig.6, the height of GBP appeared at 256°C (curve 1) is much higher than others, and the position of other peaks (curve 2 and 3) shifts toward lower temperatures (220°C and 210°C).

Fig. 7 shows the variation of internal friction with ascending temperature in the quinary

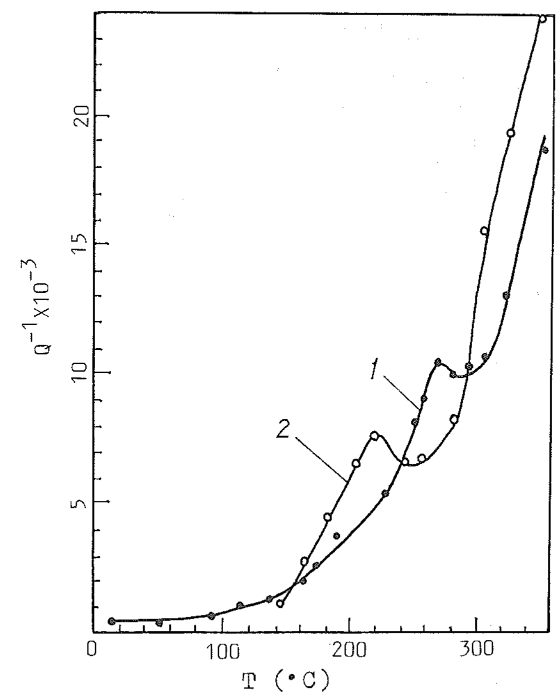


FIGURE 5. Variation of Internal Friction with Ascending Temperature in the Quinary Al-Li-Cu-Mg-Zr Alloy (No.2) Solution Treated at 520°C/1 hr and then Aged in Nature (Curve 1) or in Artificial Aging 190°C/16 hrs (Curve 2) Respectively
(the measuring heating rate is about 7°C/min; The measuring frequency is 1.0 Hz)

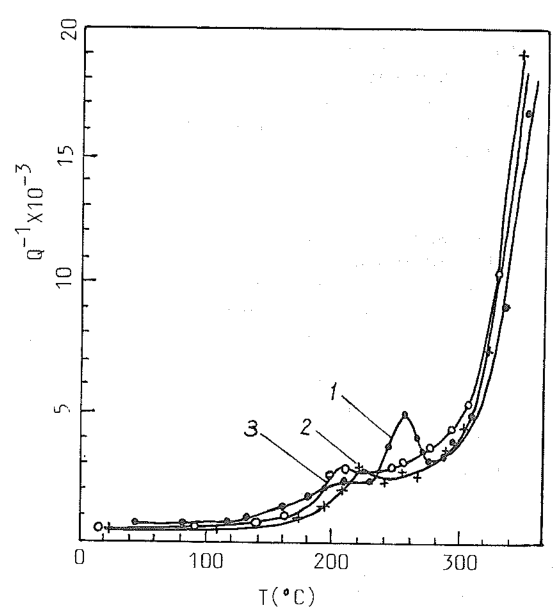


FIGURE 6. Variation of Internal Friction with Ascending Temperature in the Quinary Al-Li-Cu-Mg-Zr Alloy (No.3) Solution Treated at 520°C/1 hr and then Aged in Nature (Curve 1), in 190°C /12 hrs (Curve 2) or in 190°C/16 hrs (Curve 3) Respectively
(The measuring heating rate is about 7°C/min; The measuring frequency is 1.0 Hz)

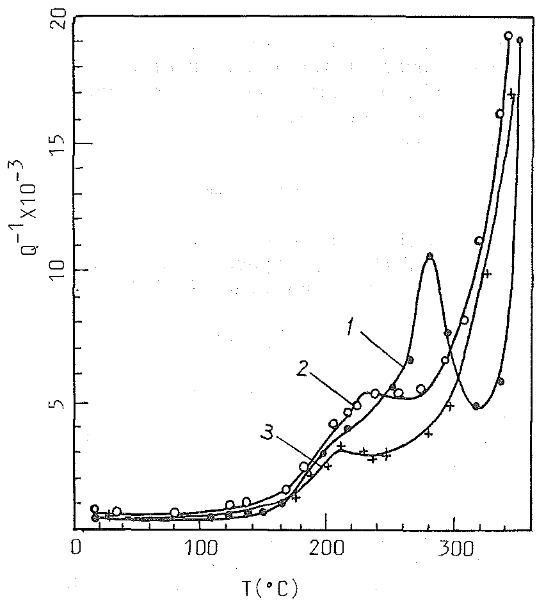


FIGURE 7. Variation of Internal Friction with Ascending Temperature in the Quinary Al-Li-Cu-Mg-Zr Alloy (No.4) Solution Treated at 520°C/1 hr and then Aged in Nature (curve 1), in 190°C/16 hrs (curve 2) or in 190°C/21 hrs (curve 3) Respectively
(The measuring heating rate is about 7°C/min; The measuring frequency is 1.0 Hz)

alloy (No.4) containing 2.73 % Li. For the sake of comparison, the heat treatment and the measuring processing of specimen No.4 were under the same condition as the No.3 (see Fig.6 and Fig.7).

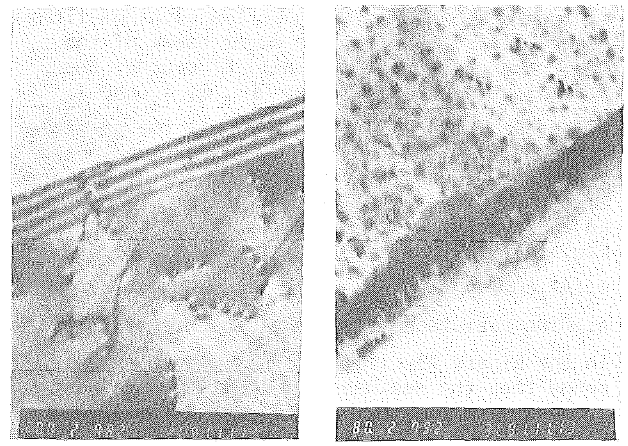
It is seen clearly from Fig. 7 that the Kê peak appeared at 276°C with the height of 10.6 X 10^{-3} and a narrow width (curve 1) for the quinary alloy in natural aging condition. But in the artificial aging condition (190°C/16 hrs and 190°C/21 hrs), the peaks appeared at lower temperatures (220°C and 210°C) with lower height and wide width separately (curve 2 and 3).

TEM Observation of the Aluminum-Lithium Alloys

Transmission Electron Microscope (TEM) observations were taken with the binary Al-Li alloy and Quinary Al-Li-Cu-Mg-Zr alloy solution treated in different aging conditions. Each studied specimen was cut by electric-spark cutting and then thinned down by chemically polishing and double-jet electrolytic polishing to film thickness for TEM observation.

Fig.8a shows the TEM micrograph of the binary Al-Li alloy solution treated in natural aging condition with grain boundary dislocations. And the precipitates were present at the grain boundaries in the binary alloy solution treated and aged at 190°C/18 hrs (see Fig. 8 b).

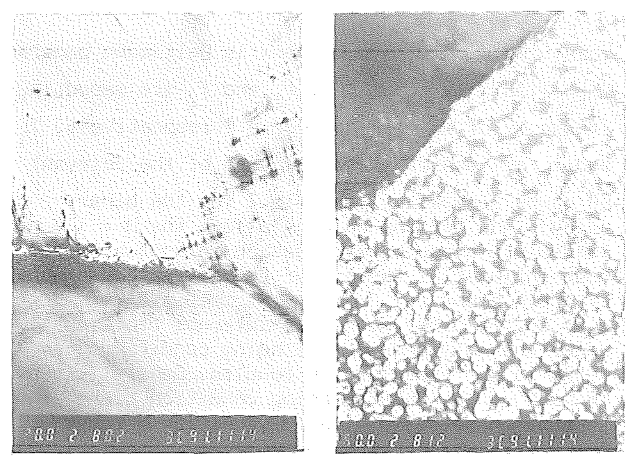
For the quinary Al-Li-Cu-Mg-Zr alloy solution treated, $\delta'(Al_3Li)$ precipitates appeared on the grain boundaries(as shown in Fig. 9 a). In the 190°C/16 hrs condition, the precipitates were present at grain boundaries and within the all grains (as shown in Fig. 9 b). According to Sanders and Starke, these precipitates include



(a) In natural aging condition (b) Aged in 190°C/18 hrs

FIGURE 8. TEM Micrograph of the Binary Al-Li Alloy Solution Treated

$\delta'(Al_3Li)$, $\delta(AlLi)$, $T_1(Al_2Cu\ Li)$ and $T_2(Al_6CuLi_3)$.[11]



(a) In natural aging condition (b) Aged in 190°C/16 hrs

FIGURE 9. TEM Micrograph of the Quinary Al-Li-Cu-Mg-Zr Alloy Solution Treated

IV.Discussion

From the above measurements and observations, it is apparent that the height of Kê peaks in the aluminum-lithium alloys (the binary Al-Li alloy and Quinary Al-Li-Cu-Mg-Zr alloy) much lower than that in pure aluminum and conventional aluminum alloys. And the position of Kê peaks in the aluminum-lithium alloys shifts toward lower temperature. According to T.S. Kê, these phenomena indicate that the viscous sliding along the grain boundaries was quite small. The internal friction is determined by the product of the distance slid and the resistance to slide along the grain boundaries.[1] Comparing with pure aluminum and conventional aluminum alloys, the solute atoms Li with the smallest atomic size factor to be considered segregate along grain boundaries and resist the grain boundary sliding in the aluminum-lithium alloys. It seems to be the major cause of the lower internal friction peaks. Of course, the precipitation of the phases δ', δ, T_1 and T_2 along the grain boundaries could be the possible effect to resist sliding. But it is to be noted that comparing with each other between the binary alloy and the quinary alloy, the heights of the Kê peaks almost are same value (see Fig.1 and Fig.5). This indicates that the $T_1(Al_2CuLi)$ and $T_2(Al_6CuLi_3)$ are not mainly responsible for sliding resistance because of absence of T_1 and T_2 in the binary Al-Li alloy. This phenomenon also means that the weakness and brittleness of grain boundary in the aluminum-lithium alloys can be ascribed mostly to the solute atoms Li and its precipitates δ' and δ adjacent to the grain boundaries.

It is seen from Fig.2 that the situated temperature of GBP is under the influence of frequency which is characteristic of relaxation. Therefore, the activation energy of the grain boundary can be calculated following the formula:

$$H = \frac{K \ln(f_1/f_2)}{\left(\frac{1}{T_1} - \frac{1}{T_2}\right)} \quad (2)$$

Then, the H = 1.2 ev. Where K is Boltzmann constant ($K = 1.38 \times 10^{-10}$ erg.°C), f_1 and f_2 are measuring frequency of curve 1 and curve 2 respectively, T_1 and T_2 are measuring temperature of the relevant Kê peaks separately (see Fig.2 for the binary alloy). And for the quinary alloy, the H = 1.4 ev. The solute atoms Li segregation is undoubted the most influential factor for the activation energy of grain boundary.

On the other hand, the internal friction is under the influence of the aging conditions as shown in the experimental results. Generally, the Kê peak of the natural aging condition higher than that of the artificial aged condition because of more atoms Li segregation, more δ' phase which is fully coherent with the matrix α (Al-Li solid solution) and more vacancy along the grain boundaries. Comparing the quinary Al-Li-Cu-Mg-Zr alloys with the binary Al-Li alloy, the background level of internal friction in the quinary lower than that in the binary. This result may be attributed to more content of Li and alloying elements Cu, Mg and Zr in the quinary alloys.

V. Conclusions

1. The height of Kê peaks in the aluminum-lithium alloys (the binary Al-Li alloy and quinary Al-Li-Cu-Mg-Zr alloy) much lower than that in pure aluminum and conventional aluminum alloys. And the situated temperature of Kê peaks in the aluminum-lithium shifts toward lower temperature.

2. According to the viscous sliding model of grain boundary, the lower Kê peaks in the aluminum-lithium alloys could be attributed to the grain boundary damping and pinning by the solute atoms Li and the precipitates δ', δ, T_1 and T_2.

3. Comparing the quinary alloys with the binary alloy, the solute Li segregation and its precipitates δ' and δ along the grain boundaries are major cause of the lower internal friction Kê peaks, to which result the weakness and beittleness of the grain boundaries in the aluminum-lithium alloys are due.

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