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Influence of alloying elements on mechanical properties of Al-Li plates①

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Abstract: The effect of alloying elements such as Cu, Mn and Zr on the mechanical properties of the Al-Li plates was studied, and the grain structure, crystallographic texture and precipitates were also investigated. It is found that the element Zr has a two-fold effect on the anisotropy of mechanical properties; the addition of element Mn can reduce the crystalline texture and the anisotropy of Al-Li plates. However, the effect of Cu element appears less pronounced.

Key words: aluminum-lithium alloy; anisotropy; texture; microstructure
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1 INTRODUCTION

In recent years, aluminum-lithium alloy has been becoming one of the most important light materials for the new aircrafts, like composites and titanium alloys. But it has not been applied as widely as being expected because Al-Li alloy is more prone to have anisotropy than the commercial non-Li-bearing aluminum alloys. Anisotropy of Al-Li alloys is a generic term used typically to describe different behaviors of mechanical properties as a function of orientation. In general, the anisotropy is commonly referred to in-plate anisotropy(IPA, R_{IPA}). There are other items of anisotropy such as through thickness anisotropy (TTA) and axisymmetric flow anisotropy(ASFA), etc[1,2]. In this paper, the influence of alloying element on the IPA of Al-Li plate was investigated.

2 EXPERIMENTAL

Six ingots with dimensions of 180 mm × 150 mm × 40 mm were direct chill cast after the melting-metal vacuum treatment. The chemical compositions of the ingots are shown in Table 1. After being homogenized, the ingots were hot-rolled at 450 ℃. The rolling rate was 0.4 m/s. The plates were finally thinned to 3 mm and the total reduction is 90.6%.

The tensile samples were cut from the plates at rolling direction (0°), transverse direction (90°) and 45° directions, respectively. The samples were T8 heat-treated which defined as 515 ℃, 0.5 h+ water quench+ 5% stretching+ 175 ℃, 16 h aging. The mechanical properties were tested on Instron 4507 machine.

After the samples were etched by Keller reagent, they were observed at Neophot-2 microscope and JSM-5600LV scanning electronic microscope (SEM). The constitutes in the alloys were detected by Link-ISIS EDX system attached in the JSM-5600LV. The fine microstructural features were investigated using a JEM-200CX transmission electronic microscope (TEM) operated at 200 kV.

The samples for texture analysis were made of three plates stuck one by one. After ground and polished, the samples were tested on the D/max-3C X-ray diffracto meter. Quantitative texture analysis was carried out on each sample by using four incomplete X-ray pole figures to evaluate Oriental Distribution Functions (ODFs). The orientation density ($f(g)$) obtained from ODF are plotted as function of the corresponding Eulerian angles.

Table 1 Chemical compositions of Al-Li plates (mass fraction, %)

Alloy	Li	Cu	Mn	Zr	Al
A	1.56				Bal.
B	1.63			0.08	Bal.
C	1.64			0.14	Bal.
D	1.58	3.06			Bal.
E	1.72	2.98	0.4		Bal.
F	1.68	2.82	0.4	0.08	Bal.

3 RESULTS AND DISCUSSION

Table 2 lists the mechanical properties on different directions of the six alloys after T8 heat-treatment. The in-plate anisotropy(R_{IPA}) in the table is expressed as[1,2]

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Table 2 Microstructure and yield strength of Al-Li plates at different directions

Alloy	Microstructure	$\sigma_{0°}$	$\sigma_{45°}$	$\sigma_{90°}$	R_{IPA}/%
A	Rx	75	66	65	12.7
B	UnRx	85	78	82	5.9
C	UnRx	97	95	96	1.5
D	UnRx	402	357	377	8.7
E	Rx	407	394	398	2.7
F	UnRx	413	358	407	7.4

Rx —Recrystallized; UnRx —unrecrystallized

$$R_{IPA}=\frac{2\sigma_L-\sigma_{LT}-\sigma_{45°}}{2\sigma_L}\times 100\% \quad (1)$$

where σ_L, σ_{LT}, $\sigma_{45°}$ mean the strength in the L, LT, 45° orientations respectively. The microstructure of the six plates under T8 state are also displayed in Table 2, where Rx is refered to recrystallized microstructure and UnRx means unrecrystallized microstructure.

The anisotropy of alloy A is very serious and the value of R_{IPA} is the largest among the six alloys, which indicates that lithium may lead to mechanical anisotropy in aluminum alloys. The recrystallization can be suspended when Zr was added in Al-Li binary alloy. For alloys B and C in Table 2, the anisotropy of the two materials with UnRx microstructures commonly is more serious than that with Rx microstructure. But in Al-Li binary alloys, the Zr addition reduces the values of R_{IPA}.

Although Cu is often added in Al-Li alloys to provide a better strength, the anisotropy of Al-Li-Cu ternary alloy is still very high. So the Cu addition has less effect on anisotropy than Zr addition in Al-Li binary. When the manganese is added in Al-Li-Cu alloy, the value of R_{IPA} distinctly drops.

Generally, the parameters which affect the mechanical anisotropy of aluminum alloy sheet and plate are the morphological texture, i.e. grain shape, crystallographic texture and alloying element, precipitate structure and distribution[3]. To date, most of the effort has been carried out on grain shape and crystallographic texture effects. The microstructures of the six Al-Li plates were observed in this paper. The results are listed in Table 2. The crystallization can be suppressed by Zr addition, otherwise, accelerated by Mn addition. For alloys A, B and C, the mechanical anisotropy drops little by little while the morphological texture becomes worse and worse, which can be seen from Table 2 and Fig. 1. Obviously, the grain shape is not the primary aspect which affects the mechanical anisotropy of aluminum alloys.

The crystallographic textures of the six alloys are identified by X-ray diffraction and ODFs. The results are shown in Table 3. It can be seen that

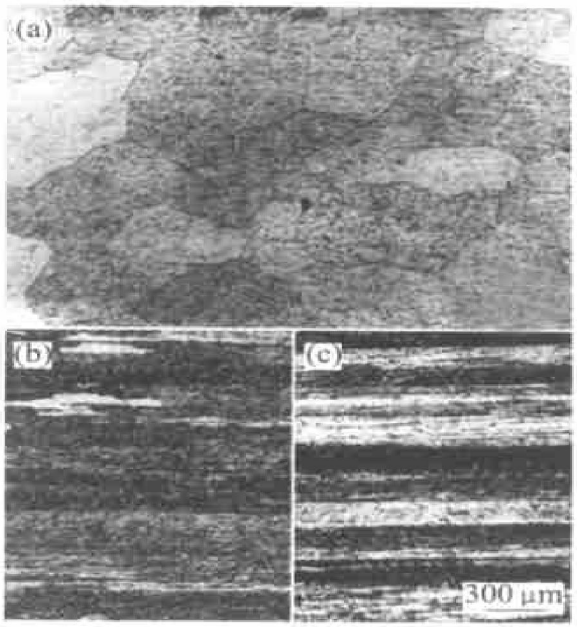

Fig. 1 Metallographic photos of alloys A, B and C
(a) —Alloy A; (b) —Alloy B; (c) —Alloy C

Table 3 Crystallographic texture of Al-Li plates

Alloys	Maximum intensity of texture					
	Cube	Goss	Copper	Brass	S	{001}⟨110⟩
A	8.15	4.0	–	–	3.0	–
B	3.00	–	4.0	–	–	8.97
C	–	–	4.0	3.0	3.0	6.34
D	2.00	1.5	4.0	1.5	2.0	6.11
E	4.85	2.0	2.0	1.0	3.0	1.50
F	1.50	–	1.5	2.0	2.0	5.36

the main texture of alloy A is typically the recrystallized texture and the Cube texture is dominant. Because of Zr-addition, the alloys B and C do not recrystallize and a hot rolling texture {001}⟨110⟩ develops. The texture component of alloy D is very complex. But the dominant component is still {001}⟨110⟩. The mechanical anisotropy of alloy D also appears. Because of Mn addition, the crystallized textures and uncrystllized textures of alloy E are in the balance. The appearance of Cube texture also implies the recrystallization in alloy E. A strong {001}⟨110⟩ texture is observed in alloy F again due to the Zr addition. Meanwhile, the value of R_{IPA} becomes higher than that of alloy E. According to the results above, the crystallographic texture has little effect on the mechanical anisotropy of the Al-Li alloy.

As mentioned above, besides the morphological texture and crystallographic texture, both the alloying element and precipitate have effects on the mechanical anisotropy of aluminum alloys. Obviously, the precipitates change with the chemical composi-

tions in Al alloys. Fig. 2 shows the precipitates in alloys A and C. Alloy A contains a large number of very fine shearable δ′ (Al_3Li) precipitates. While in alloy C, a large number of δ′/β′ (Al_3Zr) complex particles(arrowed in Fig. 2) are observed, which are non-shearable. Distinctly, the δ′/β′ (Al_3Zr) complex particles can disperse the dislocation movement, and cause a homogeneity of deformation. Since Zr inhabits the recrystallization and changes the precipitates, the anisotropy of Al-Li-Zr alloy is sharply reduced. This behavior confirms the role of alloying element and corresponding precipitate state in modifying the mechanical anisotropy of aluminum alloys.

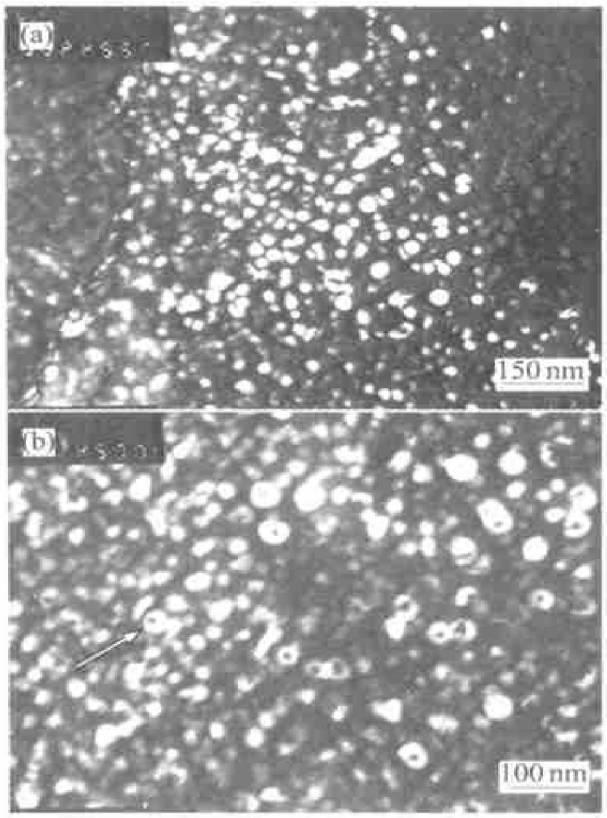

Fig. 2 Precipitates in alloy A and C
(a) —Alloy A; (b) —Alloy C

In Al-Li-Cu alloy (alloy D), the main precipitates are θ′ and T_1, as shown Fig. 3. Usually, T_1 precipitates on $\{111\}_{Al}$ planes and θ′ on $\{100\}_{Al}$. The two phases have simple relationship with the Al matrix. To analyze the effects of different precipitates in Al-Li-Cu ternary alloy on dislocation slip, Kim et al[4], Chio et al[5,6] considered their special arrangements with respect to the potential slip planes. The primary slip in aluminium alloys takes place on the octahedral {111} planes and along ⟨110⟩ directions. It has shown that the slip can also occur on the non-octahedral {110} planes and along ⟨110⟩ directions. For a {111} slip, one variant T_1 precipitate lies on the slip plane and the remaining three variants intersect the slip plane at 70.5°. As the θ′ precipitating on $\{100\}_{Al}$, all three variants intersect the {111} slip plane at 54.7°. In the case of non-octahedral {110} slip, two of the T_1 variants are perpendicular to the slip planes and two intersect them at 35.26°. Similarly, one of the three variants of θ′ will be perpendicular to the {110} slip plane and the remaining two variants will intersect the {110} at 45°[7,8]. Such directional precipitates can then result in different critical resolved shear stresses on the {111} and {110} planes. The calculating results show that the T_1 precipitate has the least obstacle on {111} slip, and θ′ precipitate on the {110} slip. The obstacle of θ′ precipitate on {111} is slightly bigger than that on {110}[8]. Thus, the T_1 and θ′ precipitates have little effect on the mechanical anisotropy of the Al-Li-Cu alloys.

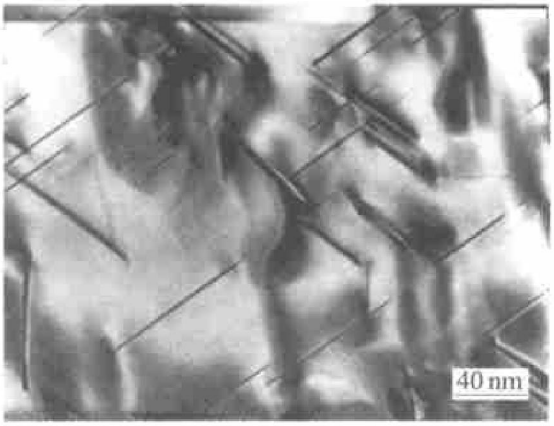

Fig. 3 Microstructure of alloy D

Fig. 4 is the microstructure of alloy E containing Mn. The spherical particle in Fig. 4 is Al_6Mn. The Al_6Mn particle can disperse the dislocations which slip on {111} planes. A large particle can be seen in the SEM image of Fig. 5, which is identified as $Al_{20}Mn_3Cu_2$ by EDX attaching on the SEM. The precipitate at grain boundaries is Al_2Cu. From Fig. 5, it can be seen that $Al_{20}Mn_3Cu_2$ particle serves as a nucleus of a grain, which is known as particle stimulate nucleation (PSN)[9,10]. Otherwise, Al_2Cu particle pins the

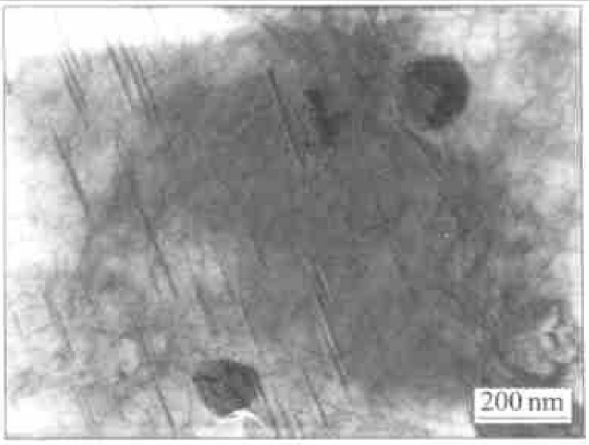

Fig. 4 Microstructure of alloy E

Fig. 5 SEM image of alloy E

movement of grain boundaries and strongly inhibits the recrystallization. The Al-Li-Cu-Mn alloy appears little anisotropy, which should owe to the Mn addition which accelerates the recrystallization.

4 CONCLUSIONS

1) The morphological texture, i. e. grain shape, has little effect on the mechanical anisotropy of Al-Li hot-rolling plates.

2) The crystallographic texture has effects on the anisotropy of Al-Li alloys, but has more obviously effects on the alloying element and precipitate structure.

3) Zr additions have two-fold effects on the anisotropy of Al-Li alloys. In Al-Li binary alloys, it can lower the value of R_{IPA}. But in Al-Li-Cu-Mn alloy, it will enhance the value of R_{IPA} because of the reservation of hot-rolling deformation crystallographic texture.

4) Mn additions can accelerate the recrystallization and reduce the value of R_{IPA}. The alloys containing Mn have more favorable effects on dispersing dislocations. So adding some alloying elements such as Mn is one of the effective ways to control the mechanical anisotropy of Al-Li alloys.

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