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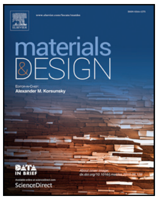

Effect of quench-induced precipitation on microstructure and mechanical properties of 7085 aluminum alloy

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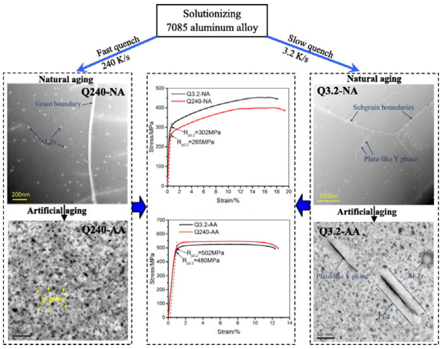
HIGHLIGHTS

- A plate-like phase with a high aspect ratio precipitates in the slowly-cooled 7085 aluminum alloy after solutionizing.
- The plate-like phase contributes to higher strength of the slowly-cooled and naturally-aged specimens.
- The plate-like phase exhibits lower aspect ratios after artificial aging and therefore smaller strengthening effect.
- The plate-like phase decreases the amount of η′ strengthening phase and therefore reduces the strength of slowly-cooled specimens after artificial aging.

GRAPHICAL ABSTRACT



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ABSTRACT

The effects of quench-induced precipitation on microstructure and mechanical properties of 7085 aluminum alloy were investigated by means of hardness test, tensile test, optical microscopy, conventional and high resolution transmission electron microscopy and scanning transmission electron microscopy. Apart from quench-induced η phase, a plate-like Y phase appears with the decrease of cooling rate from 240 K/s to 3.2 K/s after solution heat treatment. η phase exists primarily in recrystallized grains and has little strengthening effect. Y phase mainly exists in subgrains with a high density of dislocations, it has a high aspect ratio and therefore gives rise to higher hardness and strength for the slowly-cooled specimens after natural aging. After further artificial aging, the aspect ratio of the Y phase decreases and its strengthening effect becomes smaller; moreover, the presence of η and Y phases reduces the quantity of metastable η′ strengthening precipitates and therefore leads to a smaller increment in hardness and strength for the slowly-cooled specimens; consequently, the rapidly-cooled specimens have higher hardness and strength than the slowly-cooled ones.

1. Introduction

It is well known that metallurgical and micromechanical aspects control the resulting microstructure, unsoundness, strength and ductility. In this sense, the microstructure parameters are of high order of importance in order to determine the resulting mechanical behavior and

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corrosion resistance of a number of distinctive alloys [1–4]. For instance, optimized microstructure can lead to high strength and good corrosion resistance for light 7XXX series Al alloys [5,6], and they have become the primary structural materials in aerospace industry. In recent years, large structural components are desirable to decrease weight, improve reliability and extend life span of aircrafts; and therefore semi-products with large section such as thick plates or large forgings of 7XXX series Al alloys are required. It is essential to carry out continued study on the relationship between microstructure and properties of these materials in order to further improve their comprehensive properties.

7XXX series Al alloys are typical age-hardenable alloys. Solution heat treatment, quenching and aging are essential steps for the production of large semi-products of these alloys. In order to achieve high strength, rapid quenching is required to freeze as much solutes as possible in the solid solution so as to obtain the uniform dispersion of a high volume fraction of fine η' strengthening precipitates, which are supposed to have the highest strengthening effect [7], in the matrix after subsequent aging. However, slow quenching often occurs. For instance, upon quenching the cooling rate in thick plates decreases towards the center, which can lead to the undesirable phenomenon called quench-induced precipitation, resulting in lower hardness and strength [8–13], lower toughness [14,15] and lower resistance to exfoliation corrosion [16] and stress corrosion cracking [17] after subsequent aging.

According to previous investigations, the type of quench-induced phase is related to the chemical compositions of alloy and cooling rate during quenching, and it is summarized in Table 1. Starink et al. [18] observed Mg_2Si and η ($Mg(Zn,Cu,Al)_2$) phase in 7020 alloy at a cooling rate of 0.005 K/s, and S (Al_2CuMg) and η phases in 7150 alloy at cooling rates of 0.005 K/s and 1 K/s, respectively. Tiryakioğlu et al. [19] observed S phase in 7010 alloy held at 698 K and η phase held at 523–698 K during step quenching. Godard et al. [20] found S and T ($Al_{32}(Mg, Zn)_{49}$) phases in 7010 alloy held at 473–573 K and η phase held at 433–523 K during step quenching. Li et al. [21] found η phase in an Al-Zn-Mg-Cu alloy at cooling rates of 1.7 K/s and 5 K/s. Li et al. [22] found T and η phases in 7075 alloy at a cooling rate of 2 K/s. Nie et al. [23] found S, T and η phases in 7050 alloy and η phase in 7085 alloy during air quenching, but the cooling rate was unknown. Liu et al. [11,24] observed η phase in 7055 alloy at cooling rates of 2 K/s, 3 K/s and 72 K/s. Li et al. [25] found only η phase in 7085 alloy at a cooling rate of 1.8 K/s. Yang et al. [26] thought S and η phase were likely to precipitate in 7150 alloy at cooling rate of ≤10 K/s and ≤100 K/s, respectively, based on differential fast scanning calorimetry (DFSC) results. Quench-induced η, S and T phases often have a large size and therefore have little strengthening effect; moreover, they decrease the amount of Zn and Mg in the solid solution and consequently lead to a lower volume fraction of η' strengthening precipitates [19–27]. As a result, the formation of theses phases tends to reduce hardness and strength.

Recently, a new plate-like phase has been found in 7150 alloy during slow quenching. For instance, Starink et al. [18] observed a plate-like phase in 7150 alloy at cooling rates of 10 K/s and 30 K/s. Yang et al. [26] found the plate-like phase probably precipitated in 7150 alloy at cooling rates ≤300 K/s based on DFSC results. Zhang et al. [28] found the plate-like phase in 7150 alloy and named it Y phase; it precipitates at temperature and cooling rate of about 423–523 K and 0.05–300 K/s, respectively, based on differential scanning calorimetry results. It primarily contains Al, Cu and Zn and a small amount of Mg. It was suggested that the Y phase is structurally similar to $T_1(Al_2CuLi)$ phase observed in Al-Cu-Li alloys, and it has a hexagonal symmetry ($a = 0.429$ nm, $c = 1.385$ nm). Due to the high aspect ratio, the Y phase was supposed to be responsible for the higher strength of the as-quenched samples of 7150 alloy [28].

7085 alloy is an alloy with low quench sensitivity. η phase was reported to appear in this alloy during slow quenching [23,25]. In the present work, apart from η phase, a plate-like Y phase was detected in the slowly-cooled 7085 alloy specimens. The features of Y phase were investigated by conventional and high resolution transmission electron microscopy and scanning transmission electron microscopy, and its effects on microstructure and mechanical properties of the specimens after natural aging and artificial aging were discussed.

2. Experimental

A direct-chilled 7085 Al alloy ingot with a thickness of 450 mm was prepared in our laboratory. The chemical compositions were measured by Spectro Blue Sop inductively coupled plasma optical emission spectroscopy (ICP-OES), and the results are (wt%): Al-7.46 Zn-1.58 Mg-1.67 Cu-0.09 Zr. After homogenization by heating slowly to 733 K and holding for 24 h, the ingot was subjected to multi-pass hot rolling to obtain a 163 mm thick plate. Since the microstructure is generally not uniform along the normal direction in the plate [29], the samples for subsequent experiments were cut from the surface layer, as shown schematically in Fig. 1.

Fig. 2 is schematics of the experimental procedures. The samples were solution heat treated at 743 K for 15 min in an air furnace and then cooled to room temperature (about 293 K) in water and air, respectively. The time-temperature data were recorded by a thermocouple attached to the samples; the average cooling rates through critical temperature range of 460–640 K [30] were estimated to be about 240 K/s and 3.2 K/s for water quenching and air quenching, respectively. After quenching, the samples were naturally aged at room temperature

Table. 1
Quench-induced phase in some 7XXX series Al alloys due to slow quenching.

Alloy	Contents of main elements (wt%)					Cooling rate or quenching path	Quench-induced phase	References
	Zn	Mg	Cu	Zr	Al			
7020	4.37	1.19	0.04	0.14	Bal.	0.005 K/s	Mg_2Si, η	[18]
7010	6.26	2.44	1.69	0.14	Bal.	Holding at 698 K after step quenching	S	[19]
						Holding at 523–698 K after step quenching	η	[19]
	5.99	2.33	1.73	0.11	Bal.	Holding at 473–573 K after step quenching	S, T	[20]
						Holding at 433–523 K after step quenching	η	[20]
–	5.14	3.09	1.03	0.12	Bal.	1.7 K/s and 5 K/s	η	[21]
7075	5.74	2.74	1.75	0.27Cr	Bal.	2 K/s	T, η	[22]
7050	6.2	2.25	2.3	0.115	Bal.	Air quenching	S, T, η	[23]
7055	8.0	1.8	2.1	0.18	Bal.	3 K/s and 72 K/s	η	[24]
	7.9	2.2	2.1	0.15	Bal.	2 K/s	η	[11]
7085	7.5	1.5	1.65	0.115	Bal.	Air quenching	η	[23]
	7.59	1.65	1.54	0.11	Bal.	1.8 K/s	η	[25]
	7.46	1.58	1.67	0.09	Bal.	3.2 K/s	η, Y	This work
7150	6.33	2.15	2.04	0.12	Bal.	≤10 K/s	S	[18,26]
						≤100 K/s	η	[18,26]
						≤300 K/s	Y	[18,26,28]