Effect of Si addition on Solid Solution Hardening of Al-Mn Alloys*

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Abstract: Non-heat-treatable aluminum alloys owe their strength mainly to elements in solid solution. But the effect of the combination of multiple elements on strength is not well known. Small amounts of Si usually exist in many commercial alloys. Three high purity based Al-Mn binary alloys and one ternary alloy with addition of Si are investigated in this work. The varied solute contents are achieved by cast compositions and the grain structures are controlled by recrystallization. The strength is measured by tensile tests at room temperature. It is found that the addition of Si to Al-Mn alloys leads to a similar increase in strength as adding a similar amount of Mn.

Keywords: Solid solution hardening, high purity aluminum, flow stress

Introduction

Al-Mg and Al-Mn alloys are widely used, and the hardening effect of Mg and Mn in solid solution has been studied (e.g. [1]). Small amounts of Si usually exist in many commercial alloys, and may affect the strength. Tensile [2] and hot deformation experiments [3] of binary Al-Si alloys, and theoretical calculations [4] indicate that Si has a weak hardening effect. However, the effect of the combination of multiple elements on strength is not well known. The total increase of strength is not expected to be linearly dependent on each component [5]. The aim of this work was to investigate the hardening effect of Si addition in high purity Al-Mn binary alloys to study the influence of multiple elements on strength.

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Experimental

There Al-Mn binary alloys (BA1, BA2, and BA3) were made of 99.99% pure Al mixed with 99.9% pure Mn in a melting pot at about 800°C. A mold of 7cm×7.5cm×20cm was applied for directed solidification. An Al-Mn-Si ternary alloy (TA) was also made by the addition of Si to one of the binary alloys. The compositions of the alloys are listed in Table I. The cast ingots were homogenized by fast heating (200°C/h) to 635°C, where they were held for 16 hours, and finally water quenched. The cast ingots were rolled from 20mm to 4mm at room temperature. The rolled sheets were recrystallized at various temperatures for 30min in salt bath, and then cold rolled from 4mm to 1mm in thickness. The final recrystallization occurred while the specimens were held for 20min in salt bath (recrystallization temperatures in Table I). The hardness of the annealed samples was measured to determine the recrystallization temperature, and the recrystallized grain sizes were measured by optical microscopy.

The microstructures were observed by back-scattered electron imaging at 15KV in a field emission gun SEM Zeiss Ultra 55 with an EBSD detector. The textures were measured on ND-TD (normal and transverse direction) sections by coarse step EBSD mapping. The sample surfaces were electropolished in a 20% $HClO_4$ ethanol solution at room temperature and 30V for 8s. The recrystallized sheets for tensile tests were 6mm wide and the gauge section was 25mm long. An MTS 810 hydraulic testing machine was run under a constant ramp rate at room temperature, giving a true strain rate of about $10^{-3}s^{-1}$.

Table I. The compositions (mass percent) of alloys, recrystallization temperatures and grain sizes

		Mn	Si	Annealing temperature,ºC	Taylor factor *M*	Grain size,μm
PA	99.99%Al	0.00	<0.01	325	3.0	65
BA1	AlMn0.25	0.22	<0.01	350	2.9	29
BA2	AlMn0.5	0.44	<0.01	350	2.9	25
BA3	AlMn1.0	0.93	<0.01	400	2.7	37
TA	AlMn0.25Si0.1	0.22	0.10	350	3.0	33

Results and discussion

Microstructure And Textures

The microstructure was fully recrystallized (Figure 1) and no particles were observed in SEM. The grain structures of the binary alloys were relatively uniform, while the recrystallization structure of the ternary alloy was less homogeneous, containing fine-grain and coarse-grain bands, as shown in Figure 1. The coarse grain structure corresponds to the very coarse grains of the cast structures.

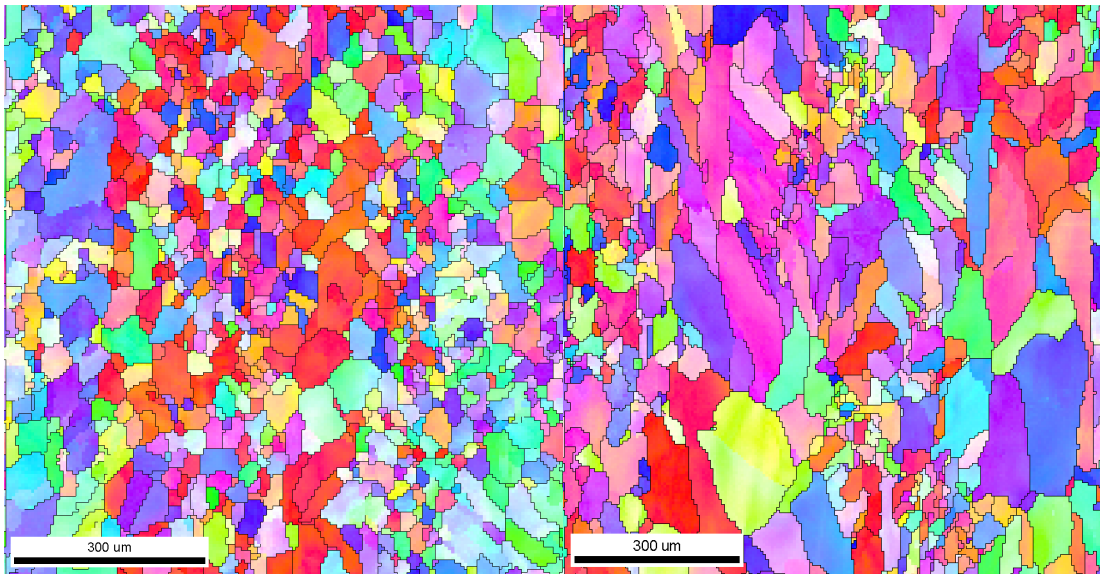

Figure 1. The grain structure of BA1(left) and TA (right).

Textures were measured by coarse step EBSD mapping. Recrystallization resulted in a Cube texture {100}<001> (Figure 2). The textures are slightly different from alloy to alloy, so that the Taylor factors were also slightly changed. Taylor factors calculated are in the range of 2.7-3.0 for all the alloys.

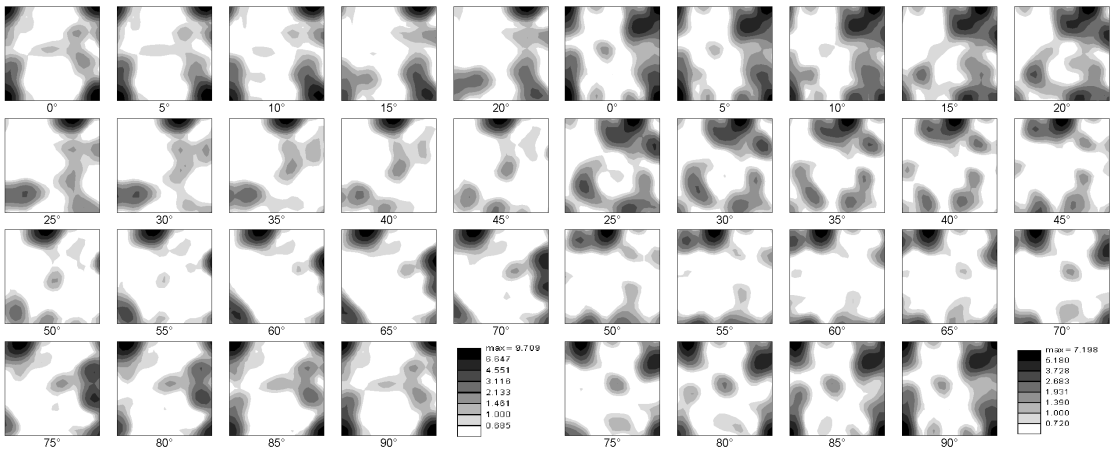

Figure 2. ODF of BA1 (left) and TA (right), showing recrystallization textures

Solid Solution Hardening

The typical stress-strain curves of all the materials are illustrated in Figure 3. Mn solutes increases both the strength of the binary alloys and the work-hardening rate at low strains (<0.1). TA and BA1 have the same Mn level, but the addition of Si leads to the higher strength of TA, although the work-hardening rates of TA and BA1 are similar. The grain size of the binary alloys is small, so the grain size effect on strength is not negligible. It can be estimated by Hall-Petch relation, where the Hall-Petch parameter, k in $kd^{-1/2}$ for high purity Al [6](k=1.27MPa*mm$^{1/2}$) is used in this work.

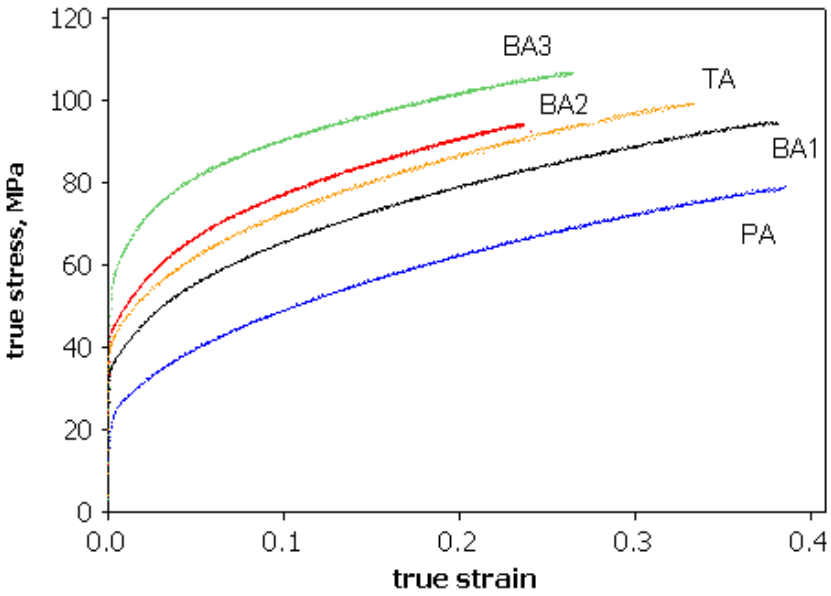

Figure 3. Stress-strain curves at strain rate of $10^{-3}s^{-1}$

Figure 2 shows that the recrystallization textures are slightly different in the alloys, so the Taylor factors vary. The contribution to the critical resolved shear stress (CRSS) caused by the solid solution was calculated from the flow stress by the equation:

$\tau=(\sigma-kd^{-1/2})/M$, (1)

where σ is the true stress, and M is the Taylor factor. The CRSS of the binary alloys at various strain levels is plotted as a function of the atomic concentration of Mn in solid solution in Figure 4. The CRSS of TA are also plotted as a function of Mn concentration in Figure 4. The relation between the CRSS and the Mn content has been expressed:

$\tau=\tau_0+Hc^n$, (2)

where H and n are constants. The parameters in equation (2) for the binary alloys are estimated by fitting the plot in Figure 4, and are listed in Table II. The difference between τ_0 and τ_{PA} is negligible, indicating all the increase in stress are due to the solutes. The solute hardening exponent n for 99.99% purity Al-Mn binary alloys is about 0.8-0.9, similar to that of the 99.999% purity Al-Mn binary alloys reported in [1]. Thus, this work confirms the slightly weaker hardening effect of Mn in high purity binary alloys as compared to the commercial purity 3xxx alloys reported in [1].

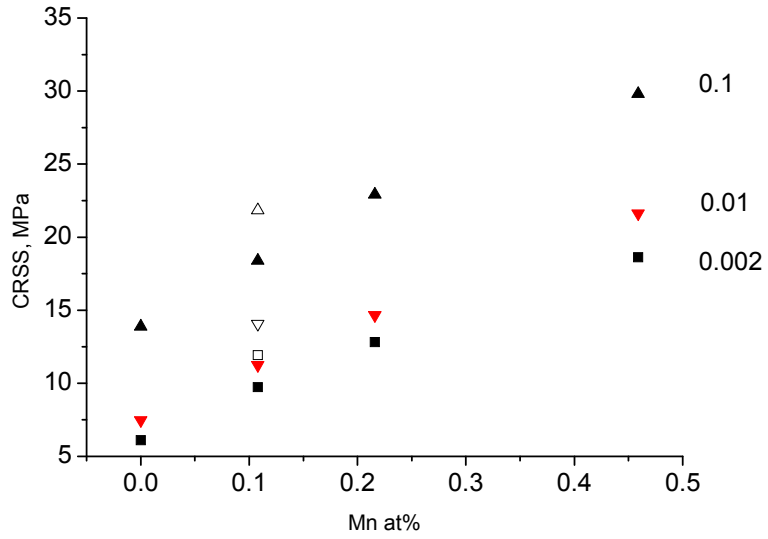

Figure 4. Shear stress at various strains (0.002, 0.01, and 0.1) as a function of Mn content in solid solution (the binary alloys, solid symbols; the ternary alloy TA, open symbols)

Table II parameters in equation (2) of high purity Al-Mn binary alloys

strain	τ_{PA}	τ_0	H	n
0.002	6.11	6.09	24.2	0.84
0.01	7.46	7.45	28.7	0.91
0.1	13.89	13.82	30.4	0.82

Tensile tests of high purity Al-0.2Si binary alloys [2] showed that the 0.2% proof stress increased by 4MPa compared to pure Al due to 0.2at%Si. The addition of 0.1at%Si into BA1 increased the 0.2% proof stress by 6.7MPa compared to BA1, suggesting that the hardening effect of Si in multi-component alloys is much stronger than in binary Al-Si alloys. It can be assumed that Si atoms act as equivalent Mn atoms, which means a Si atom multiplied by a coefficient, R_{Si}, has the same hardening effect as a Mn atom. The

coefficient R_{Si} for the flow stress of TA is 0.8-0.9 by fitting it into the trend of the binary alloys, suggesting that Si has a similarly strong hardening effect in the ternary Al-Mn-Si alloy as Mn has in the binary Al-Mn alloys. Ryen et al [1] concludes that Mn has much stronger hardening effect than Mg in solid solution. The hot deformation experiments [3] and theoretical calculations [4] indicate that Si has a much weaker effect than Mg. Thus, a small addition of Si was expected to affect the strength of the Al-Mn alloys very little. However, the ternary alloy behaves opposite the expectation. A possible explanation is that Si has a synergy effect with Mn, leading to a stronger effect than the linear sum of the concentrations. This would also explain the stronger Mn hardening in the commercial purity alloys than in the high purity binary alloys [1].

Conclusions

Manganese in solid solution of high purity alloys gives rise to a concentration dependency of strength in the power of 0.8-0.9, and a small addition of Si to the Al-Mn alloys leads to a similar increase in strength as adding a similar amount of Mn. Synergy effect between Si and Mn is a possible explanation to the significant increase in strength of the Al-Mn-Si ternary alloys.

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References

[1] Ryen Ø, Nijs O, Sjölander E, Holmedal B, Ekström HE, Nes E, "Strengthening mechanisms in solid solution aluminum alloys," *Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science*, 37 (2006), 1999-2006.
[2] Mahon GJ, Marshall GJ, "Microstructure property relationships in O-temper foil alloys," *Jom-Journal of the Minerals Metals & Materials Society*, 48 (1996), 39-42.
[3] Rønning B, Nord-Varhaug K, Furu T, Nes E, "Effect of chemical composition and microstructure on the flow stress during hot deformation of aluminum alloys," *Materials Science Forum*, 331 (2000), 571-576.
[4] Leyson GPM, Curtin WA, Hector LG, Woodward CF, "Quantitative prediction of solute strengthening in aluminium alloys," *Nature Materials*, 9 (2010), 750-755.
[5] Gypen LA, Deruyttere A, "Multi-component solid solution hardening - Part 1 Proposed model," *Journal of Materials Science*, 12 (1977), 1028-1033.
[6] Hansen N, "The effect of grain size and strain on the tensile flow stress of aluminium at room temperature," *Acta Metallurgica*, 25 (1977), 863-869.