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Effect of alloy composition and heat treatment on mechanical performance of 6xxx aluminum alloys

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Abstract: The effect of alloy composition and heat treatment, including natural ageing and pre-ageing, on the mechanical performance of eight 6xxx alloys designed with systematically varying Si, Mg and Cu contents was studied. The results show that not only the alloy composition and heat treatment before forming influence the formability, but also they have an effect on the paint bake response of the alloys. Increasing the alloy Si content, decreasing Mg/Si ratio and adding 0.3% Cu (mass fraction) were generally found to improve the tensile ductility and formability of the alloys studied, while pre-ageing was found to decrease these properties. A full property profile of these alloys in terms of strength, tensile ductility, work hardening, strain rate sensitivity, forming limit and paint bake response was presented.

Key words: 6xxx aluminum alloys; automotive sheet; heat treatment; formability; mechanical performance

1 Introduction

Al−Mg−Si(−Cu) alloys, also known as 6xxx series alloys, have been considered the most promising candidates for automotive body panel applications due to their good combination of strength, formability and corrosion resistance [1]. Mg and Si are the major solutes in these alloys, which increase the strength of the material by the formation of strengthening agents (precursors to Mg_2Si) during the paint-bake cycle [2]. Copper is often added to improve the precipitation kinetics [3,4], although the corrosion resistance of these alloys tends to be degraded by the addition of copper [5].

Stretch forming is a common deformation mode in the production of 6xxx alloy exterior automotive body panels [6]. A superior stretchability requires high work hardening and strain rate hardening capabilities [6,7], which are controlled by the alloy composition and heat treatment [8]. Furthermore, forming of 6xxx series sheet alloys is typically carried out in the naturally-aged or pre-aged conditions [9]. Pre-ageing is normally performed after solution treatment to stabilise the material and improve the final age hardening response [10]. The effect of composition and heat treatment on the formability of 6xxx alloys has been previously investigated to some degree [11,12], but controversies still exist. Most importantly, the mechanism of how the alloy composition and heat treatment influence the formability of these alloys is still unclear. This could impede the development of new 6xxx alloys for automotive panel applications.

In this study, the effect of alloy composition and heat treatment (including natural ageing and pre-ageing) on the tensile ductility and stretch formability of eight 6xxx alloys designed with systematically varying Si, Mg and Cu contents is investigated.

2 Experimental

Eight alloys whose compositions are listed in Table 1 were studied. It should be noted that the total mole fraction of Mg and Si in alloys A2, A4 and A6 is nearly the same. Ingots were cast into permanent molds, homogenised at 460 °C for 6 h, and then at 540 °C for 24 h, followed by hot rolling and subsequent cold rolling to 1 mm thick sheet.

The sheets were solution treated at 550 °C for 0.5 h

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Table 1 Alloy compositions

Alloy	w(Fe)/%	w(Mn)/%	w(Ti)/%	w(Zn)/%	w(Cu)/%	Mg		Si		x(Mg+Si)/%
						w/%	x/%	w/%	x/%	
A2	0.07	0.12	0.10	0.12	−	1.06	1.18	0.50	0.48	1.66
A3	0.06	0.12	0.11	0.11	−	0.43	0.48	0.45	0.43	0.91
A4	0.07	0.12	0.11	0.13	−	0.41	0.46	1.26	1.21	1.67
A5	0.06	0.12	0.12	0.10	−	0.41	0.46	1.50	1.44	1.90
A6	0.06	0.11	0.12	0.11	−	0.70	0.78	0.80	0.77	1.55
A7	0.08	0.12	0.11	0.12	0.29	0.96	1.07	0.48	0.46	1.53
A8	0.07	0.11	0.11	0.10	0.29	0.65	0.72	0.85	0.82	1.54
A10	0.09	0.12	0.11	0.11	0.27	0.35	0.39	1.22	1.18	1.57

in a salt bath, followed by water quenching. Then the as-quenched samples were either naturally aged for one week (NA1W) or immediately pre-aged at 200 °C for 20 s and then naturally aged for one week (PA200, 20 s + NA1W). The naturally aged and/or pre-aged alloys were isothermally aged at 170 °C for 30 min to simulate the paint-bake cycle (PB) used in automotive applications.

Hardness testing was employed to study the effect of heat treatment on the hardness of the alloys before and after the paint-bake treatment. Tensile tests, strain rate jump tests and forming limit tests were conducted on naturally aged and/or pre-aged samples. An Instron screw-driven machine with a nominal strain rate of 2×10^{-3} s^{-1} was used for determining uniaxial tensile properties. Strain rate jump tests were performed with the strain rate being changed by a factor of 10 (between the nominal strain rates of 2×10^{-4} s^{-1} and 2×10^{-3} s^{-1}). The work-hardening rate was determined by numerically differentiating the true stress−true plastic strain data using a moving regression method. Each data point on the σ−ε^p curve, and the six adjacent data points (three on each side), were used to obtain a best-fit linear regression line, and the slope of this line was treated as the work-hardening rate at that point. The resulting values of derivative were then smoothed to reduce the noise in the data. Forming limit diagrams (FLD) were determined by stretch forming of samples over a spherical punch in an Erichsen sheet metal tester. Only the values of the forming limit in the plane strain stretching condition (FLD_0) of the alloys studied are reported here. This quantity is particularly important, as 85%−90% of failures in the automotive stamping lines occur in the plane strain condition [13].

3 Results

The tensile properties and FLD_0 of the naturally aged alloys are summarised in Table 2. These data show that with increasing Si content (from alloy A3 to A4, and further to A5), both the strength and tensile ductility increase. With increasing Mg content (from alloy A3 to A2) the strength is improved, but the tensile ductility is hardly affected. However, with the same total Mg plus Si mole fraction, a reduction in the Mg/Si ratio (from alloy A2 to A6, and further to A4) leads to an increase of the tensile ductility. Furthermore, Cu is found to have a positive influence on the tensile ductility. As for the formability, increasing the Si content, decreasing the Mg/Si ratio and/or increasing the Cu content are found to increase the FLD_0 value.

Table 3 lists the tensile properties and FLD_0 values

Table 2 Tensile properties and FLD_0 of alloys after natural ageing for 1 week

Alloy	σ_Y/MPa	σ_{UTS}/MPa	ε_u/%	ε_t/%	FLD_0
A2	136	251	23.6	33.8	0.22
A3	84	183	23.0	33.6	0.21
A4	138	254	25.0	36.7	0.28
A5	147	269	25.2	36.9	0.29
A6	149	264	23.9	35.3	0.25
A7	135	261	24.8	34.3	0.28
A8	157	283	24.8	34.9	0.28
A10	137	262	25.9	37.4	0.28

Table 3 Tensile properties and FLD_0 of alloys after pre-ageing for 20 s at 200 °C

Alloy	σ_Y/MPa	σ_{UTS}/MPa	ε_u/%	ε_t/%	FLD_0
A2	132	242	22.0	31.7	0.21
A3	76	168	22.1	31.6	0.20
A4	135	250	24.7	35.6	0.26
A5	140	259	24.8	36.5	0.25
A6	151	264	23.7	35.2	0.24
A7	126	247	24.4	31.3	0.23
A8	150	274	25.0	34.5	0.24
A10	131	255	24.6	34.5	0.24

of the same alloys after pre-ageing. It is seen that in most cases, the pre-ageing treatment can decrease both the strength and the tensile ductility, albeit slightly. With regard to the formability, pre-ageing is found to reduce the FLD_0 value, especially in the alloys with high Si content and/or with Cu additions. Although the formability of the materials is decreased with the pre-ageing treatment, the paint-bake response is significantly improved for all alloys except A3 and A10, as shown in Fig. 1.

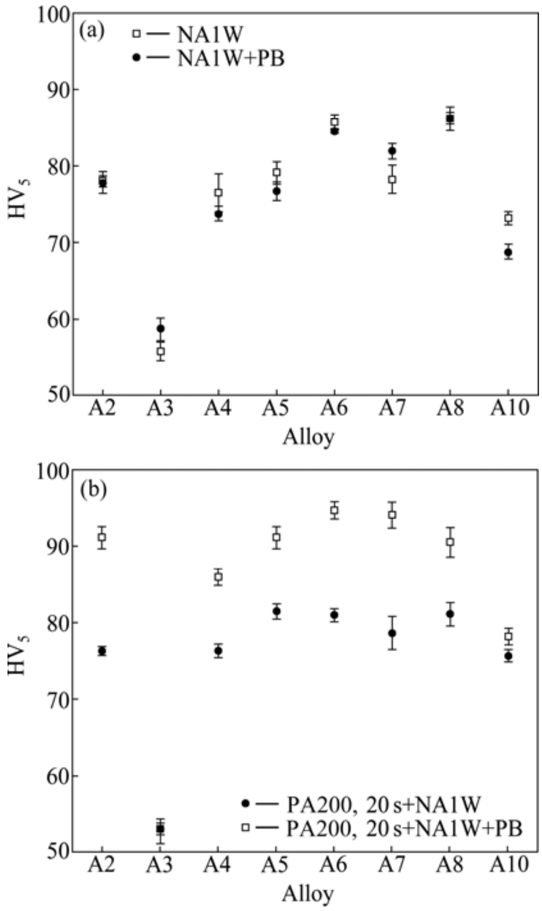

Fig. 1 Effect of natural ageing (a) and pre-ageing (b) on hardness of alloys before and after paint-bake treatment

4 Discussion

Both the tensile ductility and the stretch formability are influenced by the work hardening and strain-rate hardening behaviour of the materials [7,14]. Work hardening controls the deformation before the onset of necking, while strain-rate hardening influences the deformation beyond the onset of necking [15]. Therefore, the following discussion will focus on the influence of alloy composition and heat treatment on these two characteristics of the alloys considered.

4.1 Effect of Si and Mg content

Figure 2 shows the work hardening rate curves for alloys A2 to A5. It is seen that the alloys with high Si content or Mg content have a large work hardening rate, especially at strains close to the onset of necking. This is important for achieving desirable levels of tensile ductility and formability [16]. As for the strain rate sensitivity (SRS), high Si content alloys show a greater SRS than low Si content ones (see Fig. 3). By contrast, increase in the Mg content can reduce the SRS. It is not surprising that the alloys with higher SRS systematically exhibit a larger post-uniform elongation since the rate of neck development is believed to be controlled by the strain-rate hardening of the material [17]. Consequently, increasing the Si content can increase both the tensile ductility and the formability of the materials due to increased work hardening and strain-rate hardening capabilities. By contrast, Mg content has little influence on these properties due to the decrease in the strain-rate hardening capability.

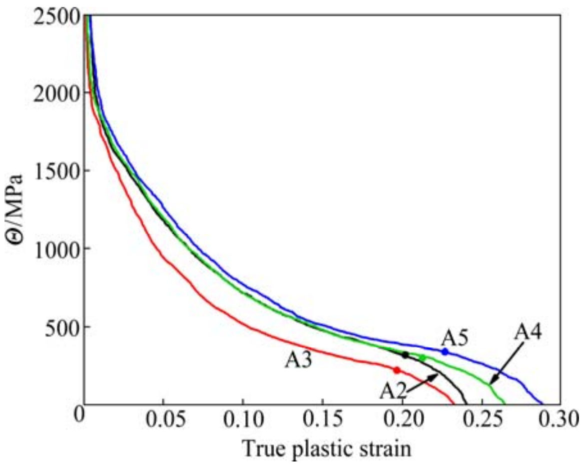

Fig. 2 Plots of work hardening rate vs true plastic strain for alloys naturally aged for one week (The dots represent the onset of necking)

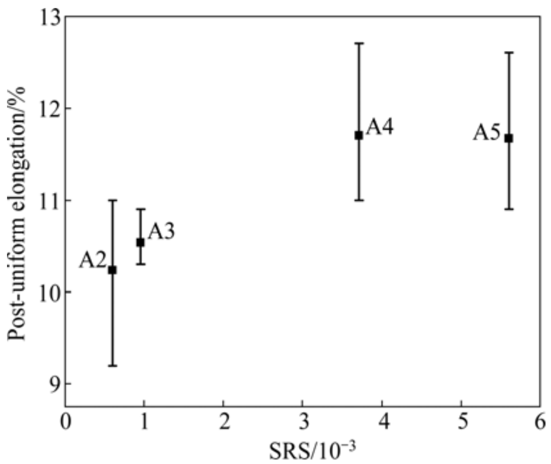

Fig. 3 Dependence of post-uniform elongation on SRS for alloys naturally aged for one week

4.2 Effect of Mg/Si ratio and Cu content

Figure 4 shows the work hardening rate curves for alloys with different Mg/Si ratios (alloys A2, A6 and A4), including copper-containing versions of these three alloys (A7, A8 and A10, respectively). As seen in Fig. 4, the alloys with lower Mg/Si ratio exhibit a higher work hardening rate at the uniform strain; the addition of Cu slightly raises the work hardening rate at strains close to the onset of necking. Increasing the Mg/Si ratio (from alloys A4 to A6, and further to A2) and/or the Cu content is found to decrease the SRS of the flow stress, which, in turn, reduces the post-uniform elongation (Fig. 5).

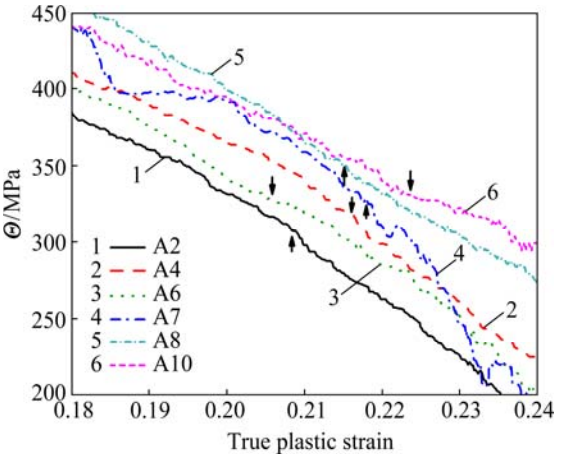

Fig. 4 Work hardening rate curves for alloys A2−A10 after one week of natural ageing (Arrows indicate uniform strain)

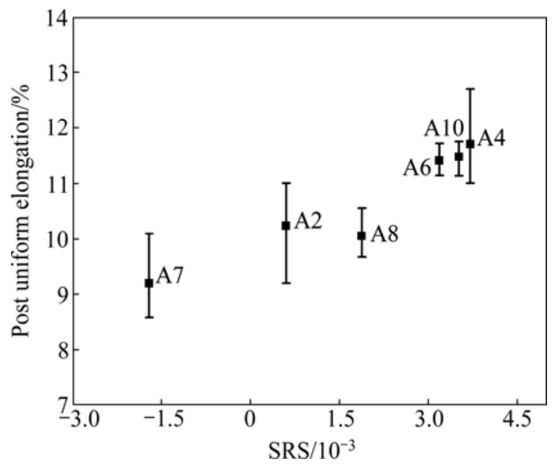

Fig. 5 Dependence of post-uniform elongation on SRS of flow stress of alloys A2−A10 after one week of natural ageing

Thus, with the high work hardening and strain-rate hardening capabilities, the material with a large Si/Mg ratio has a high tensile ductility and formability. Copper additions can increase the tensile ductility and formability due to improved work hardening capability, while reducing the strain-rate hardening capability of the materials.

4.3 Effect of heat treatment

Figure 6 shows work hardening rate curves for alloys A2 and A7 in the naturally aged and pre-aged conditions. As seen in Fig. 6, pre-ageing slightly decreases the work hardening rate in the range of the uniform strain. Pre-ageing also decreases the SRS of the flow stress (Fig. 7). It is interesting to note that the decrease in the SRS has a larger influence on the FLD_0 value than on the post-uniform elongation for alloy A5 (cf. Fig. 7 and Table 2 and Table 3). Hence, with the decreased work hardening and strain-rate hardening capabilities, the alloys in the pre-aged condition show a lower tensile ductility and formability than the same alloys in the naturally aged condition.

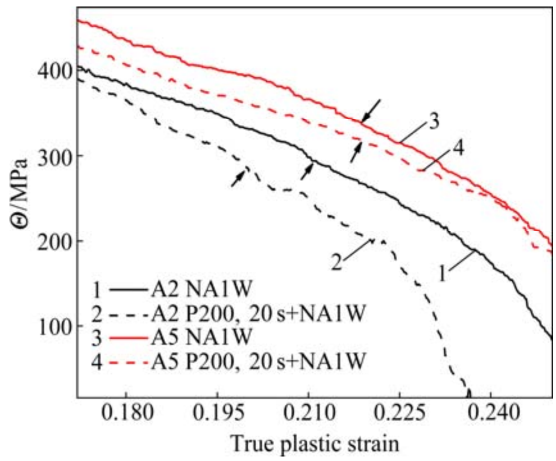

Fig. 6 Work hardening rate curves for alloys A2 and A5 (The arrows indicate uniform strain)

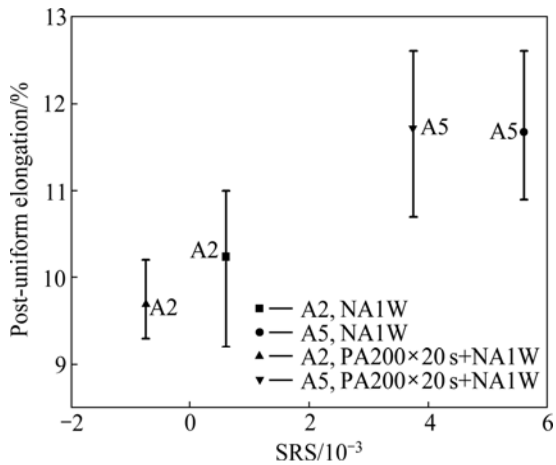

Fig. 7 Dependence of post-uniform elongation on SRS of flow stress for alloys A2 and A5

5 Conclusions

1) Increasing Si content and decreasing Mg/Si ratio can raise the tensile ductility and stretch formability of the alloys due to the increased work hardening and strain-rate hardening capability.

2) The addition of 0.3% Cu (mass fraction) also increases the tensile ductility and stretch formability of the alloys due to an enhancement of the work hardening capability, although Cu additions can slightly reduce the strain-rate hardening capability of the materials.

3) While pre-ageing for 20 s at 200 °C was found to improve the paint-bake response after natural ageing, it was also found to reduce the stretch formability of the alloys.

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合金成分与热处理对 6xxx 系铝合金力学性能的影响

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摘 要：研究合金成分(Mg，Si，Cu)和热处理(自然时效和预时效)对 6xxx 系铝合金力学性能的影响。结果表明：合金成分与热处理不仅影响材料的成形性能，而且影响材料的烘烤硬化性能；提高合金中 Si 含量或 Si/Mg 比或添加 0.3%Cu，可显著提高材料的韧性和成形性能，而预时效将减低材料的韧性和成形性能。对所研究合金的强度、韧性、加工硬化、应变敏感性、成形极限和烘烤硬化性进行了比较和总结。

关键词：6xxx 系铝合金；汽车板；热处理；成形性能；力学性能

(Edited by Sai-qian YUAN)