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THE EFFECT OF SILICON AND COPPER ON THE PRECIPITATION HARDENING OF SHEETS OF A 6XXX-SERIES ALLOY

VPLIV SILICIJA IN BAKRA NA IZLOČILNO UTRDITEV PLOČEVIN IZ ZLITIN VRSTE A 6XXX

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Today Al-Mg-Si-Cu alloys are widely used as sheet materials for various automotive details, including the car body. These alloys are subjected to quenching and aging in order to achieve higher strength. The precipitation-hardening response depends on the temperature of aging, the degree of deformation and the composition.

We studied the effects of silicon and copper as well as the effects of deformation prior to artificial aging on the mechanical properties of Al-1% Mg_2Si sheet alloys (6009 type).

It was shown that the artificial aging of naturally aged and deformed 6XXX series alloys is an undesirable operation because it results in reduced ductility with no advantage in terms of strength. The causes of this behavior are discussed.

Key words: aluminum, aging, hardening, deformation

Zlitina AlMgSiCu se uporablja v obliki pločevine za različne dele avtomobilov, vključno s karoserijo. Visoko trdnost dobijo te zlitine po gašenju in staranju. Izločilna utrditev je odvisna od temperature staranja, od stopnje deformacije in od sestave. Raziskan je bil vpliv silicija in bakra pred umetnim staranjem na mehanske lastnosti zlitin Al-1% Mg_2Si (vrsta 6009) za pločevino. Umetno staranje naravno staranih in deformiranih zlitin vrste 6XXX je neželeno, ker zmanjša duktilnost in ne poveča trdnosti. Vzroki za tako ponašanje so raziskani.

Ključne besede: aluminij, staranje, utrditev, deformacija

1 INTRODUCTION

Wrought alloys of the Al-Mg-Si-(Cu) system (6XXX series, e.g. a 6009 alloy) are widely used in various applications including the automotive industry[1]. This is due to the good combination of such properties as technological plasticity, strength, ductility and corrosion resistance. The usual operations for manufacturing autobody parts include ingot casting, hot and cold rolling, quenching of a sheet, holding for some time at room temperature (natural aging), stretching (stamping) with small degrees of deformation of 5-10%, painting and drying (artificial aging)[1]. The examination of the variation in mechanical properties during processing is very important. Moreover, the composition of the alloy may play a crucial role.

The strengthening after aging of Al-Mg-Si alloys is due to the precipitation of the coherent phase Mg_2Si (β''). It is well known that the excess of silicon facilitates the precipitation of fine β'' particles and therefore improves hardening[2]; small additions of copper to Al-Mg-Si alloys are known to refine and increase the precipitation density of these β'' particles[3]. Copper additives also decrease the harmful effect of natural aging on the properties of an artificially aged Al-Mg-Si alloy. These effects are due to the fact that copper atoms influence the nucleation and stability of GP (Mg, Si) zones in such a way that these zones become the nuclei for the coherent phase upon artificial aging. Cold deformation after natural aging may destroy GPZs and facilitate the β'' to β' transition upon artificial aging. The latter semicoherent phase has much less strengthening ability and so the strength of an aged material is decreased[4].

The effects of deformation between natural and artificial aging as well as the effects of silicon and copper concentrations were the subjects of this study.

2 EXPERIMENTAL

Alloys of the 6009 type containing 0.63% Mg, 0.25 Mn, 0.15% Zr, up to 0.77% Si and up to 0.8% Cu (here and below in wt%) were prepared in an induction furnace using pure components as starting materials. Ingots were cast in a permanent steel mold, homogenized at 480 °C for 24 h, hot rolled at 420 °C and cold rolled to a final thickness of 1 mm. The sheets were water-quenched from 520 °C (1 h) and held 30 days at room temperature (natural aging, NA state). The stretching (stamping) was simulated by a 5 or 10% tensile deformation (NAD state). Artificial aging was performed at 177 °C for 1 h, which reflects the drying mode (NADAA state). We also studied properties of artificially aged specimens not subjected to prior deformation (NAAA state). It should be pointed out that artificially aged sheets showed a recrystallized grain structure.

Tensile properties were determined using a standard procedure with 5-fold flat specimens 1 mm thick and 6 mm wide. The ultimate tensile strength (*UTS*) and 0.2% offset proof yield strength (*YS*) were accurately determined to within 15-20 MPa. Elongation was accurate to within 1%.

3 RESULTS AND DISCUSSION

The effect of excess silicon on the tensile properties of an Al-1% Mg_2Si-0.6% Cu alloy

It is well known that excess silicon has a positive effect on the internal structure and properties after aging so it is worth checking the effect of excess silicon on the behavior of Al-Mg-Si-Cu alloys during processing. For this part of the study we have chosen an alloy containing 1% Mg_2Si and 0.6% Cu with different amounts of excess silicon up to 0.4% Si. Note that the balance ratio between Mg and Si in Mg_2Si is 1.73 (in wt%).

The results in **Figure 1** demonstrate that an excess of silicon improves the strength properties in all the examined states.

In the case when no intermediate deformation has been applied the elongation also remains sufficiently high at 20-24%. The effect of artificial aging becomes noticeable (20-30 MPa) when the silicon excess is above 0.2%.

The most interesting effect is the change in the properties of sheets deformed between natural and artificial aging. The deformation after natural aging and intermediate deformation (NAD and NADAA states, respectively) increases the strength by 100-150 MPa and this improvement in strength correlates directly with the excess of silicon. This is evidently due to work hardening. The work hardening effect for naturally aged sheets (NAD - NA) increases with the concentration of silicon. This may correspond with the increasing fineness of the β" precipitates, which thus serve as more efficient obstacles preventing the movement of dislocations.

The effect of artificial aging of predeformed sheets (NADAA - NAD) decreases with the increasing silicon concentration and, for the ultimate tensile strength, almost vanishes at a silicon excess of 0.3-0.4%. Moreover, the artificial aging performed after intermediate deformation essentially decreases the elongation from 16 to 8%.

We suggest that the deformation performed after natural aging results in the partial loss of coherency of the fine β" particles and promotes the formation of semicoherent β' particles on dislocations upon artificial aging. This may cause the observed decrease in the effect of artificial aging on predeformed sheets of an Al-Mg-Si-Cu alloy.

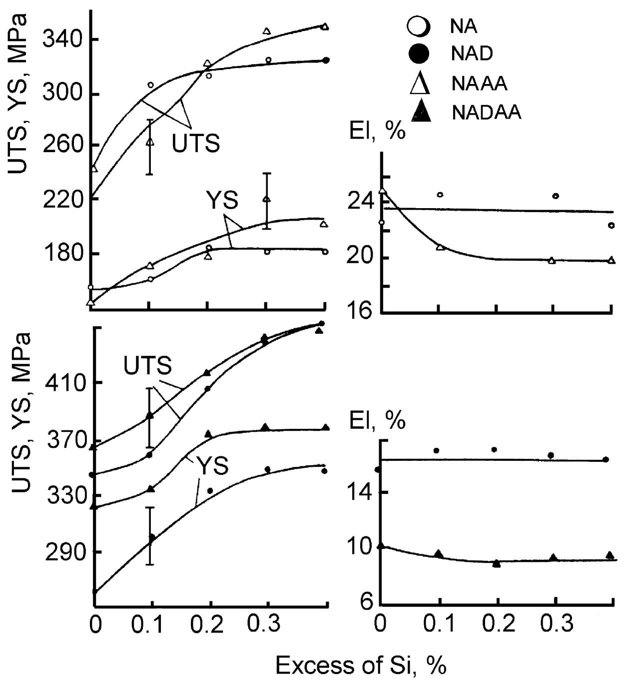

Figure 1: Effect of excess silicon on tensile properties of Al-1% Mg_2Si-0.6% Cu sheets at various stages of processing

Slika 1: Vpliv prebitka silicija na raztržne lastnosti pločevin Al-1% Mg_2Si - 0,6% Cu po različnih stopnjah procesiranja

The effect of copper on the tensile properties of an Al-1% Mg_2Si-0.4% Si alloy

Alloys with excess silicon demonstrate high tensile properties, although the effect of artificial aging on predeformed sheets is quite small.

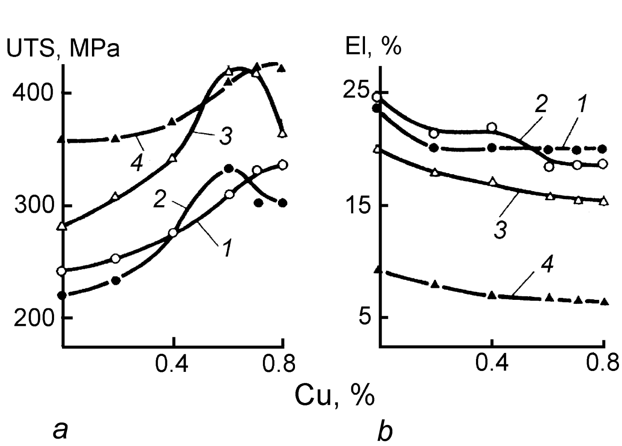

Figure 2: Effect of copper on tensile properties of Al-1% Mg_2Si-0.4% Si sheets at various stages of processing: *a*, ultimate tensile strength and *b*, elongation (*1*, NA; *2*, NAAA; *3*, NAD; and *4*, NADAA)

Slika 2: Vpliv bakra na raztržne lastnosti pločevine Al-Mg_2Si-0,4%Si v različnih stopnjah procesiranja: a-raztržna trdnost, b-raztezek (1.NA; 2, NAAA; 3, NAD; in 4, NADAA)

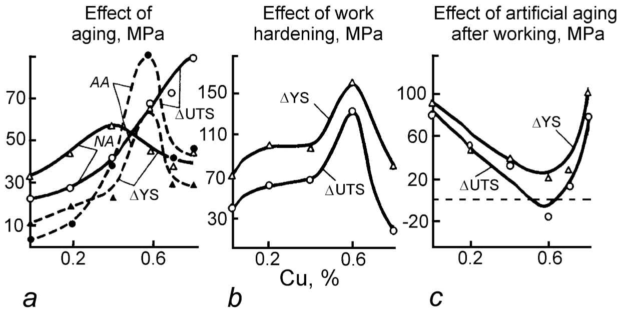

Figure 3: Effect of copper on the aging hardening (*a*), work hardening (*b*) and aging hardening after working (*c*) of Al-1% Mg_2Si-0.4% Si sheets

Slika 3: Vpliv bakra na utrditev zaradi staranja, a - po deformacijski utrditvi, b - po dodatnem staranju, c - Al-1% Mg_2Si 0,4 % Si pločevina

In order to trace the effect of copper on the tensile properties of Al-Mg-Si alloys at different stages of production we have chosen an alloy with a silicon excess of 0.4%. The concentration of copper was varied from 0 to 0.8%.

Figure 2 demonstrates the variation in tensile properties with increasing copper content. After natural aging (NA) the strength increases and elongation decreases with increasing copper concentration. It should be noted that the yield strength changes only slightly with the maximum hardening effect (ΔYS = 55 MPa) at 0.4% copper (**Figure 3a**). In contrast, the tensile strength increases monotonically (**Figure 2**). The ΔUTS also increases continuously with copper concentration from 20 to 85 MPa (**Figure 3a**).

After artificial aging without intermediate deformation the strength changes with a maximum at 0.6% Cu (**Figure 2a**). The elongation decreases with increasing copper concentration, being higher than that for the NA state up to 0.5% Cu (**Figure 2b**). However, the overall properties of NAAA specimens are higher than those of NA samples only at 0.5-0.6% Cu. The hardening effect changes in a similar way (**Figure 3a**). The maximum hardening effect for the NAAA state is ΔYS = 65 MPa at 0.6% Cu. Hence, the artificial aging performed after natural aging is more or less efficient only at 0.5-0.6% Cu.

After deformation of NA sheets by 5 or 10% the variation of properties with copper concentration is similar. The strength is considerably improved in the range from 0.4 to 0.6% Cu and the elongation monotonically decreases retaining a sufficiently high magnitude of 16-20%. The significant increase in the strength after deformation is obviously due to work hardening (**Figure 3b**) which also reaches a maximum at 0.6% Cu. The maximum contribution (NAD - NA) of work hardening is ΔYS = 160 MPa.

The artificial aging performed after intermediate deformation causes a noticeable improvement in the strength at low copper concentrations (<0.5% Cu) as well as a (2 times) decreased elongation (**Figure 2**). The effect of artificial aging after deformation (NADAA - NAD) demonstrates a minimum at about 0.6% Cu (**Figure 3c**).

We can conclude that the effects of work hardening and precipitation hardening after deformation are opposite. Therefore, there is no point in heating (artificial aging) deformed Al-Mg_2Si-Si alloys containing 0.5-0.7% Cu. In this case, we do not have any strength improvement and lose a lot of ductility. This is well illustrated by **Table 1** showing the variation of tensile properties of an Al-1% Mg_2Si-0.4% Si-0.6% Cu alloy at various stages of processing.

Table 1: Tensile properties of Al-1% Mg_2Si-0.4% Si-0.6% Mg alloy sheets at different stages of processing (numerator - longitudinal direction; denominator - transverse direction)

Tabela 1: Raztržne lastnosti pločevine iz zlitin Al-1% Mg_2Si - 0.4 % Si - 0,6 % Mg po različnih stopnjah procesiranja (števec - vzdolžna smer, imenovalec - prečna smer)

State	*UTS*, MPa	*YS*, MPa	*El*, %
Quenched	245/245	145/140	24/20
NA	310/330	190/185	18/19
NAD (5%)	340/340	315/300	17/16
NAD (10%)	445/400	350/355	17/14
NAAA	335/340	210/205	20/20
NADAA (5%)	400/385	285/295	10/10
NADAA (10%)	430/415	370/340	7/7

The obtained results can be explained as follows. After natural aging and artificial aging the GPZ (Mg, Si) and β'' phase are formed. Copper, refining these particles and increasing the density of their precipitation, provides for strength improvement up to the moment when the concentration of copper becomes sufficient to form its own GP (Al, Cu). After that the β'' refinement ceases and the precipitation of this phase proceeds as in a copper-free alloy. These effects are much more pronounced after artificial aging where one can see a maximum rather than just a changing slope.

The deformation performed after natural aging results in an increased level of strength mainly due to work hardening. The higher the precipitation density and the finer the precipitates, the larger the work hardening. **Figure 3*b*** shows that the maximum work hardening is associated with the maximum aging effect (**Figure 3*a***). When the copper concentration becomes large enough to form its own copper-bearing phase the structure coarsens and the work hardening decreases[5].

During cold intermediate deformation the GPZ (Mg, Si) and coherent β'' precipitates are cut by dislocations with relevant violation of coherency[4]. Subsequently, the artificial aging after deformation results in the precipitation of the semicoherent β' phase on dislocations and the β'' ⇒ β' transition in the grain interior. However, the effect of artificial aging after deformation is restored at high copper concentrations of 0.7-0.8%. This attests that the structure pattern formed in such alloys may be similar to that in alloys containing less that 0.2% Cu, although the phase composition is different. The essential decrease in ductility in the NADAA state is due to the hindering of dislocation mobility as a result of their pinning by β' precipitates[6].

However, it should be mentioned that in any case copper contributed positively to the strength of Al-Mg-Si alloys, at least up to 0.6% Cu. The corresponding decrease in ductility is considerably smaller for all studied modes except NADAA.

4 CONCLUSIONS

1. The effects of heat treatment, intermediate deformation and alloy composition on the mechanical properties of Al-Mg-Si sheets were examined.
2. The excess of silicon and the addition of copper favorably affect the tensile properties of sheets in all states. However, the artificial aging performed after stretching adds little to the strength and reduces the ductility.
3. The warm or hot drying of painted stamped structures from Al-Mg-Si alloys is an undesirable operation.

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