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DEFORMATION BEHAVIOR OF THE AlMg4.5Cu0.5 TYPE ALLOY SHEET

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ABSTRACT

Deformation behavior of the AlMg4.5Cu0.5 type alloy sheets was examined after cold rolling and annealing in the range of temperature from 220°C to 520°C, water quenching and natural aging. The low temperature annealed samples, characterized by fine grained recrystallized structure and high content of Cu-Mg precipitates, have shown a superior hardening ability in uniaxial tension and formability in biaxial stretching. The natural aging didn't bring any important changes of the properties in respect to the as-quenched condition of the tested material.

Keywords: Al-Mg sheet, strain hardening, formability

INTRODUCTION

In the use of Al alloys for car bodies, initially the predominant role was given to 2036-T4, copper based alloy and 5182-O, magnesium based alloy by most of car producers, both in the USA and Europe [1,2]. Today, 6000 type of heat-treatable alloys are in use in a great deal, since they appeared to be more compatible in recycling with 5000 type of non-heat-treatable alloys. However, a potential of at least 10% lower costs was estimated [3] for non-heat-treatable alloys in comparison with heat-treatable types, making as an attractive further research and improvement of their properties. An important point in making the car bodies is a paint-baking sequence, which causes a softening of the parts made by Al-Mg sheets [4,5]. The heat-treatable alloys have overcome this problem by precipitation hardening at paint-baking temperatures. The current efforts to overcome the softening problems in Al-Mg alloys resulted with the idea of addition of a small amount of copper to the Al-Mg alloys, which makes them precipitation hardenable during paint-baking sequence [6-11]. Such an alloy, with a low Cu/Mg ratio: 0.1-0.14 in wt.%, designated as AA5030, was supposed to prevent the softening of Al-Mg sheets during the paint baking procedure [12]. The aim of this work was to estimate the deformation behavior and the overall formability of AlMg4.5Cu0.5 type alloy sheet (Cu/Mg ratio = 0.1) produced by IMPOL-SEVAL Aluminum Rolling Mill.

EXPERIMENTAL

Material. The as-received Al-Mg sheets 3.0mm thick, were supplied by IMPOL-SEVAL Aluminium Rolling Mill, in cold rolled condition, and have a chemical composition (in wt.%) as Al-4.51Mg-0.052Mn-0.45Cu-0.15Si-0.34Fe-0.049Zn-0.004Ti-0.0008Na. The material was further laboratory cold rolled to 2.4 mm, annealed at

320°C/3h, then cold rolled to 1.15 mm. The machined specimens were finally annealed at 220°C/3h; 260°C/3h; 280°C/3h; 320°C/3h; 360°C/3h; 380°C/3h; 470°C/1h and 520°C/10'. The specimens were water quenched (WQ) and tested, or naturally aged for 14 days at room temperature (RT) before testing.

Uniaxial tensile testing. Tensile tests were performed using the specimens with a gauge length of 50mm and a width of 12.5 mm, oriented in the rolling direction. The applied cross-head rate was 0.75 mm/min, giving an initial true strain-rate of $\dot{\varepsilon} = 2.5 \times 10^{-4}$ [s^{-1}].

Forming limits. Gridded rectangular blanks of various widths (from 150mm to 20mm) were firmly clamped in the longer direction, and stretched in a "HILLE" sheet-metal testing machine over a 75mm diameter, unlubricated, hemispherical punch as proposed by A.K. Ghosh [13]. For each of the specimen, the dome height at maximum load and the minor strain (e_2) in the necked region were measured. Limiting dome height (LDH) values were normalized with respect to the punch radius, and plotted against the respective values of minor strain (e_2). Additional stretching has been done on full-sized samples using a combination of polyethylene sheet and mineral oil as a lubricant in order to extend the equibiaxial stretching range.

Metallographic examinations. The samples were prepared by electrochemical polishing, using perchloric acid and ethanol solution, and etching by Barker's solution. The average grain size (d_{av}) was determined using the linear intercept method.

Electrical resistivity measurements. Assuming that the precipitation process is followed by a decrease of electrical resistivity, or on the contrary, it is increased by dissolution of the alloying elements [14,15], electrical resistivity was measured to assess the relative difference in the precipitation processes. For that purpose the "Sigma Test D2.068" equipment was used.

RESULTS AND DISCUSSION

Structure and aging assessment. The grain size (d_{av}) variation with the annealing conditions for as-quenched samples, has shown in Fig.1a. It has been shown that a recrystallization process is not completed after annealing at 220°C/3h and 260°C/3h. After the recovery at 220°C/3h, at 260°C a mixture of unrecrystallized and very fine new recrystallized grains, with d_{av}~16μm, was revealed. With increasing the annealing temperature the average grain size was increased up to ~50μm (Fig.1a). After annealing at 520°C/10' the coarse grained and unhomogeneous structure was revealed (it was a mixture of ~35÷45μm and less amount of ~60÷80μm sized grains). In all other structures the grain size distribution was rather homogenous.

The electrical resistivity of as-quenched and naturally aged samples has monotonically increased by increasing the annealing temperature (Fig.1b). This indicates that the amount of alloying elements (Cu and Mg) increases in the solid solution with increasing the temperature. After reaching 470°C, it was changed less obviously, since the dissolution of the alloying elements is completed. The natural aging didn't bring any important change of the electrical resistivity, as it is shown in Fig.1b. The electrical resistivity level for samples treated by artificial aging at 180°C/30', after 5% pre-stretching, as a full aging effect in the tested material, is also shown in Fig.2, by dashed line. It is obvious that after low temperature annealing the precipitation process approaches the full aging effect.

Tensile properties. The increase of annealing temperature from 220°C to 260°C is followed by the yield stress (YS) drop from ~220 MPa to ~140 MPa, the UTS drop from ~320 MPa to ~280 MPa, and an increase of total elongation from ~11% to 23% (Fig.2). The YS, UTS and e_{tot} values were found less changeable in the range of temperatures from 260°C to 520°C, as it is shown in Fig.2a-b. The Lüders or yield point elongation, ranged up to ~1.2% for the fine grained samples, appeared to be suppressed in the samples with an average grain size of ~35÷50µm (Fig. 2b), and in the samples with recovered structure (220°C/3h).

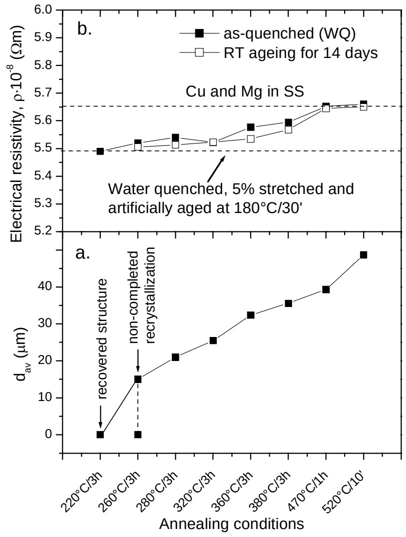


Fig. 1. The influence of annealing conditions on grain size (d_{av}) - a. and electrical resistivity – b. after water quenching and natural aging

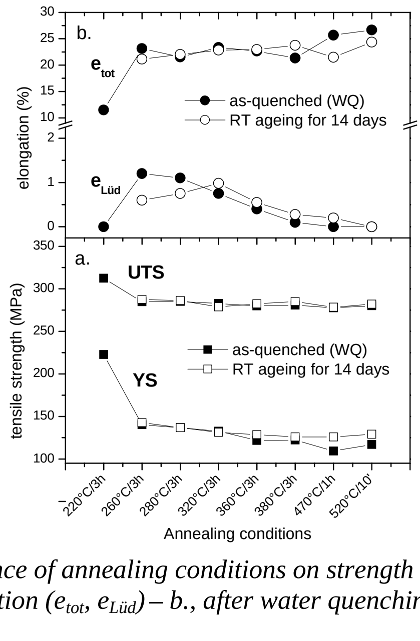


Fig. 2. The influence of annealing conditions on strength (YS and UTS) – a., total and Lüders elongation (e_{tot}, $e_{Lüd}$) – b., after water quenching and natural aging

Deformation behavior and formability. The load – extension curves of as-quenched samples in uniaxial tension are shown in Fig.3. The supposed precipitation sequences, according to some previous reports [16-20] are also noted. The basic difference in the presented curves is related to the appearance of Lüders elongation, which is avoided in the samples with recovered structure (220°C/3h), probably due to the presence of the dislocations in the subgrain structure. It is also vanished by increasing the annealing temperature, probably due to the grain size enlargement (Fig.1.a), as it was experienced earlier [21,22]. The load jump noticed at the very beginning of straining, in Fig.3 marked by arrows, also appeared to be absent in case of samples annealed at 470°C/1h and 520°C/10'.

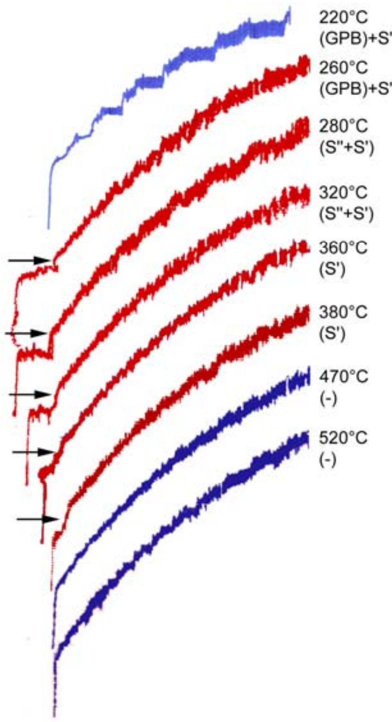


Fig. 3. Load – elongation curves for the tested material after quenching rom different annealing temperatures.

The hardening ability during straining of the tested material is shown in Fig.4. It is evident that the strain hardening rates (dσ/dε) fall very close together for all the samples with recrystallized structure. For the low temperature annealed samples (260°C/3h and 280°C/3h) the sharp drop of the dσ/dε values are ended by a kind of reversal change, i.e. by dip which vanishes with increasing the temperature. The sharp initial dσ/dε drop, known to be typical for the elastic-plastic transition in samples with no yield point elongation, could be attributed to the similarity of fitting procedure at the very beginning of straining after the yield point elongation. The load jumps in Fig.3, marked by arrows, could be attributed to the presence of additional mobile dislocations formed during the Lüdering. As the low temperature annealing is followed with the higher content of Cu-Mg precipitates (Fig.1.b) and higher density of mobile dislocations, as a possible origin of the noticed dips can be considered as the initial reaction of the mobile dislocations with second phase particles such as GPB, S" and S' phases. Later, in the range of approximately linear $d\sigma/d\varepsilon$-σ dependence, the samples annealed at 280°C/3h have shown a somewhat higher rate of hardening, especially at low stresses (strains) in comparison to the other samples with recrystallized structure. The effect of precipitates on the nature of hardening process was estimated applying the Kocks-Meckings model [23,24] of strain hardening, assuming a linear part of the $d\sigma/d\varepsilon$-σ relation, and describing it by the equation $\theta = \theta_0 - k\sigma$, where $\theta = d\sigma/d\varepsilon$, θ_0 and k are constants. After differentiating θ in respect to the flow stress σ, the $d\theta/d\sigma$ values, i.e. the slopes of the linear parts of the $d\sigma/d\varepsilon$-σ dependences in Fig.4, are shown in Fig.5 for the appropriate yield stresses σ_0. It has been shown earlier [25] that the $d\theta/d\sigma$-σ_0 dependence, in case of 6000 and 7000 type alloys, could reveal a hardening nature in the presence of precipitates in the structure. Namely, abrupt change of the $d\theta/d\sigma$ parameter from about -10 to about -35 was noticed after the dislocation reaction was changed from shearing to non-shearing Orowan type reaction in both, 6000 and 7000 type alloys [25]. In the case of tested AlMg4.5Cu0.5 alloy sheets, there is no such a change, and the $d\theta/d\sigma$ values, ranged from -9.4 to –16.2 could be related to the shearing type reaction.

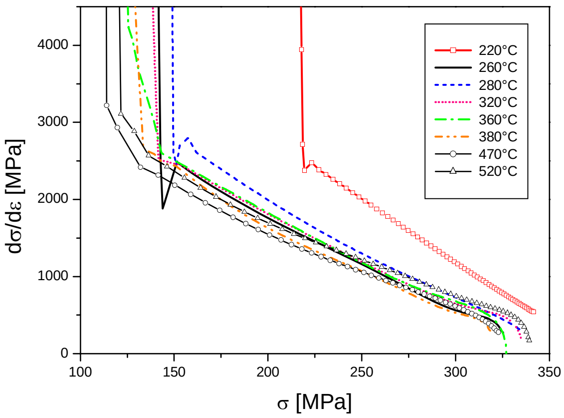


Fig. 4. Strain hardening rate ($d\sigma/d\varepsilon$) variation with the flow stress (σ) derivated from the curves shown in Fig.3

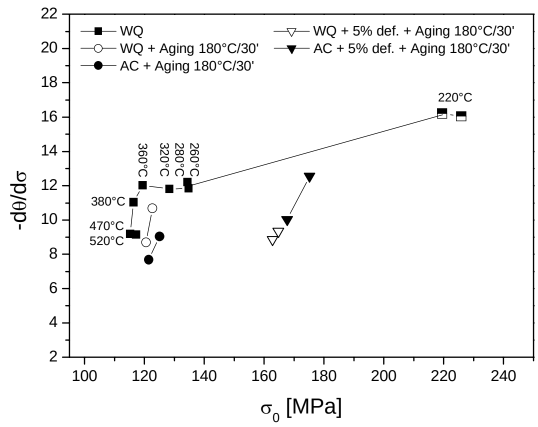
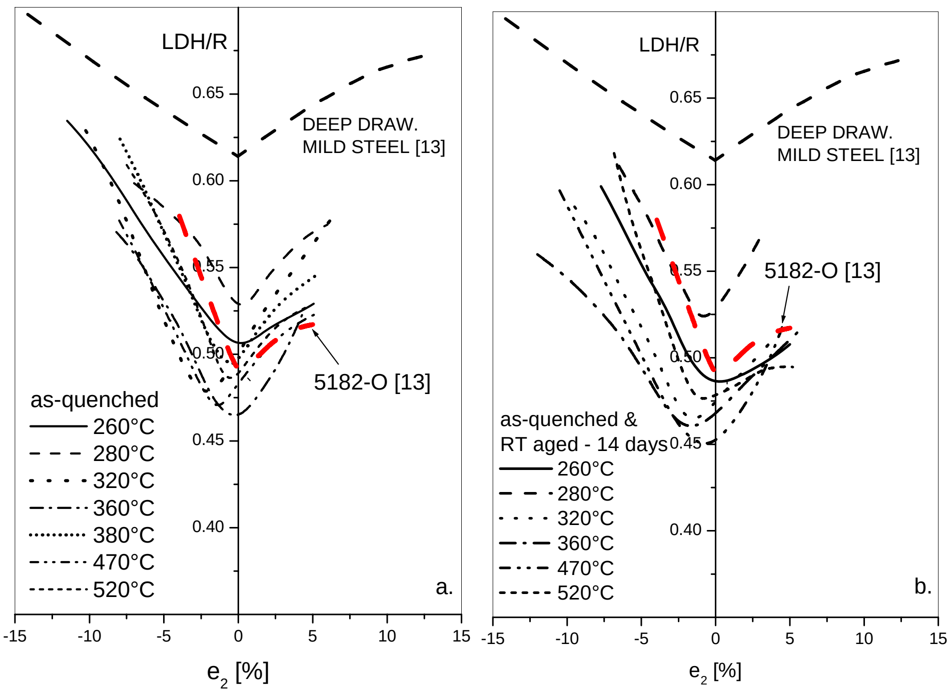


Fig. 5. Slopes $d\theta/d\sigma$ vs. yield stress (σ_0) for curves from Fig. 4

The forming limit of the tested material in as-quenched and naturally aged conditions, was presented by the normalized limiting dome height (LDH/R) vs. minor strain (e_2) curves (Fig. 6a and b, respectively), as a suitable approach for stretchability rating mode of different materials or conditions [13]. Considering the LDH/R – e_2 curves in the range of plain strain deformation (e_2=0), as a most restrictive condition [26], it was appeared that the formability level of the tested conditions are rather closely ranged, i.e. the maximal difference was about 13% - 15% for both the quenched and naturally aged materials. The stretchability of the 280°C/3h annealed samples was found to be the highest in both conditions, while all other were spaced closely at a somewhat lower level (Fig.6). For the convenience of comparison the formability of the tested material with some typical materials for forming application, LDH/R - e_2 curves for deep drawing quality of low carbon steel, and typical AlMg4.5Mn sheets (5182-O), are also shown in Fig.6. It is obvious that the tested material matches the stretchability of widely used 5182 type AlMg sheets.



a) *b)*

Fig. 6. Normalized limiting dome height (LDH/R) vs. minor strain (e_2) curves for the tested material after quenching from different annealing temperatures (a) and natural aging (b).

SUMMARY

Deformation behavior and formability of AlMg4.5Cu0.5 type sheets were tested after annealing at different temperatures and water quenching. Two groups of the samples were tested: (i) as-quenched and (ii) naturally aged for two weeks. The structure and mechanical properties of as-quenched samples were not affected by natural aging for two weeks. The annealing temperature induced precipitation-dissolution processes were followed through the electrical resistivity variations. The low temperature annealed samples (220°C÷320°C) are characterized with an intensive precipitation, approaching the electrical resistivity level pertinent to the artificially aged samples. After annealing at 470°C and 520°C the dissolution process seems to be completed. The fine grained samples are characterized by the appearance of yield point elongation, which vanishes within the range of grain size ~35÷50μm, and in the recovered (subgrain) structure.

The overall formability (measured by the Normalized Limiting Dome Heights – LDH/R) was found comparable with the basic AlMg4.5Mn alloy type (AA5182). The LDH/R curves for all the applied annealing conditions in as-quenched or natural aged conditions were rather closely spaced. However, the formability of low temperature annealed samples with fine grained structure (annealed at 280°C/3h) seems to be clearly at the upper bound of the band enclosing all the LDH/R values for both as-quenched and naturally aged materials. This finding is in accordance with the highest hardening ability experienced for the low temperature annealed samples. Analysis of the strain hardening rate variations revealed that the reaction of mobile dislocations by precipitates could be assumed to be shearing type, independently on the annealing conditions.

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