# Effect of cold rolling reduction on critical strains and final grain size of Al-Mg alloys containing Mn

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**Abstract.** Cold rolling and annealing treatments have been applied to three commercial Al-Mg alloys containing 3-6wt.% Mg and around 0.5wt.% Mn. The effects of these elements on the critical strain and final grain size have been investigated by means of optical microscopy, hardness and electrical conductivity measurements. For a given composition, it was found that the final grain size of the recrystallized material was decreasing with increase of the strain as well as with the Mg content.

## Introduction

The Al-Mg alloys which have a good combination of strength and formability are an important group of commercial Al alloys with various applications in a transport, packaging and general engineering industries. They are non-heat treatable alloys that strengthen through solid solution hardening, but they are strain-hardened during deformation. Cold deformation is particularly effective in strengthening since restoration processes are thermally activated.

Al-Mg alloys can contain even more than 6 wt.% Mg. Strength of Al-Mg alloys strongly increases with addition of Mg. Mg has a high solubillity in solid solution and therefore it provides the most enhancement of strength among all alloying additions in aluminium solid solution [1,2]. Mg, like the other solute elements, has a strong influence on recrystallization and grain growth. Mg also serves to reduse both the rate of growth and the final grain size [1,3].

Commercial Al-Mg alloys also contain elements, such Mn, Fe, Si or Cr and Ti. These elements form the second phase particles due to a limited solubility in solid solution. Although these elements have a minor influence on strength of Al alloys, they have a significant influence on annealing behaviour, i.e. they are an important parameter in the grain size control. Addition of Mn increases strength either it is in solid solution or in precipitated intermetalic phase. Mn usually precipitates as a dispersoid during preheating and hot processing increasing toughness, and, at the same time, decreasing susceptibility to intergranular cracking and stress corrosion. Mn is mainly added for the grain size control due to its grain growth inhibition. Although the predominant reason for alloying is to increase strength, alloying has important effects on the other characteristics of Al alloys: physical and electrochemical properties and corrosion resistance. Electrical conductivity is one of the most sensitive properties of Al alloys, being particularly responsive to changes in composition and temper. Electrical conductivity of Al-Mg alloys depends on whether the element is in solid solution or a second phase is formed. Elements in solid solution are always more harmful to electrical conductivity. Electrical conductivity of these alloys is mainly dependent on magnesium dissolved and decreases almost linearly with concentration of Mg in a solution [1]. The effects of other elements are submerged by Mg. During the cold deformation electrical conductivity decreases due to increase of the number of vacancies and the density of dislocations. The higher value of electrical conductivity after annealing is a result of combined effects of recovery and recrystallization and dissolution of precipitate phases, i.e. removing Mg to solution.

Grain size is one of the most important microstructural factor controlling strength and formability. A fine grain size is extremely important factor to minimize surface roughening during forming and to provide ductility during forming operation and fracture toughness. On the other hand, to avoid stretcher strain markings, the material should be formed in the fully soft temper, i.e. in this case it is necessary to avoid grain size which is too fine [4]. For these reasons, it is important to obtain optimal grain size, and to have good combination of strength and formability. Grain size is controlled by an appropriate combination of hot and cold rolling and annealing.

The aim of this work was to determine the optimal initial grain size for further spinnability testing of Al-Mg alloys.

**Experimental**

The chemical compositions of commercial Al-Mg alloys which were investigated are presented in Table 1.

**Table 1.** ***Chemical compositions of Al alloys (wt.%)***

| | **Mg** | **Si** | **Cu** | **Mn** | **Fe** | **Zn** | **Ni** | **Ti** | ***l*** |
|---|---|---|---|---|---|---|---|---|---|
| AlMg3 | 3.1 | 0.09 | 0.01 | 0.03 | 0.31 | 0.04 | 0.01 | 0.01 | Bal. |
| AlMg4.5Mn | 4.1 | 0.12 | 0,015 | 0,54 | 0,36 | 0,07 | 0,01 | 0,01 | Bal. |
| AlMg6Mn | 5,95 | 0,16 | 0,02 | 0,57 | 0,40 | 0,02 | 0,01 | 0,04 | Bal. |

In order to provide a uniform microstructure in all specimens, pre-deformation treatment was performed and it consisted of pre-rolling and annealing for 3h at 320°C. Final rolling included reductions of 10, 15, 20, 25 and 50%, and was followed by the final annealing for 3h at 320°C. The final thickness of all samples was 3mm, since they will be used for further spinnability testing on industrial scale. To reveal grain size, standard procedure included mechanical and electro-polishing, etching using Barker′s solution (25ml $HBF_4$(40%), 1000ml distilled water). Grain size was observed in the optical microscope under the polarized light. The average grain size was determined by the linear intercept method. Hardness was measured by the Vickers hardness test (HV5) and electrical conductivity was measured using Sigmatest D. 2.068.

**Results and Discussion**

Typical microstructures obtained after annealing of AlMg3 are shown in Fig.1a-e. Polygonal grains with almost uniform size characterize microstructure in all samples.

The effect of strain on the average grain size annealed specimens is shown in Fig. 1f and is given in Table 2. For all alloys average grain size increases with reduction up to maximal value, and than decreases. Maximal grain size is related to the critical strain for recrystalization [5]. For examined alloys, the critical strain values of 15, 20 and 25% were obtained for AlMg3, AlMg4,5Mn and AlMg6Mn, respectively.

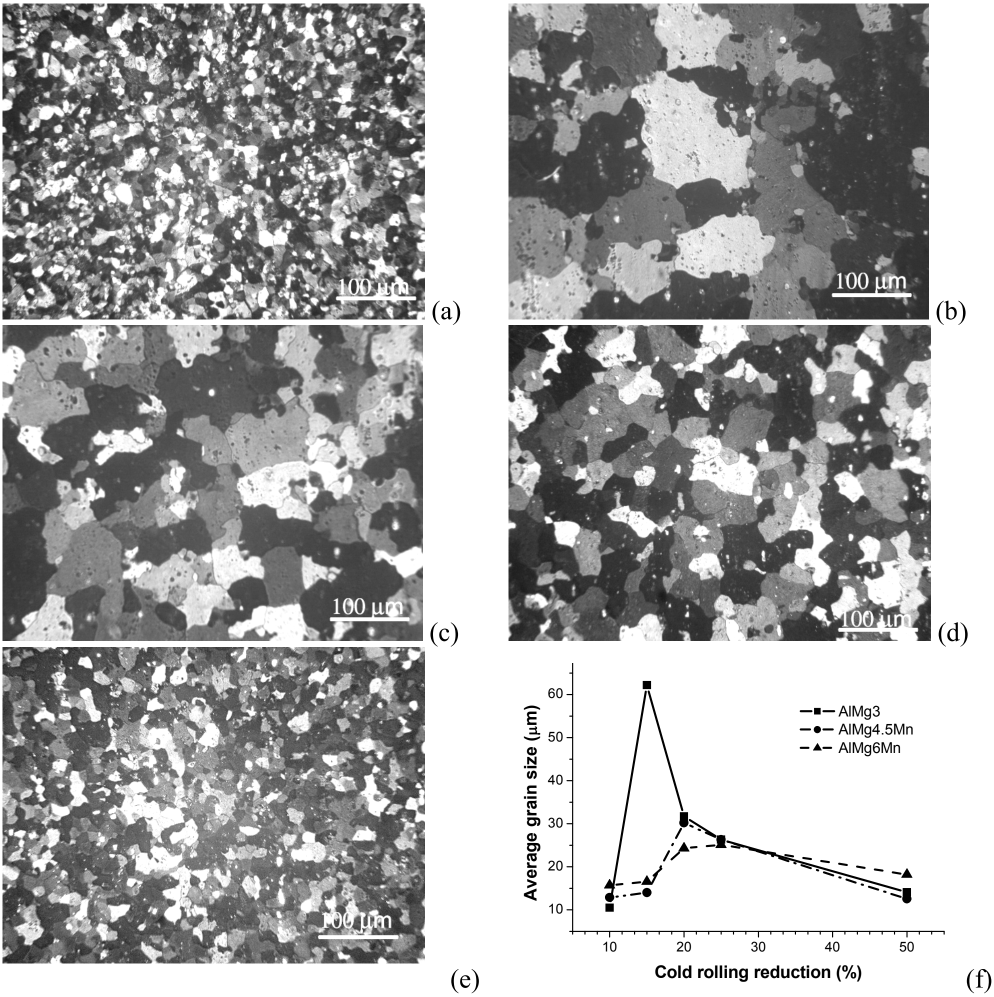



Fig. 1. *Microstructure of AlMg3 alloy annealed for 3h at 320°C after (a) 10% reduction; (b) 15% reduction; (c) 20% reduction; (d) 25% reduction; (e) 50% reduction; (f) the effect of strain on the average grain size annealed specimens*

**Table 2.** ***Average grain size after different cold rolling reduction and annealing at 320℃/3h***

| r (%) | 10 | 15 | 20 | 25 | 50 |
|---|---|---|---|---|---|
| ***AlMg3*** | 10.5 | 62.2 | 31.7 | 26.3 | 14.1 |
| **AlMg4,5Mn** | 12.9 | 14.0 | 30.2 | 26.3 | 12.6 |
| **AlMg6Mn** | 15.7 | 16.6 | 24.3 | 25.1 | 18.2 |

Since the critical strain for recrystallization has been reached the average grain size decreases as the percentage of cold deformation increases. Further increase of strain results in decrease of grain size. The recrystalizied grain size depends on nucleation rate and growth rate. The nucleation rate increases with strain. At low strain the deformation is distributed heterogeneously close to the grain boundaries and particles. Consequently, the nuclei are widely distributed in the deformed region resulting in a smaller number of nuclei per unit volume and in coarse grain. As the strain increases, more energy stored from cold work is available for the nucleation of the new grain and the recrystallized structure is finer. Also, the critical strain increases due to increase of Mg content in alloy, because the higher Mg content requires higher driving force for the structural rearrangement (recovery and recrystallization). No doubt, content of Mn has the main role in the grain size control. Mn is responsible for the differences between grain size at critical strain of AlMg3 and other two alloys. Low Mn (0.03%) in AlMg3 allowed grain coarsening, but the concentration of Mn over 0.5% inhibits grain growth and strongly decreases grain size in both AlMg4,5Mn and AlMg6Mn alloys.

The effect of strain on hardness is shown in Fig. 2, for both strained (closed symbols) and annealed (open symbols) specimens. In strained state hardness increases as the amount of deformation increases. Also, the differences in hardness between AlMg6Mn and AlMg3 increase as the amount of deformation increases. This is in agreement with the assumption that Mg content has a stronger influence on hardness at higher strain [4]. The content of Mg has an influence on hardness in annealed state too. In annealed state hardness curves for all alloys show similar behaviour. Hardness of annealed specimens decreases up to some specific strain and then slightly increases with further increase in strain. Minimal hardness values were obtained at 15, 20 and 25% for AlMg3, AlMg4,5Mn and AlMg6Mn, respectively. Also, the difference in hardness between AlMg3 and AlMg6Mn seems to be unchanged over the whole strain range. The results of Fig.2 are directly comparable with those of Fig.1. It can be noted that the largest drop in hardness is related to the critical strain of all alloys. Also, the highest hardness drop was obtained for AlMg3 alloy, medium for AlMg4,5Mn and the lowest for AlMg6Mn alloy. This behaviour is in good agreement with the grain size shown in Fig.1.

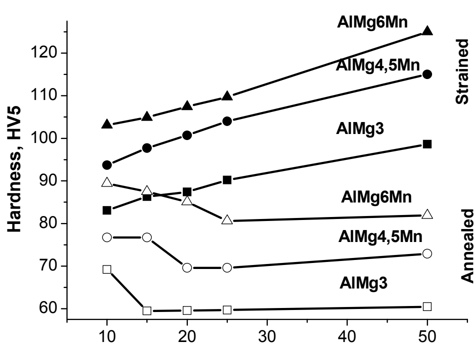



Fig. 2. *The influence of cold rolling reduction on hardness*

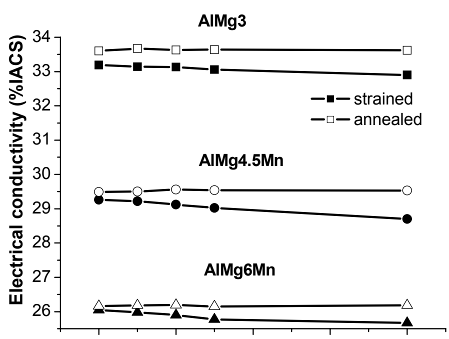
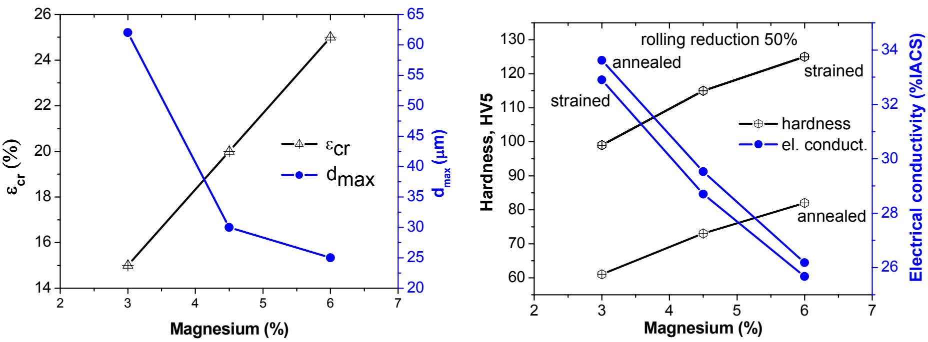



Fig. 3. *The influence of cold rolling reduction on electrical conductivity*

Results of electrical conductivity measurements are shown in Fig.3 The results indicate that the addition of Mg has a strong influence on electrical conductivity, in both, strained and annealed conditions. On the other hand, it seems that strain has a very low influence, e.g. at 50% deformation the electrical conductivity decreases from 2 to 2.5%, the result previously reported [1]. Electrical conductivity slightly decreases with increasing strain as a result of higher number of vacancies and dislocation density [1,6,7]. After annealing the electrical conductivity is slightly higher than in strained condition. Two opposite effects contribute to the variations in electrical conductivity. Annihilation of vacancies during the recovery and decrease of dislocation density during the recrystallization increase conductivity. On the other hand, dissolution of soluble precipitate phases (i.e. Mg removing to solution) decreases conductivity. Final result is that the electrical conductivity shows little increase. The other thing that can be noted on the Fig. 2 is that there are little or no changes in conductivity in the annealed condition. The strain before annealing has no influence on electrical conductivity of annealed specimens. After annealing at 320°C/3h the structures of these alloys are fully recrystallizied and the grain growth still does not start. It can be assumed that changes in the structure have no influence on conductivity.

Fig. 4 (a) presents the effect of Mg content on the critical strain for static recrystallization and related grain size. Fig 4 (b) illustrates the effect of Mg content on hardness and electrical conductivity in both 50% deformed and annealed condition. Higher Mg content increases the critical strain for static recrystallization, while decreasing related grain size. The different slopes on $d_{max}$/%Mg curve are directly related to the addition of Mn in alloys with 4,5% and 6% Mg. Also, increase of Mg content increases hardness in both deformed and annealed condition, and decreases electrical conductivity. Deviation from the linear relationship between hardness and Mg content, as well as electrical conductivity and Mg content, is also related to low content of Mn in AlMg3 alloy.




(a) (b)

Fig. 4. *Effect of Mg content on (a) the critical strain for static recrystallization and related grain size; (b) hardness and electrical conductivity*

## Summary

The effect of cold rolling reduction on the critical strain, grain size, hardness and electrical conductivity of annealed Al-Mg alloys with different content of Mg was studied. The cold rolling reduction is the parameter with the most significant influence on the annealed microstructure. The critical strain increases significantly with Mg content. For examined alloys, values of 15, 20 and 25% of the critical strain were obtained for AlMg3, AlMg4,5Mn and AlMg6Mn, yielding grain size of 62, 30 and 25µm, respectively. Hardness continuously increased in the deformed condition, while in the annealed condition hardness was observed to decrease to a minimum, then a slight increase appeared. Minimal values of hardness can be well correlated with the critical strain. The values of electrical conductivity in strained and annealed specimens were similar. Mg content increases hardness in both deformed and annealed conditions, but decreases electrical conductivity and related grain size.

## References

[1] L.F.Mondolfo, Aluminium Alloys: Structure and Properties, Boston, Butterworths, 1976.
[2] R.E.Sanders Jr., S.F.Baumann, H.C.Stumpf, Aluminium Alloys-Phisical and Mechanical Properties, vol.III, EMAS, West Midlands, UK, 1986, 1441-1484
[3] N.Ryum, J.D.Embury, Scand.J.Metall., 11 (1982) 51.
[4] R.Grimes, Grain control in aluminum, Paper No.MS 353. "Recrystallization in the Control of Microstructure", London, 1973
[5] W.M.Williams, R.Eborall, J.Inst.Metals, 81, (1952-53) 501.
[6] Dj.Drobnjak, Fizička metalurgija, TMF, Belgrade, 1986
[7] ASM Handbook, vol.2, Metals Park, Ohio, 1979