MICROSTRUCTURE AND MECHANICAL PROPERTIES OF TWIN-ROLL CAST Al-Mg SHEETS

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The influence of specific processing routes on the microstructure, texture, mechanical and technological properties of two commercial twin-roll cast alloys – AlMg2Mn0.8 (AA5049) and AlMg3 (AA5754) – was investigated. Sheets of 1.0 mm gauge were prepared in laboratory conditions with and without homogenization treatment. Non-homogenized samples were rolled also in industrial conditions. Surprisingly, it was found that homogenization results in grain coarsening and degradation of sheet anisotropy. Sheets produced by cold rolling from as-cast thickness of 6.0 mm directly to thickness of 1.0 mm and final annealing exhibit very fine grain size, higher strength combined with higher elongation and lower anisotropy as compared to the homogenized variant. The structure and mechanical properties of materials processed in laboratory and in industrial conditions are slightly different.

Key words: Al-Mg alloys, twin-roll casting, microstructure, mechanical properties, formability

MIKROSTRUKTURA A MECHANICKÉ VLASTNOSTI PLYNULE LITÝCH PLECHŮ ZE SLITIN Al-Mg

Byl studován vliv technologického postupu výroby na mikrostrukturu, texturu, mechanické a technologické vlastnosti dvou slitin – AlMg2Mn0,8 (AA5049) a AlMg3 (AA5754) – komerčně vyráběných plynulým litím mezi válce. Plechy o finální tloušťce 1,0 mm byly připraveny v laboratorních podmínkách, s homogenizací a bez homogenizace. Kromě toho byly nehomogenizované vzorky válcovány většími úběry v průmyslových podmínkách. Překvapivě bylo zjištěno, že homogenizace vede ke zhrubnutí zrna a k degradaci anizotropie materiálů. Plechy připravené nejjednodušším postupem válcováním za studena z licí

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tloušťky 6,0 mm přímo na finální tloušťku 1,0 mm s následným žíháním na měkký stav vykazují velmi jemné zrno, vyšší mechanické charakteristiky, vyšší tažnost a nižší anizotropii než plechy homogenizované na tloušťce 4 mm. Struktura a mechanické vlastnosti materiálů připravených v laboratorních a v průmyslových podmínkách je trochu odlišná.

1. Introduction

The need for low-cost aluminium sheets for automotive applications is nowadays generally recognized [1, 2]. Car-body inner panels are often manufactured from Al-Mg alloys. Recent results indicated that Al-Mg continuously cast sheets are a suitable cost effective substitution for direct-chill cast sheets [3–5]. A detailed knowledge about the effect of composition and down-stream processing parameters on sheet properties is indispensable in order to produce high quality semi-products for the demanding automotive sector. Sheets used in automotive applications must exhibit very good formability combined with high strength. Fine grains and well-balanced texture are the microstructure pre-requisites for high strength, low anisotropy and deep drawing ability. The paper describes the influence of specific processing routes on the microstructure, texture, mechanical and technological properties of two commercial twin-roll cast alloys – AlMg2Mn0.8 (AA5049) and AlMg3 (AA5754).

2. Experimental details

AL INVEST Břidličná plc, Czech Republic, cast AlMg2Mn0.8 (AA5049) and AlMg3 (AA5754) alloys on a continuous twin-roll caster (TRC) and provided them in the form of as-cast 6.0 mm sheets or sheets of 1.0 mm thickness in hard condition prepared by cold rolling directly from the as-cast strip. The exact composition of experimental materials is in Table 1.

Three laboratory processing schemes were used for both alloys:

a) final annealing of 1.0 mm gauge sheets cold rolled in industrial conditions (samples *non-homogenized 1*);

b) cold rolling from 6.0 to 1.0 mm (reduction 83 %) + final annealing (samples *non-homogenized 2*);

c) cold rolling from 6.0 to 4.08 mm thickness (reduction 32 %) + homogenization + cold rolling to 1.0 mm gauge + final annealing (*homogenized* samples).

Final annealing was carried out at 350 ℃ for 4 hours and homogenization for the same period at 450 ℃. Both heat treatments were performed in a furnace with atmosphere circulation and controlled slow heating and cooling in order to simulate industrial-scale conditions of annealing large coils. The annealing temperatures of 350 and 450 ℃ were reached in 9 and 15.5 h, respectively. After 4 hours at annealing temperature, the samples were gradually cooled during 6 and 10 h, respectively, down to 25 ℃.

Microstructure was examined by light microscopy (LM) and scanning electron microscopy (SEM) in the long transverse plane, which is parallel both to the rolling direction (RD) and sheet normal (ND). Intermetallic particles were revealed by etching in 0.5% HF water solution. Grain structure was observed under crossed polarizers after anodizing the samples in Barkers reagent. Grain size (mean intercept length) was measured in the rolling (L) and short transverse (S) directions. Texture measurements were carried out by X-ray diffraction [6]. In order to assess through-thickness heterogeneity, the measurement was performed at the surface and near the mid-thickness plane of the as-cast and homogenized sheets. The samples were prepared by grinding and etching in hydrochloric acid. Tensile tests at 0° and at 90° with respect to RD were carried out in the final soft condition. Erichsen dome height IE20 was measured in accordance with ISO 20482. Sheet anisotropy was assessed by conventional cupping test (EN 1669). The earing parameter Z was determined from mean height, $\overline{h}_{\mathrm{p}}$, and depth, $\overline{h}_{\mathrm{v}}$, of ears according to the following expression:

$$Z = \frac{h_{\mathrm{e}}}{h} \times 100\ [\%], \quad \text{where} \quad h_{\mathrm{e}} = \overline{h}_{\mathrm{p}} - \overline{h}_{\mathrm{v}} \quad \text{and} \quad h = \frac{\overline{h}_{\mathrm{p}} + \overline{h}_{\mathrm{v}}}{2}.$$

Vickers hardness (HV 10) and conductivity (Sigma test) were measured on sheet surface before and after annealing at intermediate (4 mm) and final (1 mm) thickness.

Table 1. Chemical composition of experimental materials [wt.%]

Alloy	Mg	Mn	Fe	Si	Cu	Ti	Cr	Zn
5049	1.85	0.45	0.23	0.04	0.008	0.032	0.004	0.021
5754	2.38	0.23	0.24	0.05	0.005	0.048	0.002	0.017

3. Results and discussion

3.1 Microstructure, hardness and conductivity of as–cast and homogenized samples

Typical micrographs showing second-phase dispersion in the as-cast and homogenized alloys are in Fig. 1. In both alloys, second-phase particles were present in the form of uniformly distributed small eutectic clusters (Fig. 1a). Some of the eutectic clusters in alloy (Fig. 1b) were coarser and very fine "Chinese script" phases (typical for ingot-cast materials) can occasionally be observed in them. No coarse central segregation channels (CLSC) were present in as-cast samples. The second-phase particles in the rolled samples were dispersed in the same manner as in as-cast samples. After homogenization treatment AlMnFe dispersoids were observed in both alloys (Figs. 1c,d). A few coarse CLSC with relatively large voids, probably originating from melted Al_3Mg_2 particles, were observed in the homogenized alloy 5049. No discontinuities or CLSC were observed in the homogenized alloy 5754.

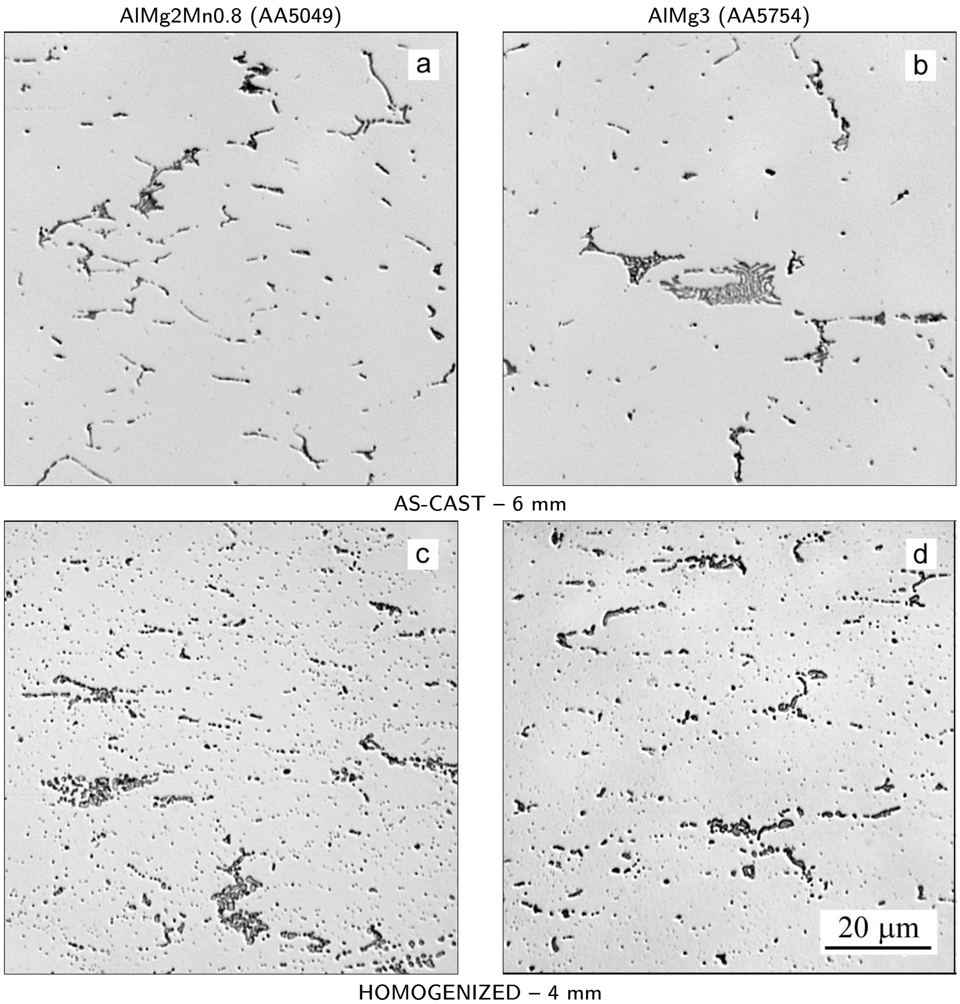

Fig. 1. Second-phase particles in studied Al-Mg sheets in the as-cast (a) (b) and homogenized condition (c) (d).

T a b l e 2. Hardness and conductivity before and after homogenization at 4.08 mm thickness

Alloy	HV 10		ΔHV 10	Conductivity κ [m·Ω^{-1}·mm^{-2}]		$\Delta\kappa$
	before	after		before	after	
5049	83	50	33	18.8	23.0	4.2
5754	86	52	35	20.4	22.3	1.9

The grains in both as-cast materials were relatively small, only slightly flattened in inner regions and more flat and inclined with respect to the surface in surface regions as it is common for twin-roll cast materials [7]. The mean grain sizes in direction L were 55 and 37 μm, the grain shape (ratio of the grain size in the long and transverse direction) was of 2.3 and 1.9 for the alloys 5049 and 5754, respectively. The grain structure after cold-rolling to 4 mm thickness was typical for as-cold-rolled Al-Mg materials; shear bands were observed. After homogenization at 450 ℃, both materials were completely recrystallized. The grains at the surface of alloy 5049 were a little coarser than in mid-thickness but it was not the case of alloy 5754. However, the difference between the size of inner and surface grains in alloy 5049 was not as pronounced as in twin-roll cast alloys AA8006 [8]. In alloy 5754, the surface grains were even slightly smaller than the grains at mid-thickness. There was not a large difference in grain size and shape between as-cast and homogenized materials. Neither the grain shape was changed by the homogenization. However, at the final gauge of 1.0 mm, the homogenized samples showed grains considerably coarser than non-homogenized samples (see below).

The results of hardness and conductivity measurements before and after homogenization are summarized in Table 2. It can be seen that the homogenization results in a large decrease in hardness connected with the complete recrystallization revealed by metallographic examinations. The decrease in hardness due to homogenization is almost the same in both alloys. Conductivity measurements indicate that the homogenization causes an increase in conductivity, which is more important in alloy 5049. The increase in conductivity in Al alloys containing Mn (besides other elements) depends most significantly on matrix depletion of Mn atoms (see e.g. [9]). Mn bearing (AlMnFe) particles precipitate and coarsen during homogenization. The process is more intensive in alloy 5049. Conductivity measurement results support metallographic observation indicating that the homogenized 5049 alloy (Fig. 1c) contains more dispersoids than the homogenized 5754 alloy (Fig. 1d).

3.2 Texture of as-cast and homogenized samples

Texture measurements were carried out both at surface and mid-thickness. The textures in all samples are weak. It was observed that the textures at surface and at mid-thickness are significantly different, which is the case of many TRC materials. The surface of as-cast samples exhibits relatively strong fibre texture $\langle 110 \rangle$, whereas a weak β-fibre is observed at mid-thickness. Surface $\langle 110 \rangle$ texture is eliminated by cold rolling to 4 mm thickness (32 % reduction). The texture of both alloys after homogenization is weak and it is typical for completely recrystallized samples. The details of texture measurements will be presented elsewhere after finishing texture analysis of final gauge sheets.

Constituent particles in the as-rolled and annealed conditions of alloy 5049 at 1.0 mm gauge are shown in Fig. 2. The non-homogenized as-rolled samples do not contain any fine particles (AlMnFe dispersoids – Fig. 2a). On the other hand,

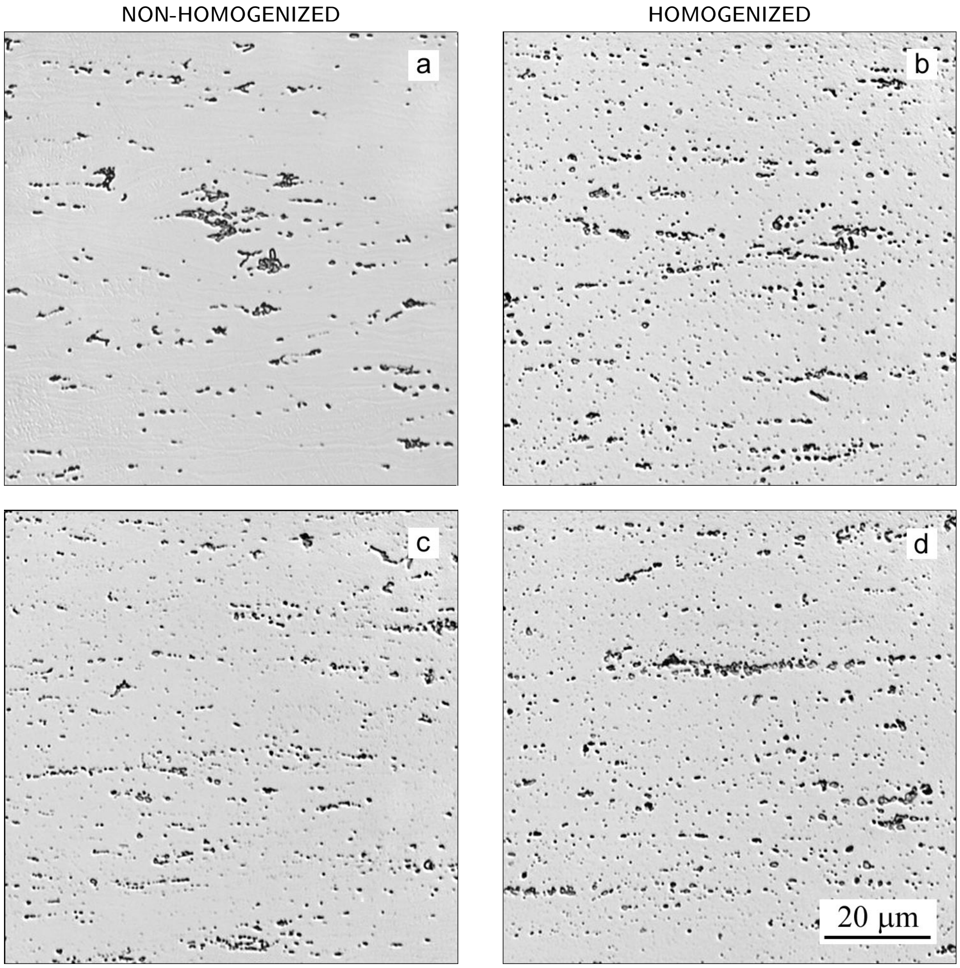

Fig. 2. Second-phase particles in non-homogenized (a) (c) and homogenized (b) (d) sheets of the AlMg2Mn0.8 (AA5049) alloy at the final gauge 1.0 mm.

dispersoids are present in the sample prepared with homogenization (Figs. 2b,d). After the final annealing at 350 ℃, dispersoids are observed also in the samples prepared without homogenization (Fig. 2c). Figure 3 shows second phase particles in the annealed 1.0 mm gauge condition of alloy 5754. In this alloy, the dispersoids are not present either in the non-homogenized (Fig. 3a) or in homogenized samples (Fig. 3b).

Typical micrographs showing the grains in 1.0 mm samples are in Fig. 4. Furthermore, the results of grain size measurements are graphically compared in Fig. 5. The grains in the as-rolled samples were severely deformed, the homogenized

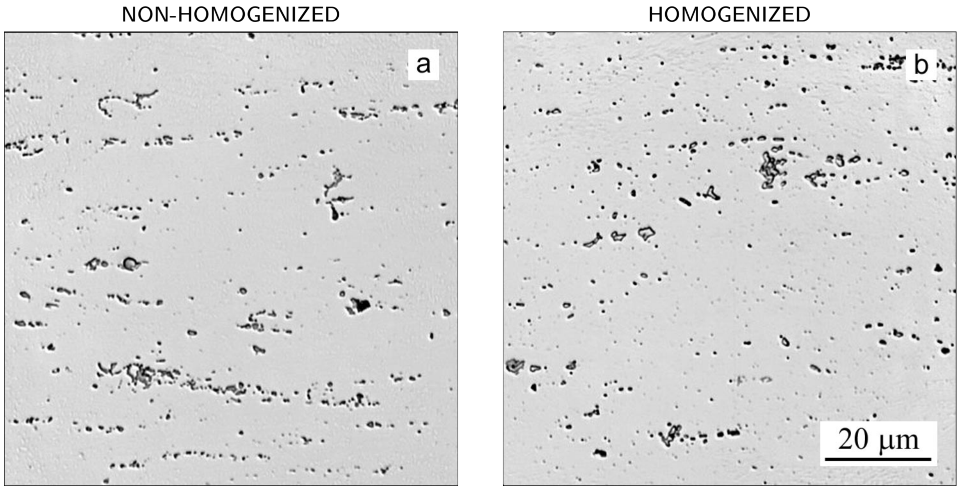

Fig. 3. Second-phase particles in non-homogenized (a) and homogenized (b) sheet of the AlMg3 (AA5754) alloy at the final gauge 1.0 mm.

samples exhibited grains larger in transverse direction as compared to those in the samples prepared without homogenization. Localization of deformation in shear bands was observed in both alloys. The shear bands were more pronounced and longer (running through larger number of deformed grains) in the non-homogenized samples and in the alloy 5754. Final annealing results in complete recrystallization in all samples. The grain size depends both on alloy composition and on preceding cold-rolling reduction. The grains in 5049 sheets (Figs. 4a,b) are coarser than those in 5754 samples (Figs. 4c,d). The samples prepared without homogenization (cold rolling reduction 83 % – *non-homogenized 1*, *non-homogenized 2*) have at the final gauge finer grains than their counterparts prepared with homogenization (75 % cold rolling reduction) – Fig. 5. The grains close to the surface of both homogenized and non-homogenized 5049 sheets are coarser as compared to the grains in inner regions. On the other hand, the non-homogenized 5754 samples have uniform and fine grain size through the whole sheet thickness, whereas the homogenized sample has slightly coarser grains in surface regions. The grains in the non-homogenized samples rolled in AIB (*non-homogenized 1*) are finer as compared to their laboratory rolled counterparts (*non-homogenized 2*). This holds both for the grains at surface and at mid-thickness. All qualitative observations concerning grain size are supported by grain size measurement results summarized in Fig. 5. The mean grain size in the longitudinal direction of the samples *non-homogenized 2* is 26 μm and 12 μm for the alloys 5049 and 5754, respectively. However, the homogenized samples show grains considerably coarsened to 34 μm and 19 μm, respectively.

The results of hardness and conductivity measurements at the final gauge of 1.0 mm are summarized in Table 3. The decrease in hardness due to annealing

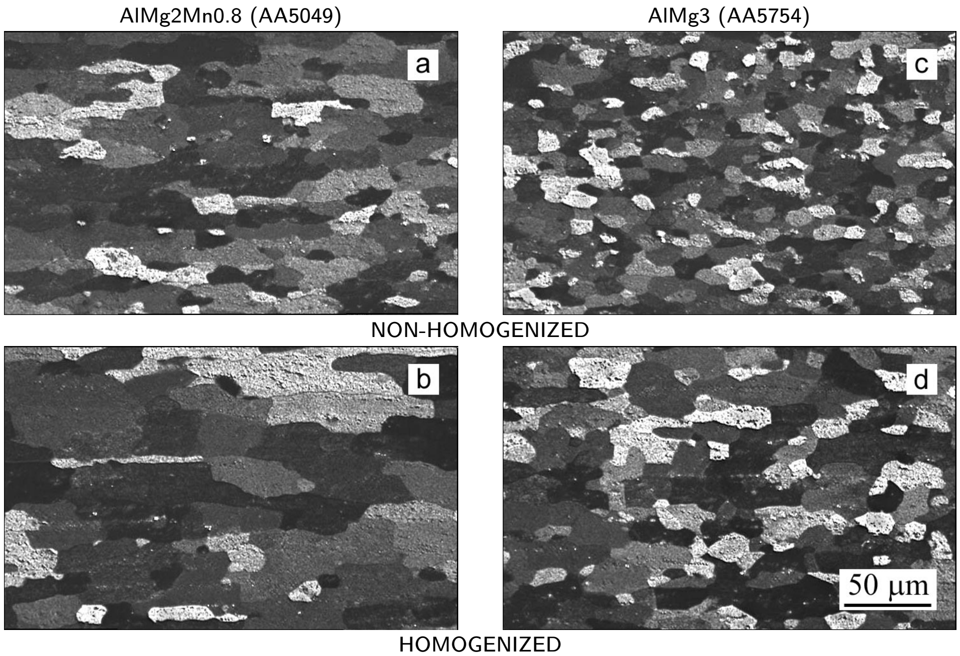

Fig. 4. Grain structure of non-homogenized (a) (c) and homogenized (b) (d) Al-Mg sheets at the final gauge 1.0 mm.

is larger in non-homogenized samples 1 and 2 of alloy 5049 as compared to their homogenized counterparts. In the case of alloy 5754, the decrease in hardness in laboratory rolled samples is similar, independently of homogenization. The sample 5754-Nh1 rolled using larger one-pass reductions (in industrial conditions) exhibits higher hardness both in the hard and soft conditions than its counterpart 5754-Nh2 rolled on a laboratory mill. The decrease in hardness is due to complete recrystallization. The difference in hardness between sample 5754-Nh1 and 5754-H could be ascribed to the difference in grain size (see Fig. 5).

T a b l e 3. Hardness and conductivity before and after final annealing of 1.0 mm gauge samples

Sample	HV 10		ΔHV 10	Conductivity κ [m·Ω^{-1}·mm^{-2}]		$\Delta\kappa$
	before	after		before	after	
5049-Nh1	103	51	51	18.9	21.1	2.2
5049-Nh2	98	51	47	19.6	21.7	2.1
5049-H	88	50	38	23.2	23.9	0.7
5457-Nh1	108	58	50	20.1	21.3	1.2
5457-Nh2	99	54	45	21.2	22.7	1.5
5457-H	97	51	46	22.6	23.3	0.7

The results of conductivity measurements indicate that depletion of solute solution of Mn atoms occurs in non-homogenized samples. The decrease in conductivity due to annealing is larger in the samples of alloy 5049 as this alloy contains more Mn than alloy 5754 (Table 1). Some increase in conductivity is also observed in homogenized samples and may be ascribed to precipitation and/or coarsening of Mn-bearing dispersoids. The occurrence of Mn-particles could be expected because homogenization treatment has been done at relatively low temperature (450 ℃), which is not sufficient for complete homogenization of Mn in TRC-cast Al alloys. However, these assumptions are of speculative character and have to be verified by resistometric measurements of homogenized samples.

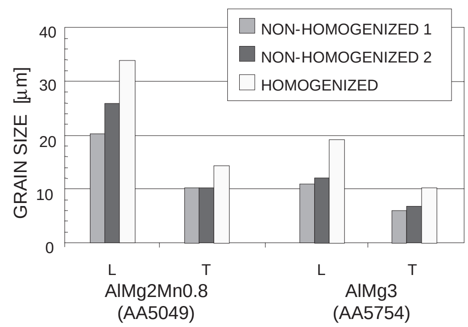

Fig. 5. Grain size of the 1.0 mm gauge sheets in the long transverse plane (L – rolling direction, T – transverse direction).

3.3 Tensile properties and formability of 1.0 mm sheets (O-temper)

The results of tensile tests carried out on samples cut both in rolling (L) and transverse (T) directions are in Fig. 6. Tensile test results indicate that the properties of Al-Mg 1.0 mm sheets prepared from TRC materials depend, likewise their grain structure, both on alloy composition and on down-stream processing procedure. As expected, the samples of alloy 5049 exhibit lower yield stress (0.2 % YS) and ultimate tensile strength (UTS) than their counterparts of alloy 5754. At the same time, 5049 samples have slightly lower tensile elongation than samples of alloy 5754 (Fig. 6). Non-homogenized samples are in general slightly stronger than their homogenized counterparts and in the same time they exhibit higher or equal elongation as compared to their homogenized counterparts. The highest values of 0.2 % YS and UTS were measured on samples rolled in industrial conditions and then annealed in laboratory (samples *non-homogenized 1*). The difference in strength between laboratory and industrially rolled samples is larger in the case of alloy 5754. The high strength of non-homogenized samples is combined with high elongation. In almost all cases, the strength in the rolling direction is slightly higher than in the transverse direction.

Figure 7 shows column diagrams comparing the values of Erichsen dome height (IE20), earing index (Earing) and formability parameter [(UTS-YS).A50] calculated from tensile properties. The values of Erichsen height of all samples are very similar. On the other hand, significant differences are observed in earing. The homogenized samples of both alloys form higher ears in 0° and 90° directions (with respect to RD) as compared to their non-homogenized counterparts. The non-homogenized sample of alloy 5754 does not form any ears, the homogenized sample also exhibits very low hills and shallow valleys. The samples of alloy 5049 have lower formability indices (UTS-YS).A50 than the samples of alloy 5754. The samples of alloy 5754 rolled in industrial conditions (*non-homogenized 1*) exhibit the highest formability indices. These samples also show the best elongation.

4. Further discussion

Although the alloy 5049 contains lower amount of main alloying elements (2.3 % Mg + Mn compared to 2.6 % Mg + Mn in 5754 alloy) it exhibits much larger number of particles, because of higher amount of the main dispersoid-forming addition – Mn (0.45 % compared to 0.23 % in the 5754 alloy) [9]. AlMnFe dispersoids form in both alloys during homogenization (450 ℃/4 h – Figs. 1c,d) or during final annealing (350 ℃/4 h) in non-homogenized samples of 5049 alloy (Fig. 2c). No dispersoids were observed in non-homogenized samples of 5754 alloy after final annealing (Fig. 3a).

The grains were relatively fine already in the as-cast materials. The grain size in the transverse direction in the central part of the as-cast sheet 5754 was 19 μm and 24 μm in the case of 5049 alloy. It did not change due to homogenization at the intermediate thickness of 4 mm (20 μm and 31 μm, respectively). The former value

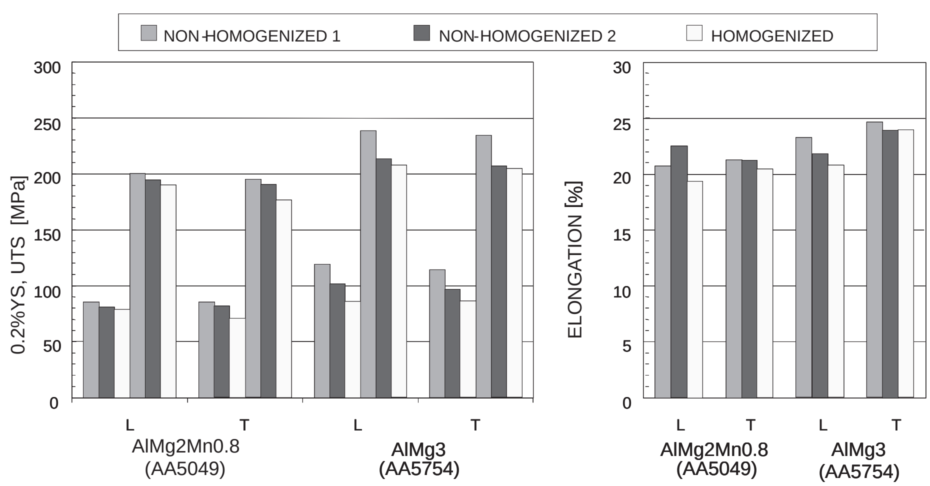

Fig. 6. Tensile mechanical properties of annealed 1.0 mm gauge sheets (O-temper).

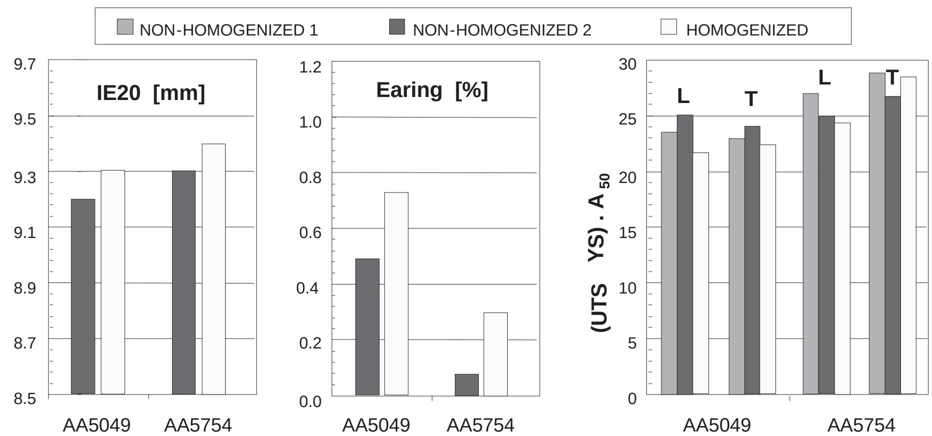

Fig. 7. Height of Erichsen dome (IE20), results of the cupping test (Earing) and formability parameter (UTS-YS).A50 of annealed 1.0 mm gauge sheets (O-temper).

(20 μm for 5754 alloy) is slightly lower than the corresponding value of 22.1 μm measured in TRC material at the 3 mm intermediate sheet thickness in a previous study [7]. At the final gauge of 1.0 mm, the grain size in homogenized 5754 sheet was 12 μm [7]. The present study shows that the homogenized material, which was subjected to nearly the same thermo-mechanical treatment as this used in [7], has somewhat finer grains (10 μm for 5754 alloy). However, the best results in this study were obtained without homogenization – final annealing of non-homogenized sheets at the 1.0 mm gauge led to a substantial grain refinement of both alloys down to 6 μm in 5754 alloy and 10 μm in 5049 alloy (transverse direction). In the case of 5754 alloy, the grain size is so small (11.6 μm in the longitudinal and 6 μm in the transverse direction – Fig. 4c, Fig. 5), that the sheets could be considered for superplastic forming.

If we compare 5049 and 5754 sheets – Figs. 4a,c or Figs. 4b,d, or homogenized and non-homogenized samples of each alloy Figs. 4a,b or Figs. 4c,d, it is somewhat surprising that materials containing more particles show larger grains than sheets containing lower amount of particles. Usually, particles pin and drag grain boundaries, which results in grain refinement. However, to produce small and stable grain size, an optimum dispersion level is required. If this level is surpassed, the grain coarsens [12]. The non-homogenized 5754 material at the final 1.0 mm gauge has uniform and fine grain size through the whole sheet thickness. From this result we can conclude, that it is due to an optimum second-phase particle size and distribution.

Likewise the grain structure, the tensile properties of 1.0 mm O-temper sheets depend on both alloy composition and down-stream processing procedure. Lower alloyed 5049 sheets having somewhat coarser grains exhibit lower yield stress and ultimate strength than their counterparts of alloy 5754 (Fig. 6). At the same time, 5049 samples have slightly lower tensile elongation (Fig. 6). Non-homogenized samples are stronger than homogenized variants and in the same time they exhibit higher or equal elongation as homogenized sheets. While the values of Erichsen dome height of all samples are very similar, significant differences are observed in cupping test (Fig. 7). The homogenized samples of both alloys form higher ears in 0° and 90° directions as compared to their non-homogenized counterparts. The non-homogenized sample of alloy 5754 does not form ears at all, the homogenized sample exhibits small earing. On the other hand, the anisotropy of 5049 sheets is higher (higher ears in both non-homogenized and homogenized conditions) – Fig. 7. The 5049 samples have also lower formability indices than 5754 samples. Tensile mechanical properties of 5754 sheets are comparable to those measured in a previous study [7].

The most surprising result of this study is that homogenization treatment at the intermediate thickness of 4 mm is not beneficial. As a matter of fact it is detrimental, resulting in grain coarsening and degradation of sheet anisotropy of both Al-Mg sheets. On the other hand, in the case of TRC Al-Fe-Mn-Si alloy (AA8006) it is indispensable. If a TRC Al-Fe-Mn-Si sheet is not homogenized, coarse grained heterogeneous structure is formed, while fine grain homogeneous structure is typical for the homogenized alloy [10, 11].

5. Conclusions

1. The simplest down-stream processing of twin-roll cast alloys AA5049 and AA5754, consisting of cold rolling of the 6 mm thick as-cast sheet down to final 1.0 mm gauge and final recrystallization annealing, is the best method for manufacturing good quality fine-grained sheets with low anisotropy.

2. Homogenization treatment at the intermediate thickness of 4 mm is detrimental. It results in grain coarsening and degradation of sheet anisotropy of both Al-Mg sheets.

3. The fact that homogenization treatment is not necessary reduces manufacturing costs and renders Al-Mg sheets more attractive for all applications.

4. It must be stressed out that the structure and mechanical properties of materials processed in laboratory and in industrial conditions are slightly different. Therefore, laboratory optimized down-stream processing parameters should always be verified in industrial conditions.

Acknowledgements

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