MICROSTRUCTURE EVOLUTION OF TWIN-ROLL CAST Al-Mg ALLOYS DURING DOWNSTREAM PROCESSING

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Microstructure evaluation of twin-roll cast AlMg3 (AA5754) and AlMg4.5Mn0.4 (AA5182) alloys in the as-cast condition and during downstream processing was performed using light and scanning electron microscopy. Primary intermetallic phases were identified by means of wavelength-dispersive X-ray spectroscopy as $Al_6(Fe,Mn)$, $Al_{12}(Fe,Mn)_3Si$ and Mg_2Si. Moreover, very coarse particles containing Al and Mg, but also Ga, Zn and Cu were found in centerline segregation channels. At the final gauge of 1 mm, the twin-roll cast (TRC) materials exhibit a homogeneous grain structure and very fine dispersion of intermetallic particles. Final gauge tensile properties of TRC alloys are nearly the same as these of equivalent materials produced by direct chill casting and hot rolling technology.

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

VÝVOJ MIKROSTRUKTURY PLYNULE LITÝCH PLECHŮ ZE SLITIN Al-Mg BĚHEM TERMOMECHANICKÉHO ZPRACOVÁNÍ

Mikrostruktura plynule litých plechů ze slitin AlMg3 (AA5754) a AlMg4,5Mn0,4 (AA5182) po odlití a během termomechanického zpracování na finální tloušťku byla charakterizována pomocí světelné a elektronové metalografie. Primární intermetalické fáze byly identifikovány pomocí vlnově disperzní RTG mikroanalýzy jako $Al_6(Fe,Mn)$, $Al_{12}(Fe,Mn)_3Si$ a Mg_2Si. Navíc byly ve středové segregaci pozorovány velmi hrubé částice obsahující Al a Mg, ale též Ga, Zn a Cu. Na finální tloušťce 1 mm mají plynule lité slitiny homogenní strukturu zrn a velmi jemnou disperzi intermetalických částic. Mechanické vlastnosti plynule litých slitin na finální tloušťce jsou srovnatelné s ekvivalentními materiály vyrobenými litím do ingotů a válcováním za tepla.

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1. Introduction

Aluminium sheets are produced either by conventional direct-chill (DC) casting and hot rolling method or by a continuous twin-roll casting (TRC) technology. Twin-roll casting offers high productivity, larger coils, low investment costs, and energy and materials savings [1, 2]. The TRC method is well established for producing aluminium foil, heat exchanger fins and several grades of building and construction sheet.

A primary goal in today's automotive industry is weight reduction resulting in fuel economy improvement and emission reductions [3]. Aluminium alloys, having one-third density of steel and a superior strength-to-weight ratio could provide up to 50 % weight reductions when used in automotive sheet applications. However, to perform the same function, Al alloy sheets produced by conventional DC casting and hot rolling route cost usually four or five times more than steel sheet [4]. Therefore, production of low-cost/high-quality Al-Mg (AA5xxx) sheets by twin-roll casting can help to increase the employment of wrought aluminium alloys in automotive applications. The first results of research and development efforts have shown that the mechanical properties, formability and corrosion resistance of Al-Mg twin-roll cast alloys are equivalent or superior when compared with DC cast and hot-rolled materials [5, 6].

The present paper describes microstructure evolution of twin-roll cast AlMg3 (AA5754) and AlMg4.5Mn0.4 (AA5182) sheets during downstream processing from the as-cast condition to the final gauge of 1 mm. Equivalent DC cast and hot rolled alloys were processed in the same manner as the TRC strips and were used as reference materials. The standard tensile properties of all final gauge materials are compared.

2. Materials and procedures

Twin-roll cast strips of AlMg3 and AlMg4.5Mn0.4 alloys 6.2 and 5.7 mm in thickness, respectively, were cast at 1400–1700 mm width on FATA Hunter *Speed Casters®* by Assan Aluminium Works, Tuzla, Istanbul, Turkey. Equivalent DC-cast and hot rolled plates of 9 mm thickness were supplied by Aluminium Works Al Invest, Břidličná, Czech Republic. The chemical composition of the experimental

Table 1. Chemical composition of studied alloys [wt.%]

Alloy		Si	Fe	Cu	Mn	Mg	Cr	Al
AlMg3 (AA5754)	TRC	0.172	0.294	0.038	0.258	2.770	0.066	96.170
	DC	0.160	0.230	0.041	0.280	2.889	0.017	96.440
AlMg4.5Mn0.4 (AA5182)	TRC	0.184	0.289	0.046	0.331	4.096	0.169	94.750
	DC	0.160	0.270	0.091	0.460	4.300	0.015	94.610

materials is in Table 1. The downstream processing was carried out in laboratory conditions in Research Institute of Metals, Panenské Břežany.

In order to obtain approximately the same starting condition as this of the TRC alloys, the DC cast materials were first hot-rolled (starting temperature 490 °C) to 5.5 mm thickness. All materials were then cold rolled to 3 mm (reduction 35–39 %) and subjected to homogenisation annealing for 4 h at 450 °C. After cold rolling with reduction 70–72 % to 1 mm thickness the sheets were annealed for 4 h at 350 °C to obtain sheets in the soft (O) temper. Both heat treatments were performed in a furnace with atmosphere circulation and controlled slow heating and cooling in order to simulate industrial conditions of annealing in large coils. The annealing temperature 350 and 450 °C was reached in 9 and 15.5 h, respectively. After 4 hours at the annealing temperature the samples were gradually cooled during 6 and 10 h, respectively, down to 25 °C.

Samples for microstructure examination were taken after each technological step in the long transverse plane (L-S), i.e. in the plane parallel to the rolling direction and perpendicular to the rolling plane. The examinations were performed by metallographic microscope Nikon equipped with digital image recording facilities. The intermetallic particles were revealed by etching in 0.5 % HF solution, the grain structure was observed in crossed polarizers after anodising in Barker's reagent. The grain size of the samples was measured in the rolling (L) and transverse (S) directions in the center and close to the surface of the sheets. Phase analysis of intermetallic particles was performed on scanning electron microscope (SEM) ZEISS DSM 940 equipped with wavelength-dispersive X-ray (WDX) microanalyser Microspec WDX-3PC. Regions containing parts of Center Line Segregation Channels (CLSCs) were examined using the backscattered electron (BSE) signal and X-ray maps of Mg, Si, Fe, and Mn distribution were recorded.

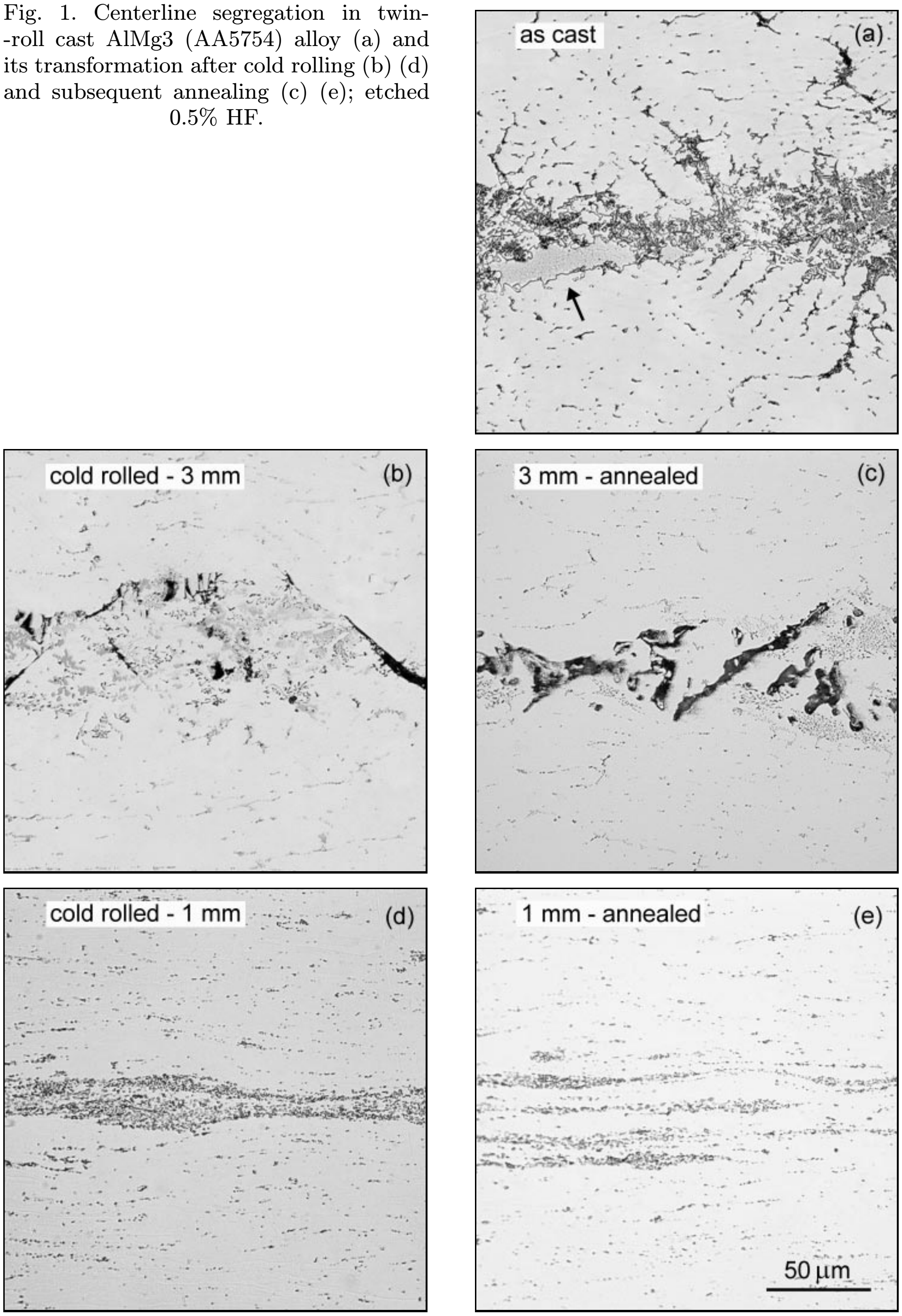
The tensile properties of 1 mm gauge sheets were measured using Instron 1176 testing machine controlled by Merlin Series IX software. Tensile tests were performed on standard 50 mm gauge length samples taken in the longitudinal (0°), transverse (90°) and 45° directions with respect to the rolling direction. The test specimens were deformed at crosshead speed of 2 mm/min, which corresponds to an initial strain rate of $\sim 4 \times 10^{-4}$ s^{-1}; the sampling frequency of data acquisition was 10 pts/s.

3. Results and discussion

3.1 Character and evolution of second-phase particles

The as-cast TRC samples contain different intermetallic phases in the form of eutectic colonies or individual particles. Typical micrographs of these second-phase particles are in Fig. 1 and Fig. 2. A characteristic feature of twin-roll cast alloys is the formation of CLSC, situated approximately in strip mid-thickness.

Fig. 1. Centerline segregation in twin-roll cast AlMg3 (AA5754) alloy (a) and its transformation after cold rolling (b) (d) and subsequent annealing (c) (e); etched 0.5% HF.



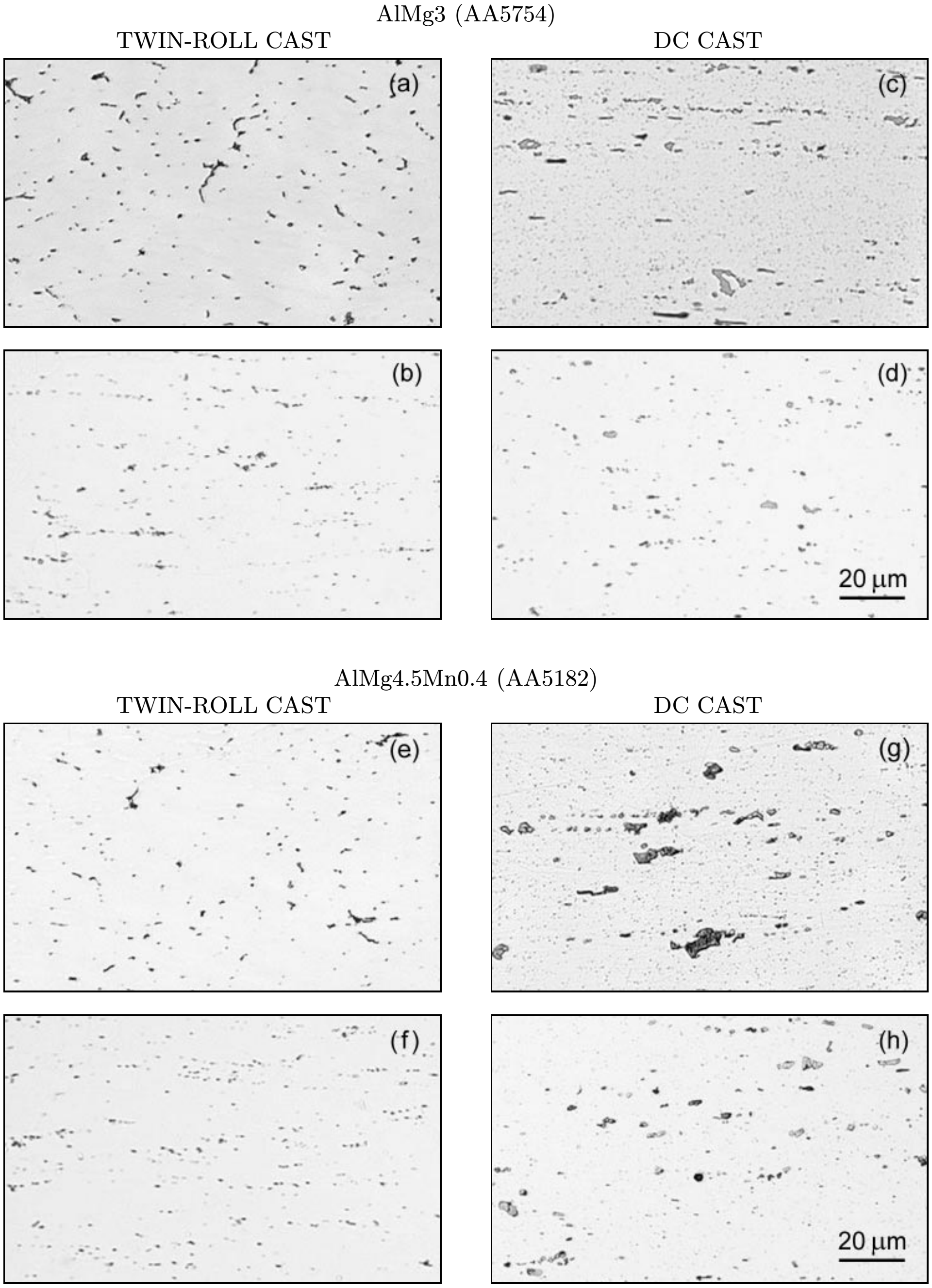


Fig. 2. Comparison of intermetallic particles of twin-roll cast and DC-cast alloys: (a) (c) (e) (g) – as cast, (b) (d) (f) (h) – final gauge.

The channels are not always situated strictly in the middle of strip thickness but they are often more or less shifted towards one of the surfaces. The CLSCs are fragmented (discontinuous) and the fragments have different length and width. The mean length and thickness of the fragments in the studied alloys are about 900 μm and 130 μm, respectively. Fig. 1a shows part of a CLSC fragment in the AlMg3 as-cast alloy. The CLSCs take the form of large clusters of fine intermetallic particles surrounded by aluminium matrix. Besides the fine particles the channels often contain coarse compact particles of different appearance. Surface segregation, individual coarse particles or elongated clusters of coarse eutectics, were observed in a surface layer of 20 to 30 μm in thickness at both strip surfaces. Outside the segregation patterns, the primary second-phase particles form small eutectic clusters. The microstructure of the as-cast AlMg4.5Mn0.4 alloy is very similar to AlMg3 strip microstructure.

The composition of coarse CLSC particles was determined by WDX using BSE signal and X-ray maps. It was found that the concentration of magnesium in CLSCs is significantly higher than outside CLSC. Quantitative local chemical analysis of coarse particles in CLSC was performed. Three types of particles were identified: 1. containing Al, Fe and Mn; 2. containing Al, Fe, Mn, and Si; 3. containing Mg and Si. Besides these phases containing the main alloying elements, the CLSCs in both TRC alloys contain also very coarse light-colour particles (one of them in Fig. 1a is marked by an arrow). These particles are Al and Mg rich, but contain also Ga, Zn and Cu – elements that are not usually added to Al-Mg commercial alloys. The amount of Ga in the particles is between 0.7 and 0.9 wt.%, the content of Zn is between 0.2 and 0.3 wt.% and the content of Cu ranges from 0.3 to 0.5 wt.%. The origin of these particles is unknown.

The composition of any of the measured particles does not correspond exactly to the stoichiometric formulas of known intermetallic phases Al_6(Fe,Mn), Al_{12}(Fe,Mn)$_3$Si and Mg_2Si. This discrepancy is due to the small particle size and to the fact that in all cases a certain non-zero volume of the matrix (depending on particle size) is included in the region from which the X-ray signal is acquired. In order to overcome ambiguous phase identification, the ratio of alloying elements was determined [6]. Even using this information, the results of local chemical analysis do not match exactly the stoichiometry of known phases. It is obvious that the particles in CLSC are complex and their composition is far from the composition of equilibrium phases usually cited in literature [7]. Nevertheless, from the results of the present study it can be concluded that CLSCs in both alloys are predominantly clusters of Al-Fe-Mn particles without any Si. It is highly probable that these particles belong to the phase Al_6(Fe,Mn) usually found in TRC aluminium alloys [8]. A few particles with Fe (and Mn) with small amount of Si were also observed and they are probably one of the variants of α-AlFe(Mn)Si phase, which is frequently described in literature as Al_{12}(Fe,Mn)$_3$Si [9]. The CLSC probably contain also particles of the binary Al_8Mg_5 phase but such particles were not found. Several coarse Mg_2Si particles were observed in AlMg4.5Mn0.4 as-cast strip.

As can be seen from Fig. 1, the microstructure heterogeneities observed in as-cast strips are not eliminated by consecutive downstream procedures such as homogenisation and cold rolling. Coarse CLSCs and particles are fractured by cold rolling (Fig. 1b) and transformed by homogenisation – they gradually coarsed and get rounded shapes (Fig. 1c). However, they are still present in transformed form in the final gauge strips (Fig. 1d,e). Microstructure defects of such type can have detrimental impact on final gauge sheet properties, especially on strength, tensile elongation and, thus, on material formability. For this reason, they are undesirable in materials for applications, where high formability is required (e.g. in automotive sheets). Appropriate tuning of the casting conditions of TRC strips should be carried out in order to eliminate coarse segregation patterns.

The size and distribution of intermetallic particles in DC-cast and hot-rolled materials significantly differ from these of TRC strips. Fig. 2 shows a comparison of the microstructure of DC-cast alloys and twin-roll cast materials outside centerline segregation patterns. It can be clearly seen (Fig. 2c,g) that the particles in both DC-cast materials are coarser that in TRC strips and they are aligned in rows along the rolling direction. The particles in the sheets become finer during the downstream processing, regardless the casting technology used. Nevertheless, at the final gauge thickness of 1 mm, the particles in the DC-cast materials are still coarser than those in TRC strips (Fig. 2b,d,f,h).

A difference in particle size at surface and in the sheet inner volume was observed in both TRC and DC-cast materials. The particles are finer close to the surface of the sheets for both casting technologies, but the difference is more pronounced in DC-cast sheets. This through-thickness heterogeneity is due to differences in the cooling rate near the surface and in the interior of the as-cast strips or blocks and also to differences in material flow during rolling.

3.2 Grain structure evolution

The grain structure of TRC as-cast samples of AlMg3 alloy is shown in Fig. 3a,b. It can be seen that the grains in the strip interior are only slightly elongated in the casting (rolling) direction (Fig. 3b), whereas in the surface layers they are highly flattened (Fig. 3a). Furthermore, the grains close to the surface are not parallel to the rolling direction as in the strip interior but they are inclined with respect to the surface plane. The micrographs in Fig. 3 show also the evolution of the size and shape of grains during the downstream processing of this material. It is evident that after the first rolling pass (to 3 mm thickness) the grains become severely elongated in the rolling direction and shear bands can be distinguished in their interior (Fig. 3c,d). There is a marked difference in grain shape between the

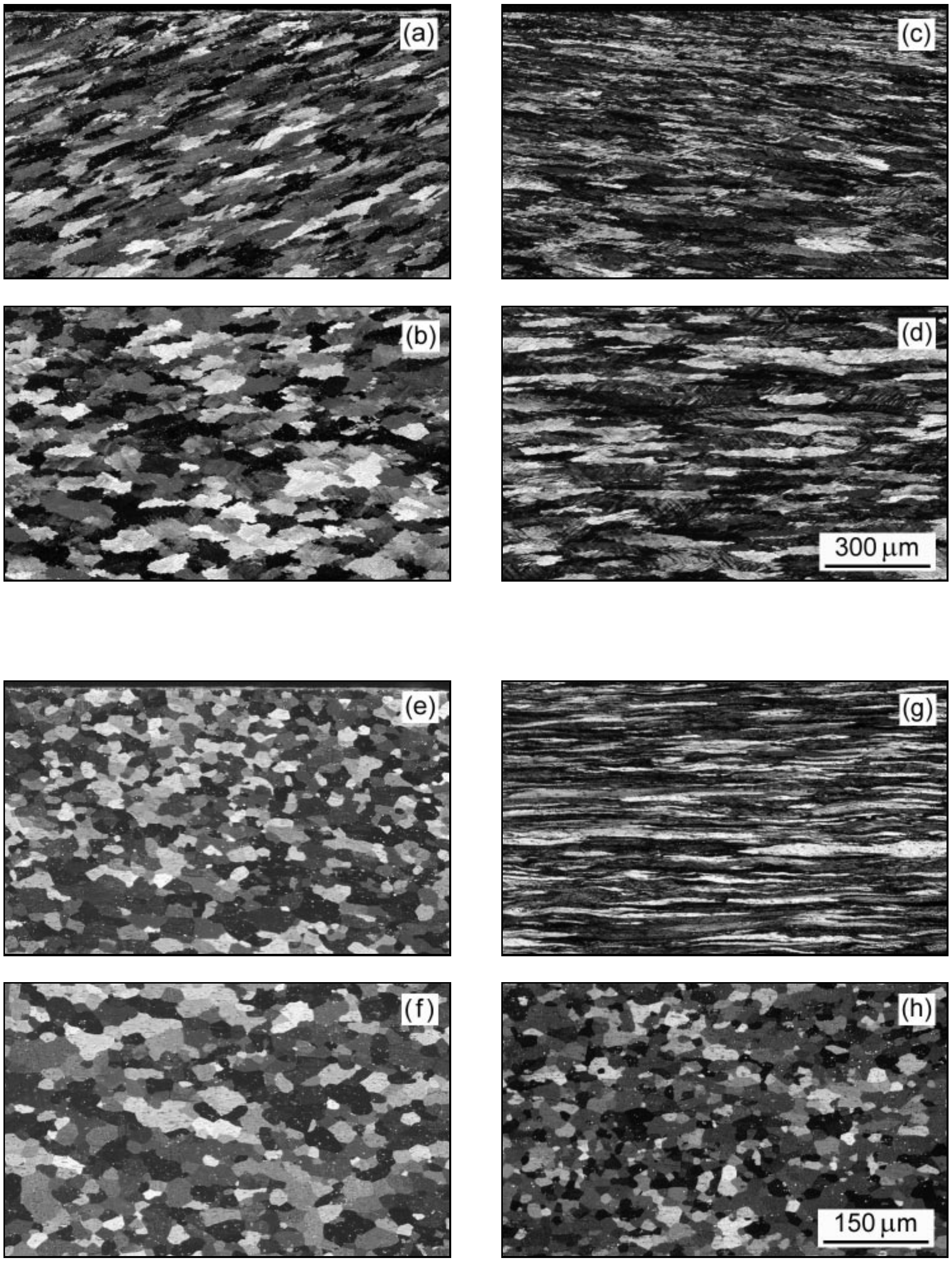


Fig. 3. Grain structure of AlMg3 (AA5754) twin-roll cast alloy: as cast (a) (b), cold rolled to 3 mm (c) (d), annealed at 3 mm (e) (f), cold rolled (g) and annealed (h) at 1 mm (electrolytical etching Barker, polarized light); (a) (c) (e) – surface of the sheet, (b) (d) (f) (g) (h) – center of the sheet.

surface (Fig. 3c) and center of the sheet (Fig. 3d). After the homogenisation treatment, the sheet becomes fully recrystallized, the grains are equiaxed, but there is still some difference in grain size between the surface and the center of the sheet. Subsequent cold rolling (Fig. 3g) and final annealing (Fig. 3h) produce homogeneous grain structure. The grain structure of TRC as-cast AlMg4.5Mn0.4 alloy and its evolution during downstream processing are very similar to these of AlMg3 alloy.

The grain size of all samples was measured in the rolling and transverse directions in the center and close to the surface of the sheets. Table 2 summarizes the results of the measurements in the transverse direction. It can be seen that there are not significant differences in sheet grain sizes obtained using the two different production technologies. In comparison with the DC casting and hot rolling method, the TRC technology has a relatively shorter processing route with a lower number of procedures to control the microstructure. Nevertheless, it can be seen from Table 2 and Fig. 3 that the resulting grain structure at the final gauge is homogeneous in both technologies. The differences in the grain size in the center and close to the surface of both TRC sheets are even smaller than in the case of DC cast materials.

Table 2. Comparison of the transverse grain size in μm after annealing at 3 mm and 1 mm thickness (the aspect ratio of grains in different alloys ranged from 1.4 to 1.6)

	AlMg3		AlMg4.5Mn0.4	
	TRC	DC	TRC	DC
3 mm – surface	16.6	23.4	18.4	18.2
– center	22.1	24.6	21.9	19.9
1 mm – surface	11.2	11.6	10.5	11.9
– center	11.9	12.7	10.4	12.8

3.3 Mechanical properties at final gauge

The tensile properties of both twin-roll cast and DC-cast alloys are compared in column graphs in Fig. 4. The data shown in the graphs are average values from three tensile tests. The twin-roll cast alloys compare well with their DC-cast counterparts. The somewhat higher yield stress and tensile strength of the DC-cast materials are probably due to the higher solute content in these alloys (Table 1). The anisotropy of the yield stress and tensile strength is not pronounced, the elongation values of all alloys are very similar.

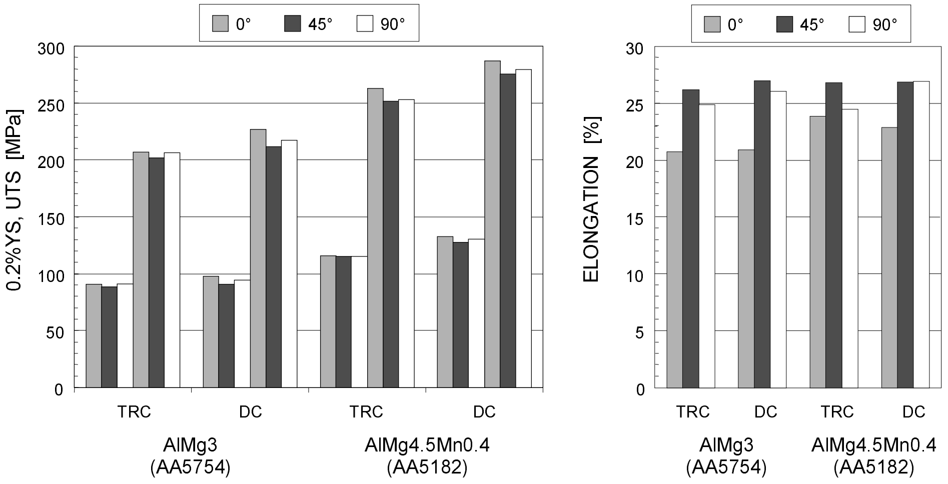


Fig. 4. Comparison of tensile mechanical properties of twin-roll cast and DC-cast and hot rolled materials at the final gauge of 1 mm.

4. Summary

1. A typical feature of the studied TRC strips is the presence of relatively coarse centerline segregation channels (CLSC). The channels, often shifted to one of the strip surfaces, are formed by clusters of $Al_6(Fe,Mn)$, $Al_{12}(Fe,Mn)_3Si$ and Mg_2Si intermetallic particles. Large particles containing Al, Mg, but also Ga, Zn and Cu were also found in CLSC. These coarse segregation patterns transform during downstream processing, but they are still present in final gauge sheets.

2. The grain structures of both twin-roll cast materials in the as-cast condition are heterogeneous, with coarse and less deformed grains in the interior of the strip and very long and heavily deformed grains at both surfaces. Subsequent downstream processing transforms the heterogeneous grain structure to a homogeneous one at the final gauge.

3. The mechanical properties of twin-roll cast alloys in the final gauge are similar to the properties of DC-cast materials.

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REFERENCES

[1] LI, B. Q.: JOM, *47,* 1995, p. 13.
[2] JAMET, M.: Aluminium Today, *11,* 1999, p. 19.
[3] WARREN, A. S.: Aluminium, *67,* 1991, p. 1078.
[4] McVAY, G. L.—COURTRIGHT, E. L.—JONES, R. H.—SMITH, M. T.: Light Metal Age, *56,* 1998, p. 6.
[5] BIROL, Y.—ZEYBEKOGLU, H. G.—KARA, G.—DÜNDAR, M.—CAKIR, O.—AKKURT, A. S.—YILDIZBAYRAK, G.—ROMANOWSKI, CH.: In: Aluminum 2001, TMS Annual Meeting, New Orleans, Louisiana, February 11–15, 2001. Eds.: Kaufman, G., Green, J. Das, S., The Minerals, Metals & Materials Society, Warrendale, PA, p. 107.
[6] SLÁMOVÁ, M.—JANEČEK, M.—KARLÍK, M.: Al-Mg twin-roll continuously cast strips: Characterisation of as-cast and 1.0 mm gauge materials. Research Report VÚK Panenské Břežany, No. 25/01-V, 2001.
[7] MONDOLFO, L. F.: Aluminium Alloys: Structure and Properties. London, Butterworths 1976.
[8] LUIGGI, N. J.: Met. Mat. Transactions, *28B,* 1997, p. 125.
[9] POLMEAR, I. J.: Light Alloys: Metallurgy of the Light Metals. 3$^{\text{rd}}$ edition. London, Arnold 1995.

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