Inhomogeneity and anisotropy of mechanical properties of extruded aluminium alloys investigated by the acoustic emission technique

P. Dobroň[1]*, F. Chmelík[1], V. Očenášek[2], P. Homola[2]

[1] *Department of Physics of Materials, Charles University, Ke Karlovu 5, CZ 121 16 Prague 2, Czech Republic*
[2] *Research Institute for Metals, VÚK Panenské Břežany, Ltd., Panenské Břežany 50, 250 70 Odolena Voda, Czech Republic*

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Abstract

The process of extrusion is responsible for a strong anisotropy of mechanical properties in many aluminium alloys, specifically with respect to the position of the material in the extruded profile. The inhomogeneity and anisotropy of mechanical properties through the profiles of AlMg3 and AlCuMgLi alloys have been investigated by the measurements of the acoustic emission (AE). Extruded profiles were exposed to a solution heat treatment and, for the AlCuMgLi alloy, also to a subsequent artificial ageing. AlMg3 alloy is a solid solution and, therefore, non-age hardenable alloy. Samples taken from different positions along the extrusion direction (ED) and in the transversal direction (TD), i.e. perpendicular to ED were deformed in tension at room temperature (RT) and at an initial strain rate of 8.33×10^{-4} s^{-1}. The results of AE are related to deformation curves and discussed with respect to microstructural changes during plastic deformation.

Key words: AlMg3 (AA5754) alloy, AlCuMgLi (1441) alloy, acoustic emission, direct extrusion, artificial ageing

1. Introduction

Extruded aluminium alloys exhibit a strong fibre texture, which results in a dependence of mechanical properties (e.g. tensile yield strength – TYS, ultimate tensile strength – UTS) on the position of the material in the extruded profile. Such behaviour is unfavourable for using in technical applications and therefore deserves a considerable research interest to better understand the deformation process during extrusion and to reduce the mechanical anisotropy. Cieslar et al. [1, 2] have studied the influence of the phase composition of an AlCuMgLi alloy (achieved by natural or artificial ageing) on the jerky flow during mechanical tests at a constant stress rate. These results point out that the concentration of free Li atoms in supersaturated solid solution, and also the ageing process have a significant influence on the critical onset strain of the jerky flow.

The acoustic emission (AE) is defined as transient elastic waves generated by sudden release of energy due to local dynamical changes in the material structure such as dislocation slip and twinning [3]. A direct correlation of AE parameters with the stress--strain curve yields information on the dynamic processes involved in plastic deformation of aluminium alloys.

This paper deals with mechanical testing and AE measurements performed on dumb-bell shaped profiles of two aluminium alloys with a different chemical composition. Non-age hardenable AlMg3 and age hardenable AlCuMgLi alloys were used for the study. The profile form has been designed in order to study the inhomogeneity of mechanical properties through the profile cross section.

*Corresponding author: tel.: +420 22191 1611; fax: +420 22191 1490; e-mail address: dobronp@karlov.mff.cuni.cz

Table 1. Chemical composition of experimental materials (wt.%)

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Li	Al
5754	0.18	0.27	0.048	0.342	3.458	0.19	0.02	–	Balance
1441	0.03	0.08	1.710	0.050	0.990	–	–	1.81	Balance

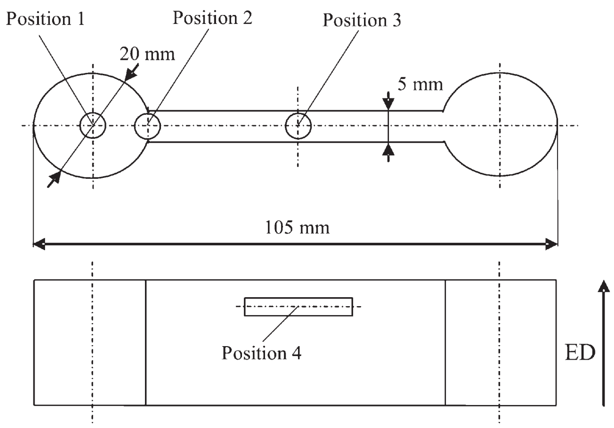

Fig. 1. Schematical drawing of extruded profile with setting out of sample positions.

2. Experimental procedure

Dumb-bell shaped profiles (Fig. 1) were produced by extrusion of aluminium alloys AlMg3 (AA 5754) and AlCuMgLi (1441), respectively. Chemical composition of experimental materials is given in Table 1. Both aluminium alloys were processed by direct extrusion at an initial billet temperature of 400 ℃. The profile was extruded from a billet of 187 mm in diameter and an extrusion ratio of 1 : 28 was applied. For the investigation, AlMg3 alloy in an as-extruded condition was used. In the case of AlCuMgLi alloy, the heat treatment T6 was performed after the extrusion process, consisting of the solution annealing at 530 ℃ with subsequent water cooling and artificial ageing at 165 ℃ for 36 hours (finished by air cooling).

The microstructure was analysed on polished and etched cross section of the profile with respect to the extrusion (ED) and the transversal direction (TD) by using a light microscopy. For the sample preparation, the Barker's reagent based on fluoroboric acid was used.

Tensile samples (diameter 4 mm × 20 mm) were deformed in a universal testing machine INSTRON® 5500R at RT and at an initial strain rate of 8.33×10^{-4} s^{-1}. Samples were taken from the positions 1, 2, 3 along ED (Fig. 1) and from the position 4 along TD (see also Fig. 1).

Table 2. Mechanical properties of experimental materials as a function of the position inside the extruded profile

Alloy	Position	TYS (MPa)	UTS (MPa)
AA5754	1	90	246
	2	85	243
	3	89	250
	4	87	250
1441	1	421	605
	2	411	519
	3	379	534
	4	367	540

The computer-controlled DAKEL-XEDO-3 AE system was used to monitor AE on the basis of two-threshold-level detection, which yields a comprehensive set of AE parameters involving count rates $\dot{N}_{C_1}$ and $\dot{N}_{C_2}$ (count number per second [4]) at two threshold levels. The two-threshold-level detection allows to separate burst AE, what occurs mainly due to an instable fashion of plastic deformation, from the total AE. A miniaturized MST8S piezoelectric transducer (diameter 3 mm, almost point AE detection, flat response in a frequency band from 100 to 600 kHz, sensitivity 55 dB ref. 1 V_{ef}) was attached on the specimen surface with the help of silicon grease and a spring. The total gain was 90 dB. The AE signal sampling rate was 4 MHz, the threshold voltages for the total AE count N_{C_1} and for the burst AE count N_{C_2} were 730 and 1450 mV, respectively. The full scale of the A/D converter was ± 2.4 V.

3. Experimental results

Micrographs of the microstructure of both alloys with respect to the position of the samples inside the extruded profile are shown in Fig. 2. In the extruded AlMg3 alloy grains extended into ED are found. The narrowest grains are in the sample from the position 3 (Fig. 2c) and the largest value is found in the sample from the position 1 (Fig. 2a). In the AlCuMgLi alloy a non-recrystallized structure (i.e. containing high density of dislocations produced by extrusion) with a fibre texture along the ED is found, which is typical for extruded materials [5]. The fibre texture is the most pronounced in the sample from the position 3 (Fig. 2f).

Mechanical properties of the materials as a function of the position inside the extruded profile are presented in Table 2. The non-age-hardenable AlMg3 alloy does not show any dependence of mechanical properties on the position of the samples. Presented values are typical for non-age-hardenable aluminium

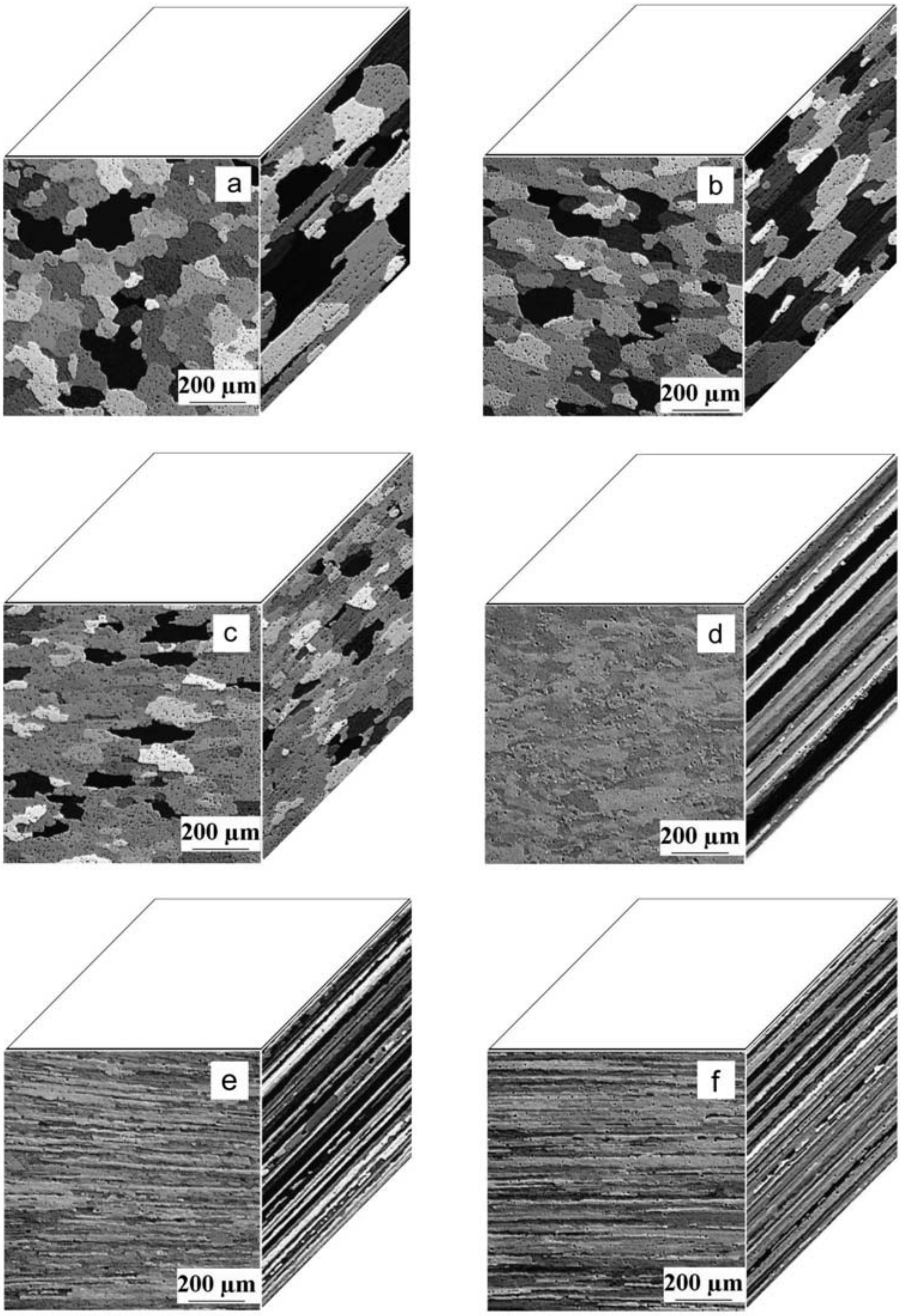

Fig. 2. Micrographs of aluminium alloys: AlMg3 from a) position 1, b) position 2, c) position 3 and AlCuMgLi from d) position 1, e) position 2, f) position 3.

alloys [6]. In the case of the AlCuMgLi alloy, a considerable inhomogeneity and anisotropy of mechanical properties is found. The highest TYS and UTS values are obtained in the position 1 on the edge of the profile and they decrease towards the position 3 in the centre of the profile. The sample from TD has the lowest TYS from all positions in the profile of the AlCuMgLi alloy and its UTS is comparable with that of the position 3 for the same alloy.

Stress-strain and AE count rate-time curves of the AlMg3 alloy from positions 1 and 4 are presented in Figs. 3 and 4, respectively. The deformation curves for samples taken from all positions exhibit serrated fashion of yielding, i.e. the Portevin-Le Chatelier (PLC) effect. Serrated flow in Al alloys signifies an inhomogen-

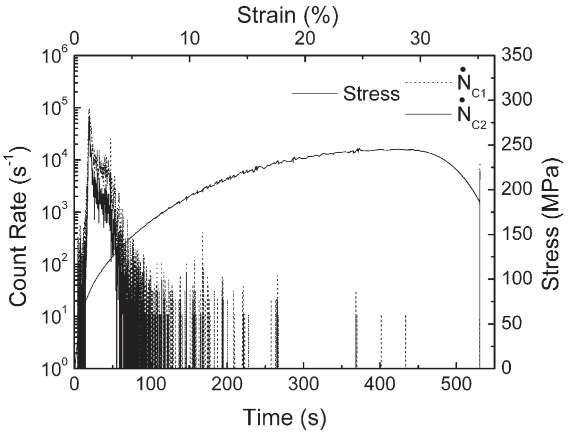

Fig. 3. Stress-strain and AE count rate-time curves of 5754 alloy, position 1.

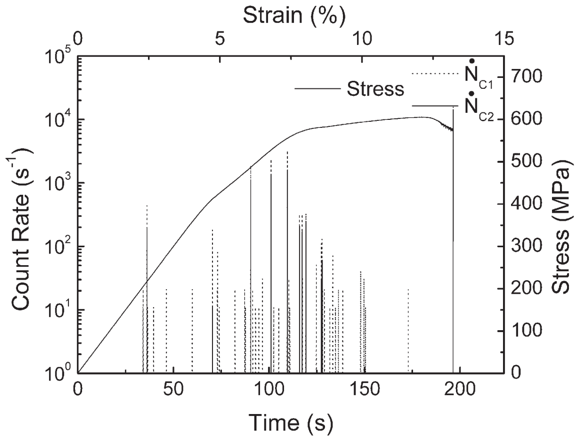

Fig. 5. Stress-strain and AE count rate-time curves of 1441 alloy, position 1.

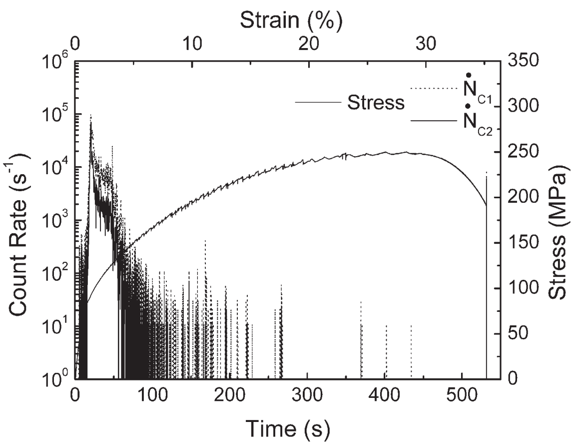

Fig. 4. Stress-strain and AE count rate-time curves of 5754 alloy, position 4.

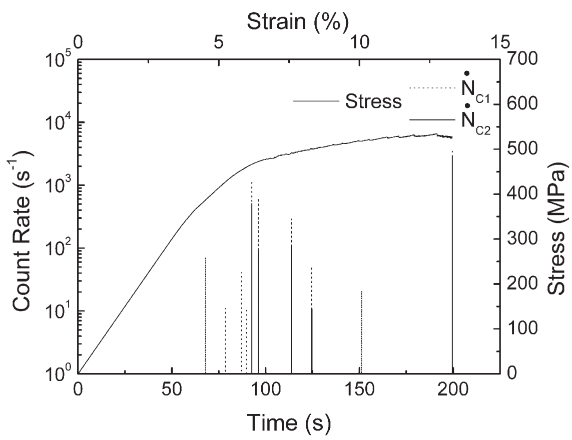

Fig. 6. Stress-strain and AE count rate-time curves of 1441 alloy, position 3.

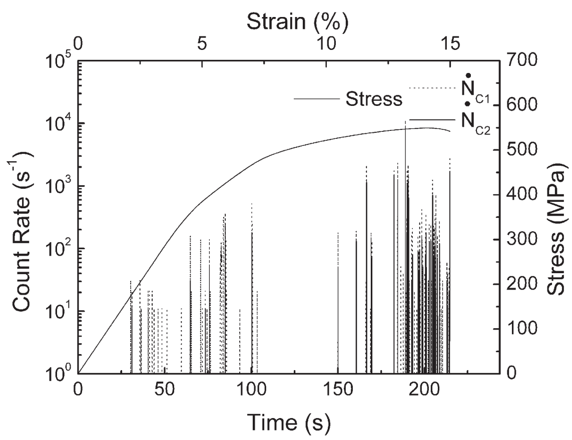

Fig. 7. Stress-strain and AE count rate-time curves of 1441 alloy, position 4.

eous fashion of plastic deformation. Almost the same results with the B-type of the PLC effect (according to the Brindley and Worthington classification [7]) were obtained by Chmelík et al. [8] for a similar AlMg alloy.

Stress-strain and AE count rate-time curves of the AlCuMgLi alloy from the positions 1, 3 and 4 are presented in Figs. 5–7. All deformation curves are smooth indicating no PLC effect.

Measurements of the AE activity at two threshold levels (N_{C_1}, N_{C_2}) are very helpful to recognize AE signals having a burst character with large amplitude. For the AlMg3 alloy the AE count rate measured at both threshold levels exhibits a local maximum, which is related to the macroscopic yield point and followed by a decrease of the AE parameter. This behaviour is typical for many metals and alloys, especially those in an annealed or recrystallized condition [3, 9, 10]. On the contrary, such a peak is not found for the AlCuMgLi alloy. The AE activity is much higher in the AlMg3 alloy than in the AlCuMgLi one.

4. Discussion

The profile of the AlMg3 alloy does not show any significant inhomogeneity and anisotropy of mechanical properties. Consequently, the deformation texture has no significant influence on the deformation behaviour of the profile. This behaviour is consistent with the occurrence of the PLC effect, because by the inhomogeneous fashion of plastic deformation (propagation of deformation bands), the slip propagation is not substantially affected by the presence of grain boundaries [11–13].

The anisotropy of mechanical properties is only found in the age-hardenable AlCuMgLi alloy. The extrusion ratio (ER) is very important parameter, which influences the mechanical properties of a final profile. Dumb-bell shaped profile has varying cross sections in the positions 1, 2 and 3 and therefore the ER is also variable in a dependence on the position inside the profile; the higher is the ER the lower is the grain size. The microstructure from position 1 with largest grain size should contain the lowest density of dislocations. Thus, in the position 1, there is a tendency to more intense strain hardening than in the positions 2 or 3, which results in the highest TYS and UTS values. The small mechanical anisotropy between ED (position 3) and TD (position 4) is observed and can be ascribed to the orientation of the deformation texture.

In this alloy, the PLC effect does not occur and the precipitates are assumed to control the deformation behaviour. Due to the artificial ageing of the alloy, the coherent δ'-(Al_3Li) and T_1-(Al_2CuLi) phases (heterogeneously distributed in the grains) and the semicoherent S'-phase (Al_2CuMg) are precipitated [14]. The main age hardening phase is the coherent δ'-phase.

The local maximum of the AE count rate related to the macroscopic yield point of AlMg3 alloy is due to a massive dislocation multiplication, what is an excellent source of AE [15]. The following decrease in the AE count rates can be ascribed to a consequence of strain hardening due to dislocation-dislocation interactions, which leads to increasing forest dislocation density. With increasing density of forest dislocations, the free path of moving dislocations decreases and therefore is responsible for the reduction of the AE activity. This scenario does apply also for the PLC effect [13]. The breakaway of dislocations from solute atoms atmospheres manifested by the serrations on the flow curve is accompanied by burst AE signals superimposed on the master AE count rate *vs.* time curve.

The AE activity in AlCuMgLi alloy is closely associated with the non-recrystallized alloy structure and precipitates. Due to high density of dislocations, a low AE activity from dislocation sources may be anticipated (cf. less AE signals for the sample from the position 1 than for that from the position 3). Furthermore, the low AE activity indicates that the coherent δ'-phase precipitates are rather overcome by dislocation climb and the incoherent or semicoherent precipitates are overcome by Orowan bowing (cf. large AE activity due to shearing of coherent precipitates, observed in [8]). Thus, the occasional AE signals occurring in the final stage of the deformation of the sample from the position 4 might be the indication of cracking of coherent precipitates during the deformation.

5. Conclusions

For the AlCuMgLi alloy, the extrusion process, especially due to the varying cross section of dumb-bell shaped profile, is responsible for the mechanical inhomogeneity and anisotropy with respect to the position inside the extruded profile. For the AlMg3 alloy, the deformation curves exhibit serrated fashion of yielding (the Portevin-Le Chatelier effect) and the deformation texture has no significant influence on the deformation behaviour of the profile. This may be explained by the fact, that during the Portevin-Le Chatelier effect the slip propagates in terms of deformation bands and is not affected by grain boundaries substantially. In the AlCuMgLi alloy, the PLC effect does not occur and the non-recrystallized dislocation microstructure containing unshearable precipitates is assumed to control the deformation behaviour. The acoustic emission activity depends on the dislocation mobility, on the dislocation density and on the precipitation structure. With increasing density of forest dislocations and increasing amount of unshearable precipitates, the free path of moving dislocations decreases and therefore the AE activity is reduced. The occasional burst AE signals occurring in AlCuMgLi alloy can originate from cracking of coherent precipitates, especially during the terminal stage of deformation.

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