FATIGUE INHOMOGENEITY AND ANISOTROPY OF AGE-HARDENABLE Al-ALLOYS EXTRUSIONS

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The inhomogeneity and anisotropy of mechanical properties of age-hardenable Al--alloys extrusions studied by tensile and compression tests are largely described in recent literature. The aim of the present paper is to describe the main features of the anisotropy and inhomogeneity of fatigue lives and to compare them with those observed recently in the same alloys under tensile tests. The paper deals with several age-hardenable alloys from the systems: Al-Li, Al-Cu-Mg, Al-Zn-Mg-Cu and Al-Mg-Si. The high-cycle fatigue of two particular model extruded shapes of large-sized cross-section was investigated. The results of the tests indicate that the fatigue lives of the extrusions prepared from all investigated alloys are remarkably inhomogeneous and anisotropic.

Key words: aluminium alloys, extrusion, inhomogeneity, anisotropy, fatigue properties, mechanical properties, texture, solid solution decomposition

NEHOMOGENITA A ANIZOTROPIE ÚNAVOVÝCH VLASTNOSTÍ VÝLISKŮ Z VYTVRZOVATELNÝCH SLITIN HLINÍKU

Výsledky nehomogenity a anizotropie mechanických vlastností sledované zkouškou tahem a tlakem u výlisků z vytvrzovatelných slitin hliníku jsou podrobně popsány v řadě prací. Cílem tohoto příspěvku je popsat základní rysy nehomogenity a anizotropie únavových vlastností a porovnat je s výsledky nehomogenity a anizotropie mechanických vlastností stanovených zkouškou tahem. Příspěvek se zabývá vytvrzovatelnými slitinami typu Al-Li, Al-Cu-Mg, Al-Zn-Mg-Cu a Al-Mg-Si. Sledována je vysokocyklová únava dvou speciálních modelových profilů většího průřezu. Výsledky měření ukázaly, že únavové životy lisovaných profilů z těchto slitin jsou výrazně nehomogenní a anizotropní.

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1. Introduction

Extrusions of large cross-sections prepared from aluminium age-hardenable alloys exhibit pronounced inhomogeneity and anisotropy of mechanical properties. Recently, these effects were intensively studied [1–7]. It was shown that both the inhomogeneity and anisotropy of mechanical properties are related to the inhomogeneity of material flow during extrusion, i.e. to the shape of extruded cross-section, material substructure (recovered or recrystallized) and degree of solid solution decomposition. The largest differences in mechanical properties are observed usually in profiles of complicated cross-section and after partial recrystallization and in the peak-hardened conditions. Overageing or solutionising reduce the anisotropy and inhomogeneity to values observed usually in non-age-hardenable Al-based alloys [7–11]. It has been shown that both the inhomogeneity and the anisotropy are related to the crystallographic texture of the material created during extruding and subsequent heat treatment. Mechanical properties reach their maximum values in the positions of the cross-sections where a double fibre texture of $\langle 111\rangle + \langle 100\rangle$ type has been formed. On the other hand, minimum values are in the positions exhibiting strong rolling texture [1, 11]. The double fibre textures are usually observed in circular parts of profiles, while the rolling textures appear in flat parts.

The inhomogeneity and anisotropy of fatigue properties were not studied at large extent because fatigue tests are much more expensive and time consuming as compared to tensile tests. Also the difficulties connected with material extracting and preparation of specimens of requested shapes from profiles of complicated cross--section limited the number of performed fatigue tests. However, the variation of mechanical properties along the profile cross-section may significantly influence the local toughness of the material and the crack propagation rate. Thus, performing tests at different positions across the cross-section of an extrusion may result in an invalid interpretation of the experimental observations.

The present paper deals with high-cycle fatigue properties of model profiles prepared from several aluminium alloys. Conventional tensile tests described in [8–10] preceded the present study. The aim of the paper is to identify and describe the anisotropy and inhomogeneity of extrusion fatigue properties and to compare their main features (presence, type) with those observed in tensile properties.

2. Experimental details

Two model profiles (see Fig. 1) enabling a systematic study of the inhomogeneity and anisotropy of mechanical properties were designed. The cross-sections of both profiles contain flat and round parts. Such a shape enables to simulate the extreme types of crystallographic textures formed during extruding of Al alloys and consequently the extreme values of mechanical properties. The profile 1 with round parts at both ends of the cross-section is used for the evaluation of

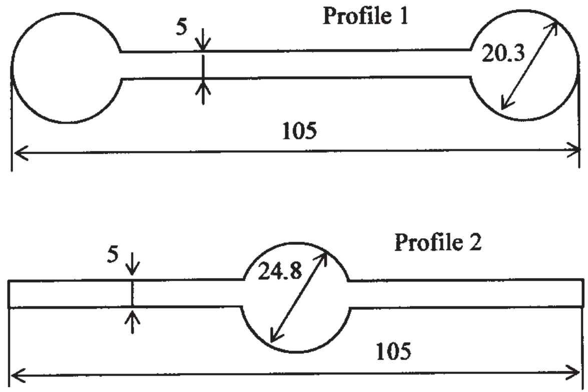


Fig. 1. Model profiles 1 and 2.

T a b l e 1. Chemical composition of alloys [wt.%]

Alloy	Type	Cu	Mg	Mn	Li	Si	Fe	Zr
Al-Cu-Li	1450 (2090)	2.59	0.04	–	2.05	0.02	0.09	0.11
Al-Li-Cu-Mg	1441 (8090)	1.71	0.99		1.81	0.03	0.08	0.06
Al-Cu-Mg	2124	4.02	1.36	0.71	–	0.19	0.21	–
Al-Zn-Mg-Cu	7075	1.80	2.51	0.005	–	0.07	0.16	–
Al-Mg-Si	6082	0.05	0.98	0.78	–	1.01	0.28	–

the inhomogeneity of longitudinal tensile properties. The profile 2 with one round part in the centre of the cross-section enables the study of tensile anisotropy. High-strength Li-containing alloys (Russian alloys with designations 1441 and 1450) and AlCuMg (AA2124), AlZnMgCu (AA7075) and AlMgSi (AA6082) alloys were used in the study. The chemical compositions of the alloys are given in Table 1. Both model extrusions were prepared from billets 187 mm in diameter with an extrusion ratio $\lambda = 28$. The profiles were solution-treated and quenched into cold water, prestrained to 2–3 % and aged at various temperatures. The conditions of the thermo-mechanical treatments used are summarized in Table 2.

All fatigue tests were performed at a high-frequency testing machine Testronic 8601 at frequency of 80 Hz and one stress level $S_{\max} = 330$ MPa. Since the alloy 1450 exhibited a very long fatigue life at $S_{\max} = 330$ MPa (more than 10^7 cycles), a stress level of 360 MPa was used for this alloy. The asymmetry of the loading cycle was $R = 0$, the stress-concentration factor of the specimens was $K_{\mathrm{t}} = 1.1$. For the inhomogeneity studies, flat specimens with longitudinal axes parallel to the

Table 2. Thermo-mechanical treatment of all studied alloys

Alloy	Solution treatment [°C/h]	Natural ageing [days]	Artificial ageing [°C/h]	Temper
1450	530/1	> 14	165/36	T851
1441	530/1	> 14	165/36	T851
2124	495/1	> 14	–	T351
	495/1	> 3	190/12	T851
7075	475/1	> 3	120/24	T651
6082	530/1	> 3	160/5	T651

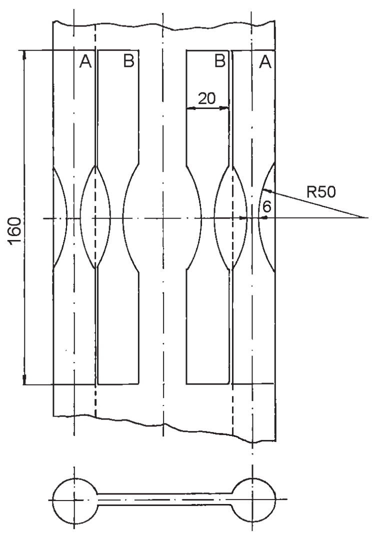


Fig. 2. Spots **A** and **B** of fatigue test specimen positions for profile 1.

extrusion direction were extracted from the round part of the profile (spot **A**) and flat parts (spots **B**). The positions in profile 1, where specimens were taken, are schematically indicated in Fig. 2. Figure 2 also shows the shape of the experimental specimens. Specimens for the evaluation of anisotropy were cut at angles of 0°, 45° and 90° with respect to the extrusion direction having their active length in the spot **A** of the round part of the profile. Not less than 6 specimens from each alloy were tested at each stress level. The parameter $N_{\mathrm{p}=50}$, equal to the number of cycles to fracture occurring with probability of $P = 50$ % was chosen for characterization of the fatigue behaviour.

3. Experimental results

3.1 Inhomogeneity of fatigue lives

The inhomogeneity of fatigue lives was monitored in model profiles of type 1 of the alloys 2124–T351, 1441–T851 and 1450–T851 and profile 2 of the alloys 2124–T851, 7075–T651 and 6082–T651. The mean values of $N_{\mathrm{P}=50}$ obtained for samples taken in spots **A** and **B** are summarized in Table 3 and Fig. 3 and Fig. 4. In all alloys under investigation, the fatigue lives in spots **A** were always higher than in spots **B**. The largest differences between spots **A** and **B** were observed in alloy 1450–T851, the smallest ones in alloy 1441–T851.

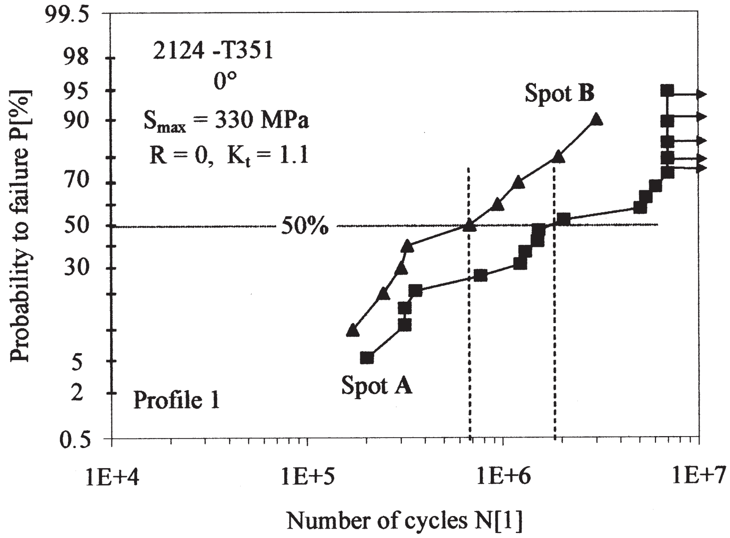


Fig. 3. Fatigue life distribution curves at **A** and **B** spots, profile 1, 1450–T851 alloy.

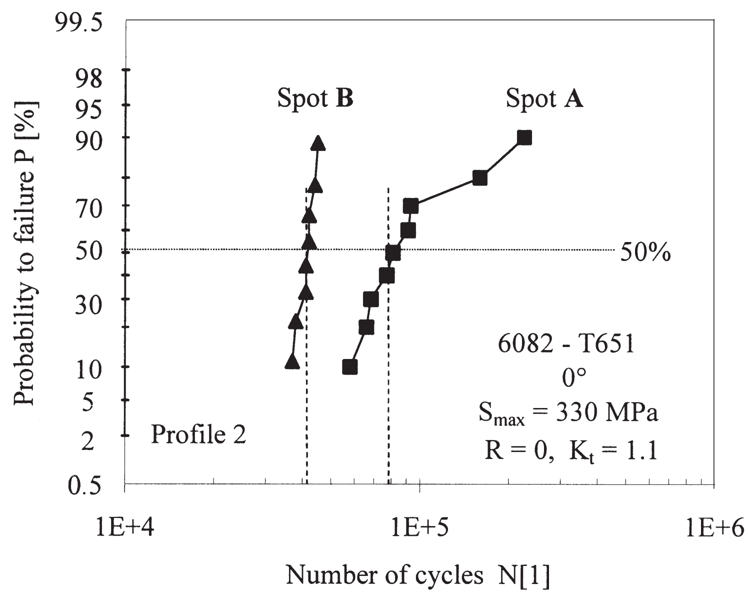


Fig. 4. Fatigue life distribution curves at **A** and **B** spots, profile 2, 6082–T651 alloy.

Table 3. Number of cycles to fracture $N_{P=50} \times 10^{-4}$ in all investigated alloys

Profile	1			2		
Alloy	2124-T351	1441-T851	1450-T851	2124-T851	7075-T651	6082-T651
Spot **A**	180	31	150	8.7	38	8.1
Spot **B**	68	26	23	6.5	13	4.2

3.2 Anisotropy of fatigue lives

The anisotropy of fatigue lives was investigated in alloys 2124–T851, 7075–T651 and 6082–T651 using specimens cut from model profiles of type 2 extracted from spots **A**. The results are summarized in Table 4 and for selected alloys also in Fig. 5 and Fig. 6. All alloys exhibit significant differences in fatigue lives of the different specimen orientations. The only exception is the alloy 6082–T651, in which nearly no difference between the specimens with orientation of 90° and 45° was found. Specimens with orientation 90° exhibit the shortest lives, the longest ones are observed for specimens with an active part parallel to the extruding direction. The most pronounced anisotropy (i.e. the largest difference between directions 90° and 0°) was observed in alloy 7075–T651. In this case, the values

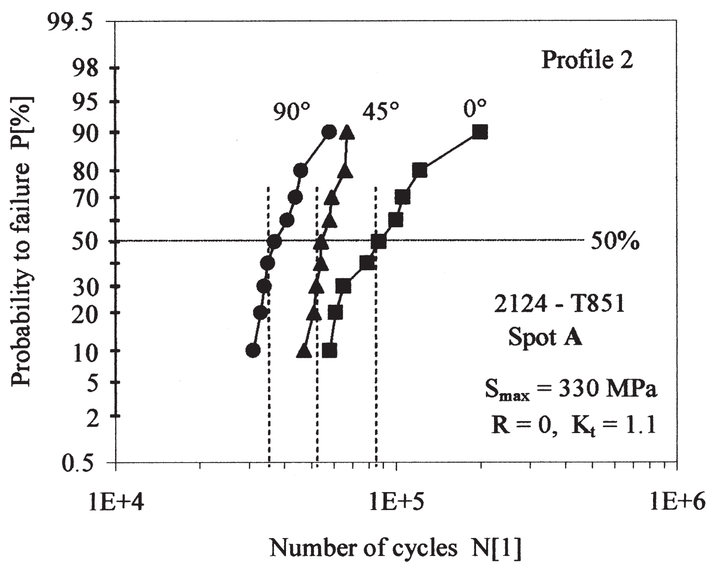


Fig. 5. Fatigue life distribution curves for different orientation at **A** spot, profile 2, 2124–T851 alloy.

Table 4. Number of cycles to fracture $N_{P=50} \times 10^{-4}$ for two different orientations in the spot **A** of the cross-section, profile 2

Orientation/Alloy	2124-T851	7075-T651	6082-T651
0°	8.7	38	8.1
45°	5.4	7.7	2.2
90°	3.7	3.4	2.2

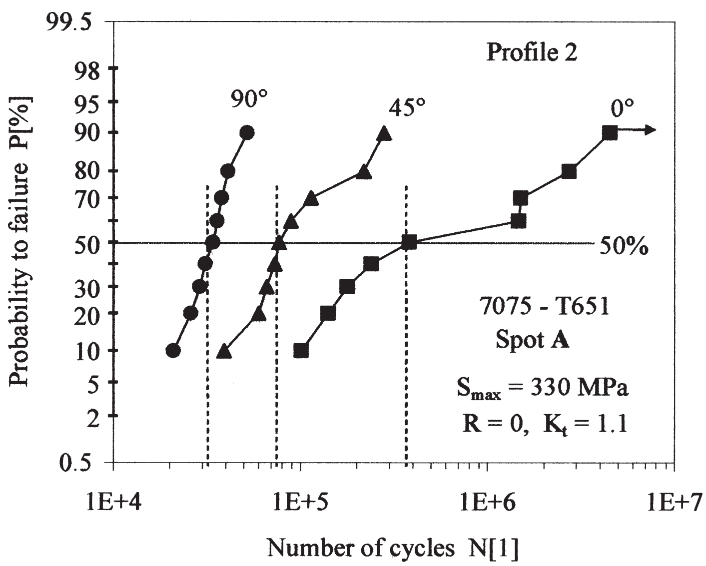


Fig. 6. Fatigue life distribution curves for different orientation at **A** spot, profile 2, 7075–T651 alloy.

of $N_{P=50}$ differ by more than one order of magnitude and reached 3.4×10^{-4} and 3.8×10^{-5} cycles for directions 90° and 0°, respectively.

4. Discussion

The above reported results show that the main features of the anisotropy and inhomogeneity of fatigue lives do not depend on the type of the alloy. The tensile properties of the alloys under investigation exhibit similar anisotropy and inhomogeneity. As an example, a set of strength curves of alloy 2124–T351 is given in Fig. 7. The other alloys have similar tensile anisotropy and inhomogeneity but the measured families of curves are shifted as a result of the different effect of strengthening particles.

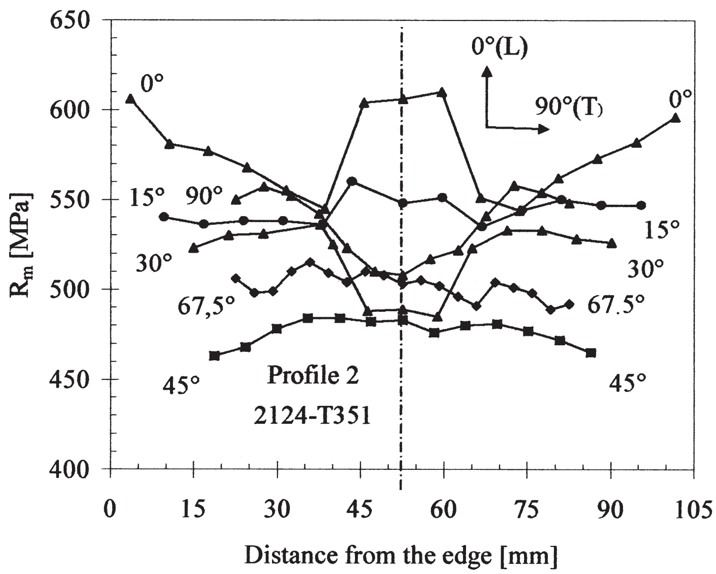


Fig. 7. Cross-section heterogeneity and anisotropy of the ultimate strength of 2124–T351 alloy, profile 2.

Nevertheless, a certain difference in the anisotropy of tensile strength and fatigue lives was observed. Since the fatigue anisotropy tests were performed only for specimens from spot **A** of the profile 2, we can compare only these results. The largest values both of strength and fatigue were recorded in specimens with 0° orientation, whereas the smallest values of strength were observed in specimens with 45° orientation but the minimal values of fatigue lives were found in specimens with 90° orientation.

The inhomogeneity and anisotropy of strength and fatigue lives of high strength age-hardened Al alloys are related to their structure and substructure. An inhomogeneous structure is at first generated by the inhomogeneous flow of the material during extruding and as a result, all these materials exhibit strong texture. The final structure and texture form during subsequent thermo-mechanical treatment. Examples of the partially recrystallized fiber structure in the spots **A** and **B** of alloy 2124 (profile 1) are given in Fig. 8 and the corresponding texture pole figures are in Fig. 9.

The decomposition of the solid solution occurs in an aligned structure, which varies with the position in the profile. It can be assumed that the coupling between the position dependent texture and the precipitation of strengthening particles evokes the anisotropy and the inhomogeneity of the mechanical properties. How-

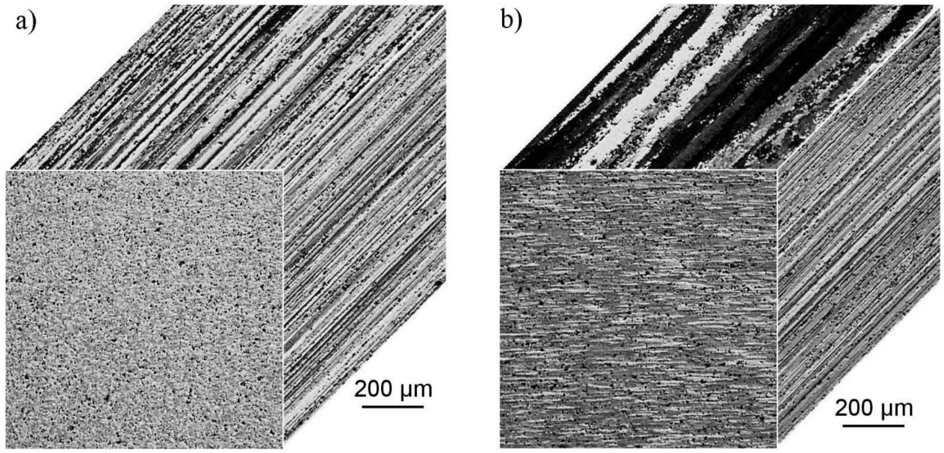
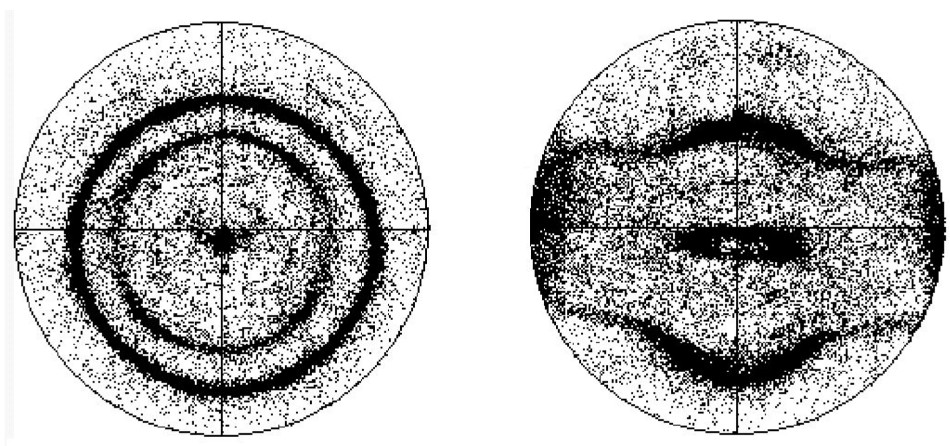


Fig. 8. Structure in spots A (a) and B (b) of profile 1, alloy 2124–T351.



a) b)

Fig. 9. EBSD {111} pole figures in the circular part (a) – spot **A** and in the flat part (b) – spot **B**, of the profile 1, samples normal parallel to extrusion direction, 2124–T351 alloy.

ever, as our observations indicated, the features of inhomogeneity and anisotropy do not depend on alloy composition. Since the spectrum of the strengthening precipitates covers various types and shapes of particles with different crystallographic

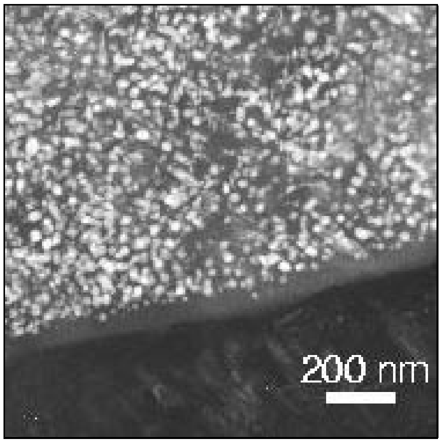


Fig. 10. Precipitation free zones in an 1450–T851 alloy.

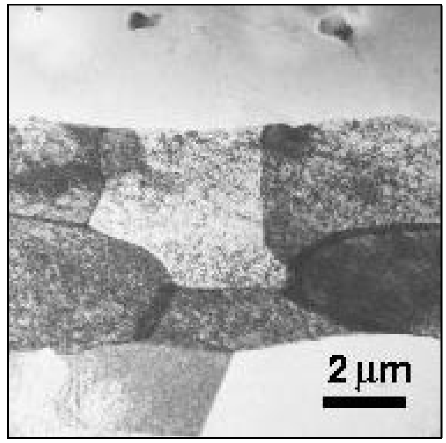


Fig. 11. Cross-section of flat subgrains in the flat part (spot **B**) of the 1450–T851 alloy.

orientations, the sensitivity of the anisotropy and inhomogeneity to the type of precipitate is rather implausible. From this point of view, also the principal role of the texture is doubtful. The presence of distinct anisotropy and inhomogeneity, hence, may be explained by other possible causes. One of them is worthy of mentioning: the presence of less strengthened precipitation free zones (PFZs) in different parts of profiles [9]. A series of transmission electron microscopy studies showed that PFZs of size in the range of 100–300 nm are generally observed in all precipitation strengthened Al alloys in the peak-aged conditions and are caused by solutes segregation on both, subgrain and grain boundaries. An example of the δ' (Al_3Li metastable phase) PFZs near the subgrain boundary in alloy 1450–T851 is displayed in Fig. 10. The shape and size of subgrains are different in flat (flat subgrains of about 2 μm $\times$ 5 μm $\times$ 5 μm) and round (subgrains of cube shape with the linear size of 5 μm) parts of profiles

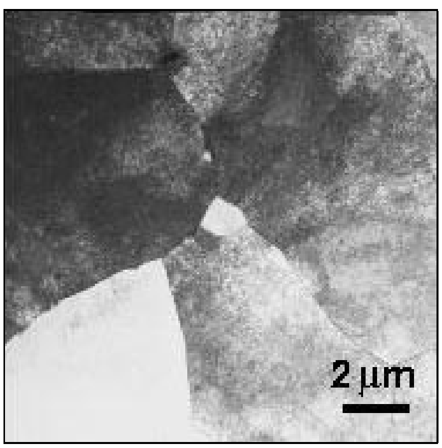


Fig. 12. Cross-section of subgrains in the round part (spot **A**) of the 1450–T851 alloy.

(see Fig. 11 and Fig. 12). Hence, also the volume fractions of PFZs zones differs in specimens extracted from spots **A** and **B**, contributing to the inhomogeneity of the observed mechanical and fatigue properties. On the other hand, the asymmetric shape of subgrains and asymmetric distribution of PFZs with respect to loading axes have a pronounced impact on the anisotropy. The significant impact of softer PFZs on mechanical and fatigue properties of high strengths Al-based alloys is in agreement with conclusions received from anisotropy observations performed on rolled thick plates of 7475 and 7075 alloys [12].

5. Conclusions

The results of the investigation of the inhomogeneity and anisotropy of fatigue properties of age-hardenable Al alloys can be summarised as follows:

– Strong inhomogeneity and anisotropy of fatigue properties was observed in high-strength Al alloys extrusions.

– The inhomogeneity and anisotropy of fatigue properties is related to the inhomogeneity and anisotropy of tensile strength.

– The anisotropy of fatigue lives differs from the anisotropy of tensile strength by the orientation for which the minimum values are measured. The smallest fatigue lives are recorded in the direction perpendicular to the direction of extruding while the lowest strength is measured for 45° orientations.

– The main features of observed inhomogeneity and anisotropy do not depend on alloy composition.

– The presence of precipitation-free zones and heterogeneous substructure are supposed to be the main cause of the inhomogeneity and anisotropy of mechanical properties.

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