HETEROGENEITY AND ANISOTROPY OF MECHANICAL AND FATIGUE PROPERTIES OF HIGH-STRENGTH ALUMINIUM EXTRUSIONS

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Abstract

The properties of hot extruded aluminium shapes exhibit pronounced heterogeneity across the cross-section and are very anisotropic. The paper presents the results of an investigation aimed at modelling plastic deformation heterogeneity resulting from the process of extrusion. Two special shapes have been prepared so as to obtain the two limit types of extrusion structure found in real extrusions. The level and variation of static mechanical and fatigue properties has been evaluated. The study was focused on high-strength aluminium alloys of AA 2124, AA 2090 and AA 8090 type.

Keywords: *Aluminium alloy extrusions, mechanical properties, fatigue properties, heterogeneity and anisotropy of properties.*

1. Introduction

High strength aluminium alloy extrusions exhibit heterogeneous and anisotropic mechanical properties. Mechanical property values depend on the cross-section position from which test samples are cut and on their orientation with regard to the extrusion direction. The property heterogeneity and anisotropy are caused by the heterogeneity of material flow during the extrusion process. The grain structure and texture are markedly heterogeneous and act in concordance with precipitation hardening which intensifies mechanical property heterogeneity and anisotropy. Several works [1,2,3] have demonstrated that mechanical property values are determined by the texture formed at the particular cross-section positions. The mechanical properties are the highest at the positions where a double fibre texture <111> and <100> forms or where the fraction of this texture is the highest. The lowest mechanical properties are measured at these positions where texture of rolling type forms.

Our previous investigations [3,4] were focused on property heterogeneity and anisotropy assessed mainly by conventional tensile tests. The present paper describes the tests aimed at assessing the heterogeneity and anisotropy of some other properties such as fatigue life and fatigue crack growth rate. Using specially designed extrusion shapes the heterogeneity and anisotropy of three high strength aluminium alloys were studied.

2. Experimental

Three alloys were selected for testing: the AA 2124 alloy and two Al-Li alloys - the Russian 1450 (AA 2090 type) and 1441 (8090 type) alloys. The alloy composition is in Table 1. Two extrusion profile shapes have been used - Shape I a Shape II which dimensions are shown on Fig. 1. The profile shapes were designed in such a way that in each of them both positions with extreme mechanical property levels (the highest and the lowest) were present. The highest mechanical properties were measured in the circular parts exhibiting double fibre texture <111> and <100>, the lowest - in the flat parts with texture of rolling type.

The profiles were directly extruded with extrusion ratio of 28 from billets 187 mm in diameter. The AA 2124 alloy was tested in the T351 temper (solution treated at 495°C, 2% straightened and naturally aged). The alloys 1441 and 1450 were tested in the T851 temper, obtained by solution annealing at 530°C, 2.5% straightening, natural ageing longer than 14 days and artificial ageing at 165°C for 36 hours. Extrusion and heat treatment parameters were set so as the solution annealing do not evoke full recrystallization. For both profile types the tensile properties in the longitudinal (L) direction were measured. Test specimens were cut from 16 positions on the cross-section of Shape I and from 15 positions of Shape II (Fig. 1). The tensile properties in the long transverse direction (T) were assessed but for Shape II. Special short cylindrical test specimens 4 mm in diameter and with gauge length of 5 mm were used. This allowed to assess the tensile strength in T-direction on a profile width as large as 70 mm.

Table 1. Chemical composition of the alloys used (in wt.%)

Alloy	**Designation**	**Cu**	**Mg**	**Mn**	**Li**	**Si**	**Fe**	**Zr**
AlCuMg	AA 2124	4.02	1.36	0.71	-	0.19	0.21	-
AlCuLi	1450	2.59	0.04	-	2.05	0.02	0.09	0.11
AlLiCuMg	1441	1.71	0.99	-	1.81	0.03	0.08	0.06

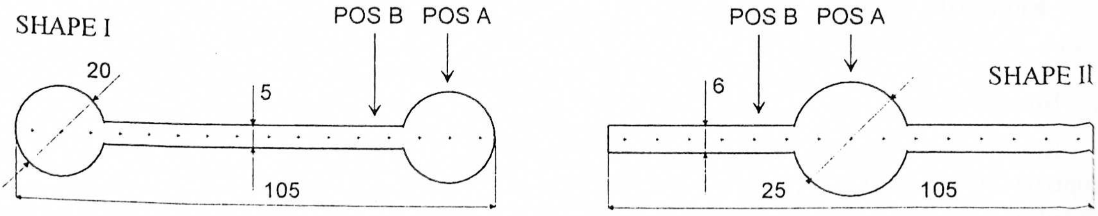

Fig. 1. Shape and size of special designed extrusions.

Specimens for fatigue tests in L-direction were cut always from the position where the highest (pos. A) and the lowest (pos. B) tensile properties have been measured (see Fig. 1). Flat fatigue test specimens with stress concentration factor $K_t = 1.1$ were prepared from Shape I. All fatigue tests were performed at stress ratio $R = 0$ with a frequency of 80 Hz. Only one stress level, $\sigma_{max} = 330$ MPa (alloys AA 2124 and 1441) or $\sigma_{max} = 360$ MPa (alloy 1450), was used. At least 6 specimens from each alloy were tested at these stress levels.

CT-test specimens of dimensions $W = 50$ mm, $B = 4.5$ mm were used for fatigue crack growth rate (FCGR) measurements. The specimens were cut from Shape II in such a way that the crack rate was measured at the positions A and B in two directions: L-T and T-L. Crack rate was measured on a length of 8 mm, using bondable Krak-gages and the testing equipment Fractomat. The specimens were cycled on a Testronic resonance machine under two stress ratios: $R = 0.2$ and 0.5, resp with increasing ΔK and a frequency of about 70 Hz. The linear part of the FCGR curve was of interest.

3. Results

3.1 Mechanical properties

The tensile property values in L-direction of the specially designed profiles confirm the expected effect of shape on property heterogeneity across the cross-section (Fig. 2). All tested alloys exhibit the highest longitudinal strength R_m and proof stress $R_{p0.2}$ in the centre of the circular part of the profile and the lowest property values in the flat part, respectively. In Shape II maximum R_m and

$R_{p0.2}$ values are observed also at the ends of the flat profile part. The property changes across the cross-section are similar for all alloys. The largest differences between maximum and minimum tensile property values is observed in 1441 Shape I where $R_{p0.2}$ values differ by 160 MPa, the smallest difference is found in AA 2124 profiles where it amounts to 80 MPa.

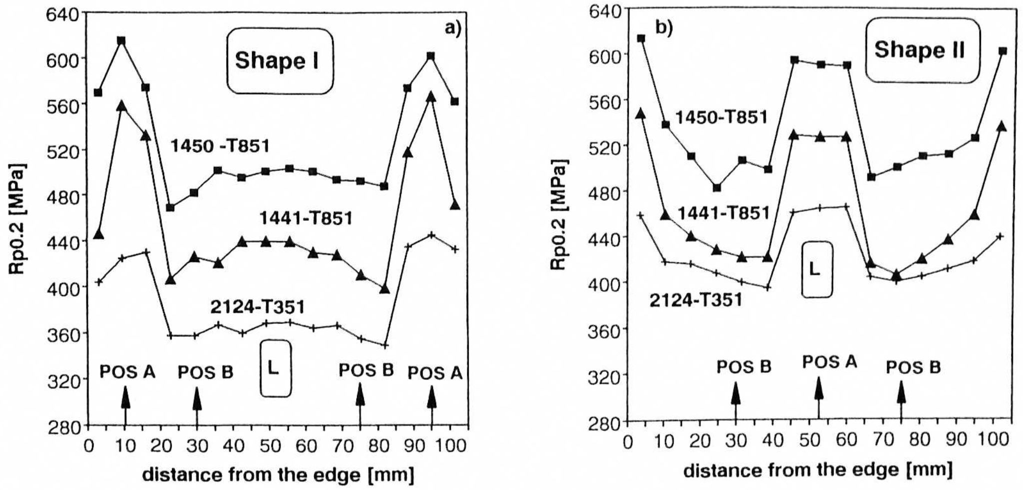

Fig. 2. Dependence of $R_{p0.2}$(L) on the cross-section position of Shape I (a) and Shape II (b).

Strength values in L- and T-directions of Al-Li alloys for Shape II are compared on Fig. 3. The position dependencies of strength of the alloys are similar again. A pronounced minimum of R_m(T) is always observed in the centre of the circular profile part. The maximum values R_m(L) are always found in the flat part near the transition to the circular part. The position of R_m(T) extreme values coincides with the position of R_m(L) extremes - at the position where the lowest (highest) longitudinal strength is measured the highest (lowest) transverse strength is measured.

3.2 Fatigue properties

The results of the test on Shape I profiles indicate that the fatigue life changes in dependence on the position on the cross-section in the same manner as tensile properties. The fatigue lives at position A are for all alloys investigated significantly longer than at position B. Figure 4 shows the distribution curves (plotted in log-normal probability scale) of AA 2124 alloy. The largest difference between positions A and B is observed for 1450 alloy, the smallest for 1441 alloy. The position A exhibits the highest R_m(L) values and also higher fatigue lives. It is evident that there is a correlation between fatigue lives and R_m, $R_{p0.2}$ values.

3.3 Fatigue Crack Growth Rate

The measurement of FCGR on CT-specimens cut at different positions of the cross-section was strongly influenced by the anisotropy and heterogeneity of profile structure formed during extrusion. In many cases it was not possible to evaluate the crack propagation rate due to the fact that either during or after precracking the crack deviated markedly from the direction perpendicular to the loading force. For this reason crack propagation rate in AA 2124 and 1450 alloys in the L-T direction for both positions A and B was not evaluated. Similarly, the FCGR measurement in T-L and L-T directions at pos. A of 1441 alloy gave not acceptable results. A systematic crack deviation of about 30° from the expected propagation direction was observed. On Fig. 5 the crack deviation in 1441 alloy is shown.

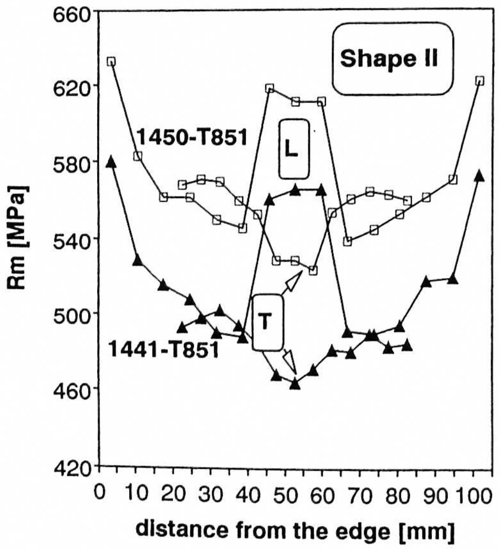

Fig. 3. Dependence of $R_m(T)$ and $R_m(L)$ on cross-section position - Shape II, 1441 and 1450 alloys.

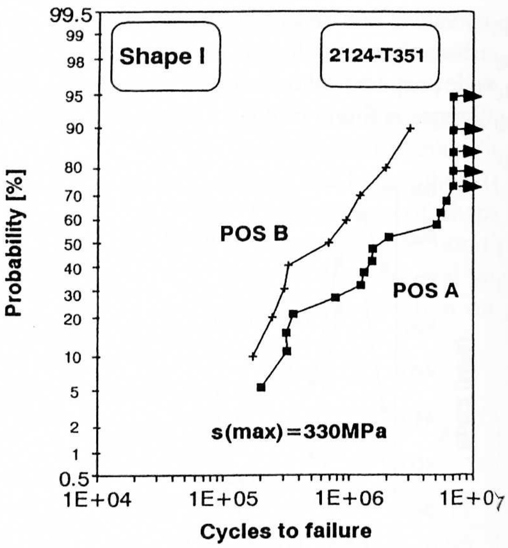

Fig. 4. Fatigue life distribution curves in log-normal probability scale, R = 0, K_t = 1.1, A and B positions, AA 2124 alloy.

When typical crack propagation occurs in the expected direction the difference between the crack rate at position A and position B is significant but for 1450 alloy Shape II for R = 0.5 (Fig. 6). For AA 2124 and 1441 alloys either the difference between positions A and B is not significant or it is not possible to evaluate it due to the reasons mentioned above.

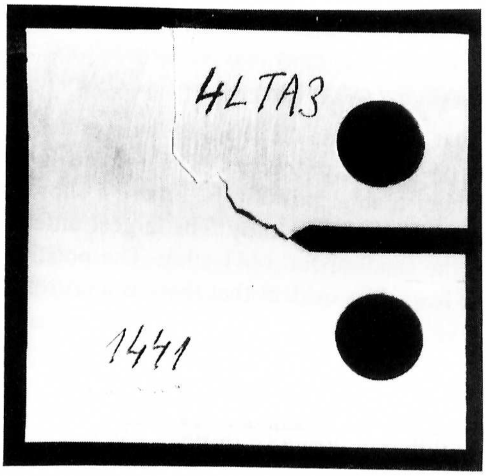

Fig. 5. CT-specimen with typical crack deviation. 1441 alloy, position A.

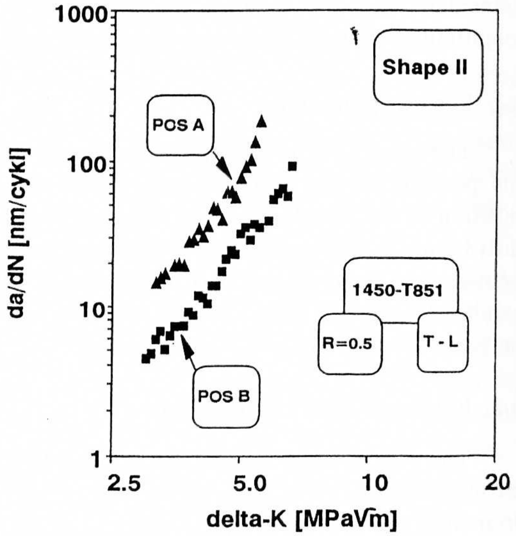

Fig. 6. Difference of crack propagation rate between positions A and B - 1450 alloy.

4. Discussion

The results of proof stress, strength and fatigue life heterogeneity and anisotropy are summarised in Table 2. The results indicate that heterogeneity and anisotropy are systematic. The correlation of longitudinal and transverse properties is very close. The highest longitudinal values correspond to the lowest transverse and conversely. It was found that at some positions of the profile of more complicated shape $R_m(L) - R_m(T)$ has a value of about +100 MPa and at the positions close to them this difference changes of polarity to a value of -30 MPa. From this implies that in profiles of more complicated shape one can expect marked gradients of mechanical and fatigue properties and high property anisotropy. It is worthy of mentioning that in complicated shape profiles there are positions with highly aligned structure where the longitudinal and transverse R_m and $R_{p0.2}$ exhibit similar values or even the transverse R_m and $R_{p0.2}$ values may be higher than the longitudinal ones.

Table 2 Summary of mechanical and fatigue property heterogeneity and anisotropy.

		Tensile test R_m [MPa]				Fatigue test N_0 (P = 50%) [1]
		Shape I	Shape II			Shape I
Alloy	Position	L	L	T	L - T	L
AA 2124 T351	A	590	590	480	+ 110	$2.0\cdot 10^6$
	B	480	520	530	- 10	$0.7\cdot 10^6$
	A - B	+ 110	+ 70	- 50		A/B = 2.9
1441 T851	A	600	565	465	+ 100	$0.6\cdot 10^6$
	B	475	485	500	- 15	$0.25\cdot 10^6$
	A - B	+ 125	+ 80	- 35		A/B = 2.3
1450 T851	A	630	620	525	+ 95	$1.2\cdot 10^6$
	B	520	540	570	- 30	$0.2\cdot 10^6$
	A - B	+ 110	+ 80	-45		A/B = 6.0

The nature of $R_m(T)$ curves across the cross-section of Shape II indicates that, if the curve is extrapolated up to the profile edge, at this position minimum values can be expected, similarly as in the centre of the circular part. It means that near the edges of Shape II a crystallographic texture identical with that in the central circular part forms and the longitudinal properties exhibit a maximum whereas the transverse properties - a minimum. The gradual increase of $R_m(L)$ (decrease of $R_m(T)$) from the circular part to the edge of the profile is probably due to the change of the fraction of different texture components.

The evaluation of FCGR heterogeneity and anisotropy was perturbed by the frequent occurrence of crack departure from the plane of symmetry of the CT-specimen. Nevertheless, the experiments proved that fatigue crack growth rate in extrusions is significantly heterogeneous and anisotropic. The FCGR heterogeneity (difference between positions A and B) is significant but for 1450 alloy. For the AA 2124 and 1441 alloys no difference was observed or the difference was not significant, considering the scatter of the results. A difference of the sensitiveness to loading parameters between positions A and B was observed for AA 2124 and 1450 profiles. For both alloys for the position A the FCGR curves measured at R = 0.2 are shifted towards lower da/dN values in comparison with FCGR curves at R = 0.5 whereas for the position B both corresponding FCGR curves are practically the same (Fig. 7a and 7b, resp.). The pronounced FCGR anisotropy, even though it was not possible to quantify it, was indicated by the significant difference of the loading during precracking between T-L and L-T orientations of test specimens. This difference is the most pronounced for 1441 alloy.

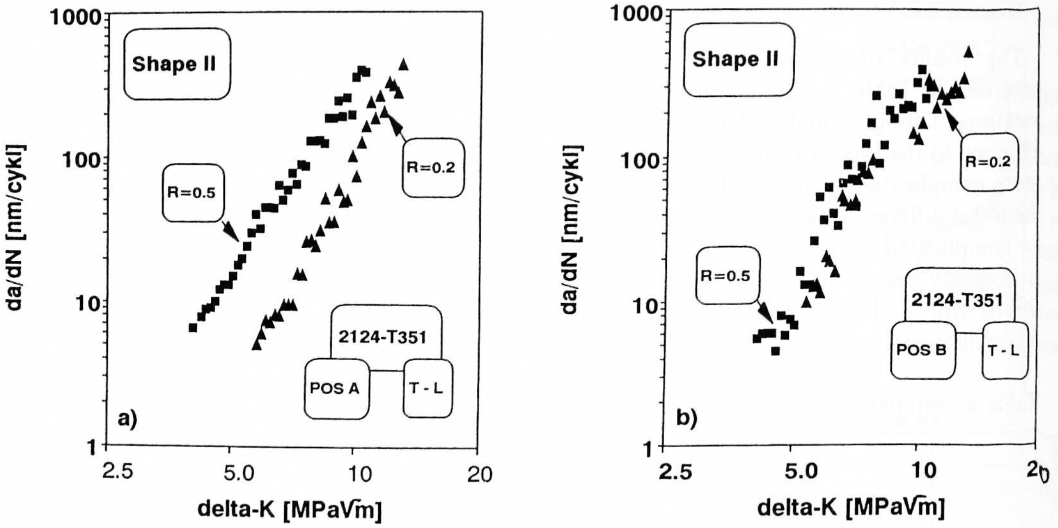

Fig. 7. Influence of stress ratio and specimen position on FCGR data for AA 2124 alloy.

5. Conclusions

The results of the heterogeneity and anisotropy study can be summarised as follows:

1. The alloy structure formed as a result of the heterogeneous material flow during the extrusion of profiles determines the pronounced heterogeneity and anisotropy of their properties.
2. There are characteristic positions on the cross-section where minimum or maximum values of the mechanical properties in the longitudinal and the transverse direction are measured.
3. The fatigue properties also depend on the cross-section position and they are correlated with tensile properties. Positions exhibiting higher tensile properties exhibit also longer fatigue lives.
4. The fatigue crack propagation rate is also heterogeneous and anisotropic. Due to the heterogeneous and anisotropic structure of extrusions for some orientations of the CT-specimens a significant crack deviation from specimen plane of symmetry is observed.
5. Tensile properties and fatigue behaviour of the investigated alloys are very similar but some differences are observed.

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References

[1] G.Tempus, W.Calles and G.Schorf: Mat. Sci. and Techn. 7 (1991), 937.

[2] I.G.Palmer, R.E.Lewis and D.D.Crooks: Aluminum Lithium Alloys, TMS-AIME, Warrendale, PA (1981), 241.

[3] V.Očenášek, K.Šperlink, J.N.Fridlyander and L.N.Leshiner: Proc. of ICAA-5, Grenoble, France (1996), 1349.

[4] V.Očenášek, V.Sedláček, M. Slámová and K.Šperlink: Proc. of Int. Conf. [TMP]^2, Stockholm, Sweden (1996), 277.