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Plastic anisotropy of ultrafine grained Al alloy AA6016 produced by accumulative roll bonding

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Abstract. In order to quantify the plastic anisotropy of the ultrafine grained aluminium alloy AA6016 produced by accumulative roll-bonding (ARB) the Lankford parameter is measured by tensile testing as a function of the number of ARB cycles. The experimental results are compared with those from texture-based Taylor simulations. Increasing differences between experiment and theory at higher number of ARB cycles may be attributed to highly oriented microstructural features.

Introduction

In general, the mechanical properties of polycrystalline materials are anisotropic. The level of the plastic anisotropy depends on the type and intensity of texture. In addition, microstructural features like dislocation cell, subgrain and grain structures elongated in the rolling direction may contribute to the plastic anisotropy. The Lankford parameter is an important quantity to characterize the plastic anisotropy of metal sheets. In the case of deep drawing, for example, the Lankford parameter can help to estimate the occurrence of undesirable effects like thinning and earing.

It is the aim of the present work to measure the Lankford parameter of the ultrafine grained aluminium alloy AA6016 produced by accumulative roll-bonding by tensile testing and compare it with texture-based simulations published recently [1].

Experimental details

Sheets with different number of ARB cycles were produced according to the procedure described in detail in [1, 2]. The chemical composition of the aluminum alloy used is listed in Table 1.

Table 1: Chemical composition of aluminium alloy AA6016.

	Si	Cu	Fe	Mn	Mg	Cr	Zn	Ti	other	Al
[wt.%]	1.0-1.5	0.2	0.5	0.2	0.25-0.5	0.1	0.2	0.15	0.15	balance

The microstructure of the starting material and the sheets after 2, 4, 6 and 8 ARB cycles was investigated by orientation imaging microscopy. The global textures were measured by neutron diffraction on a stack of eight sheets with a size of 10 mm × 10 mm. Because of their high penetration depth neutrons allow bulk texture measurements. The orientation distribution function (ODF) was calculated from the measured pole figures (200, 220, 111) using the harmonic method with a maximum series expansion coefficient of 22 [3, 4]. The Euler angles used are in the Bunge notation [5].

The tension tests were performed with a Zwick/Roell Z250 deformation machine at a constant strain rate of 9.2×10^{-4} s^{-1} in air at room temperature. The optical system Aramis (producer GOM mbH, Germany) was used to register the strain within the sheets and measure the elongation (tensile strain ε_x) and width contraction (transverse strain ε_y) simultaneously. Therefore, the sheet plane of the sample was covered statistically with a dot pattern which during the deformation is recorded by two cameras. The software Aramis splits the measuring surface into predetermined sections that can be identified by their characteristic dot pattern. The relative change of the position of the segments during the deformation is documented for every snap shot yielding $d\varepsilon_y$ and $d\varepsilon_x$ and hence the Lankford parameter r_α, which assuming volume constancy is given by

$$r_\alpha = \frac{d\varepsilon_{width}}{d\varepsilon_{thickness}} = \frac{d\varepsilon_y}{d\varepsilon_z} = -\frac{d\varepsilon_y}{d\varepsilon_x + d\varepsilon_y} = \frac{q}{1-q}, \tag{1}$$

with $q = -d\varepsilon_y/d\varepsilon_x$ being the contraction ratio.

The Lankford parameter depends on the direction of the sample within the sheet plane with α defining the angle between tensile axis and rolling direction. As usual, the Lankford parameter in this work is measured at three angles $\alpha = (0°, 45°, 90°)$, in the following referred to as r_{RD}, $r_{45°}$ and r_{TD} (RD = rolling direction, TD = transverse direction).

From this orientation dependent Lankford parameter the normal anisotropy $<r>$ and the planar anisotropy Δr can be obtained characterizing the anisotropy of the whole sheet:

$$< r > = \frac{1}{4}(r_{RD} + 2r_{45°} + r_{TD}) \tag{2}$$

$$\Delta r = \frac{1}{2}(r_{RD} - 2r_{45°} + r_{TD}) \tag{3}$$

With the help of these two parameters the mechanical anisotropy of the sheets can be quantified.

The Lankford parameter after a critical axial strain becomes constant. The ARB material used was ductile enough to reach the plateau value and this is taken for further discussion. In order to minimize the influence of local inhomogeneities at least three samples taken from the same sheet were measured for each direction.

Based on the global texture of the sheets in [1] the Lankford parameters for different ARB cycle numbers are simulated using the full and relaxed constraints (FC and RC) Taylor theory of crystal plasticity [6 - 8]. To do this, the Taylor factor M of the polycrystalline aggregate was calculated as a function of strain mode, i.e. contraction ratio q [9 - 11]. As in a free tensile experiment q is not determined by the experimental conditions, it is assumed that the true q value corresponds to a minimum of the required deformation work, that is to the minimum of the Taylor factor [12 - 14]. Taking q_{min} at minimum M the calculated Lankford parameter is given by

$$r_\alpha = \frac{q_{\alpha,\min}}{1 - q_{\alpha,\min}}. \tag{4}$$

In the following experimental and calculated Lankford parameters will be compared and discussed.

Results and discussion

The evolution of microstructure and texture of the ARB Al alloy investigated has already been published elsewhere [1]. Therefore, here only a brief overview is given in Figs. 1 and 2. During ARB the coarse globular grain structure in the starting material changes to an ultrafine grained lamellar structure (Fig. 1). The texture of the initial state consists of a strong cube and a minor Goss component. During ARB this texture changes rapidly and the copper component becomes dominant. Moreover, the rotated cube and the brass component form (Fig. 2).

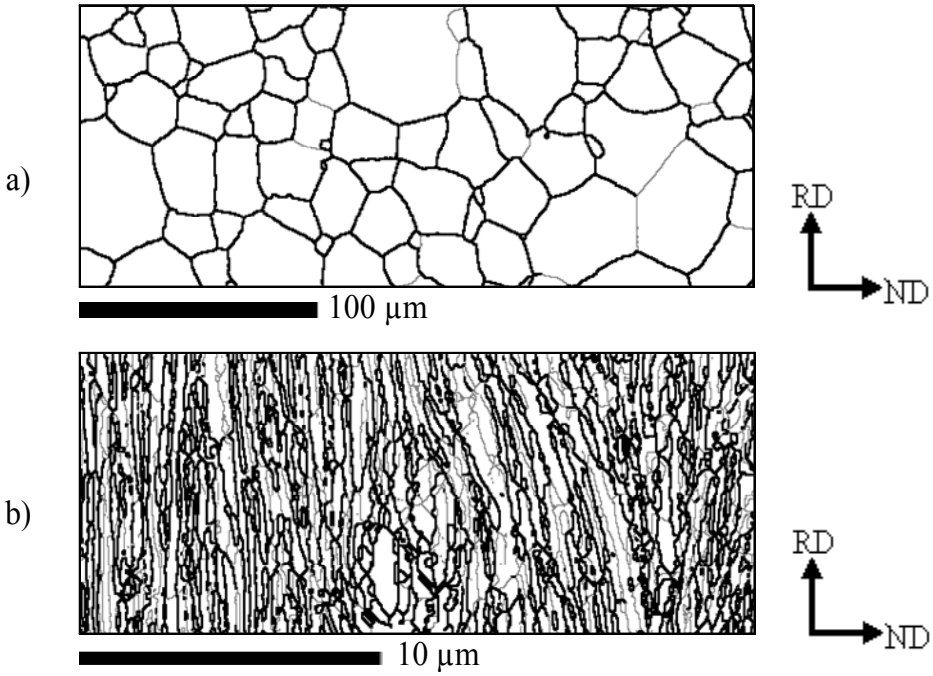


Fig. 1: Grain structure in the initial (a) and the ARB sheet after 8 cycles (b) reconstructed from an orientation map. Thin and thick lines represent low and high angle grain boundaries with misorientations 3° - 15° and >15°, respectively. (ND = normal direction, RD = rolling direction)

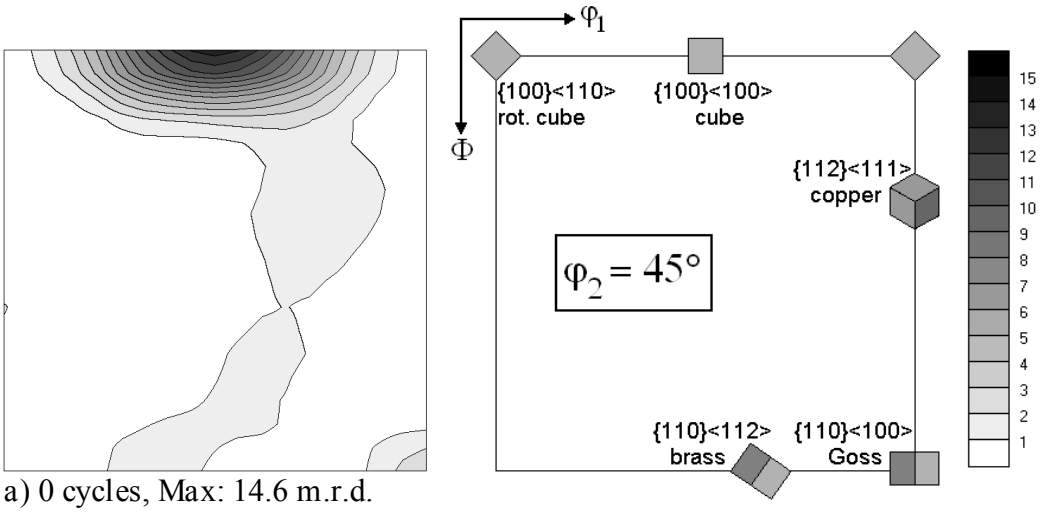
Figure 3 shows the evolution of the Lankford parameter for the three directions as a function of the number of ARB cycles. The experimentally measured curves show the same trends as the simulations. $r_{45°}$ values increase strongly with the number of ARB cycles while r_{RD} and r_{TD} both decrease slightly. In the initial state r_{RD} and r_{TD} are higher than $r_{45°}$. After two ARB cycles this relation is reversed. Results of both simulations are in qualitative agreement with experiment, but they are still too high. Obviously, the FC Taylor model leads to the highest values. The calculations strongly overestimate the mechanical anisotropy for high deformations. The same discrepancy between experiment and simulation was found by Park et al. [15].

The normal anisotropy $\langle r \rangle$ and the planar anisotropy Δr are shown in Fig. 4. $\langle r \rangle$ increases steadily with increasing number of ARB cycles. Δr decreases and changes sign, shifting earing from the RD/TD positions (Δr positive) in the initial state to the 45° positions (Δr negative) in the 'high-cycle' ARB state. This is valid for both experimentally obtained and simulated values.

Regarding the deep drawing properties the evolution of $\langle r \rangle$ and Δr is contrasting. A large value of the normal anisotropy $\langle r \rangle$ » 1 reduces thinning of the walls. For minimal earing a planar anisotropy $\Delta r \approx 0$ is desirable. Thus, for good deep drawing conditions r_α should be large and comparable for all directions. Except for the starting material, $\langle r_{exp} \rangle$ is smaller than $\langle r_{FC} \rangle$ and $\langle r_{RC} \rangle$ leading to more wall thinning than the simulations predict. On the other hand, the experimental Lankford parameters for different directions (Fig. 3) do not differ as much from each

other as in the simulations and therefore Δr is much smaller reducing earing. According to experiment the best conditions for deep drawing are fulfilled for 'low-cycle' ARB.

Finally, reasons for the deviations between experiment and simulations will be discussed. In a similar investigation on rolled molybdenum sheets there was good agreement between experimental and simulated Lankford parameters [16]. In our case the differences are much larger. This may possibly be due to a higher deformation degree. An increasing number of ARB cycles leads to a stronger change of the microstructure [1]. During deformation the coarse globular grain structure in the starting material changes to an ultrafine grained lamellar grain structure. The dislocation density is assumed to increase with strain, too. For high strains the influence of highly oriented microstructural features and grain refinement on the plastic anisotropy may become relevant and therefore according to [17 - 19] should be considered in future simulations.



a) 0 cycles, Max: 14.6 m.r.d.

b) 4 cycles, Max: 6.7 m.r.d.

c) 8 cycles, Max: 10.1 m.r.d.

Fig. 2: Texture after (a) 0, (b) 4 and (c) 8 ARB cycles displayed as ODF sections at $\varphi_2 = 45°$ with intensities given in multiples of a random distribution (m.r.d.). The key figure shows the position of the main texture components.

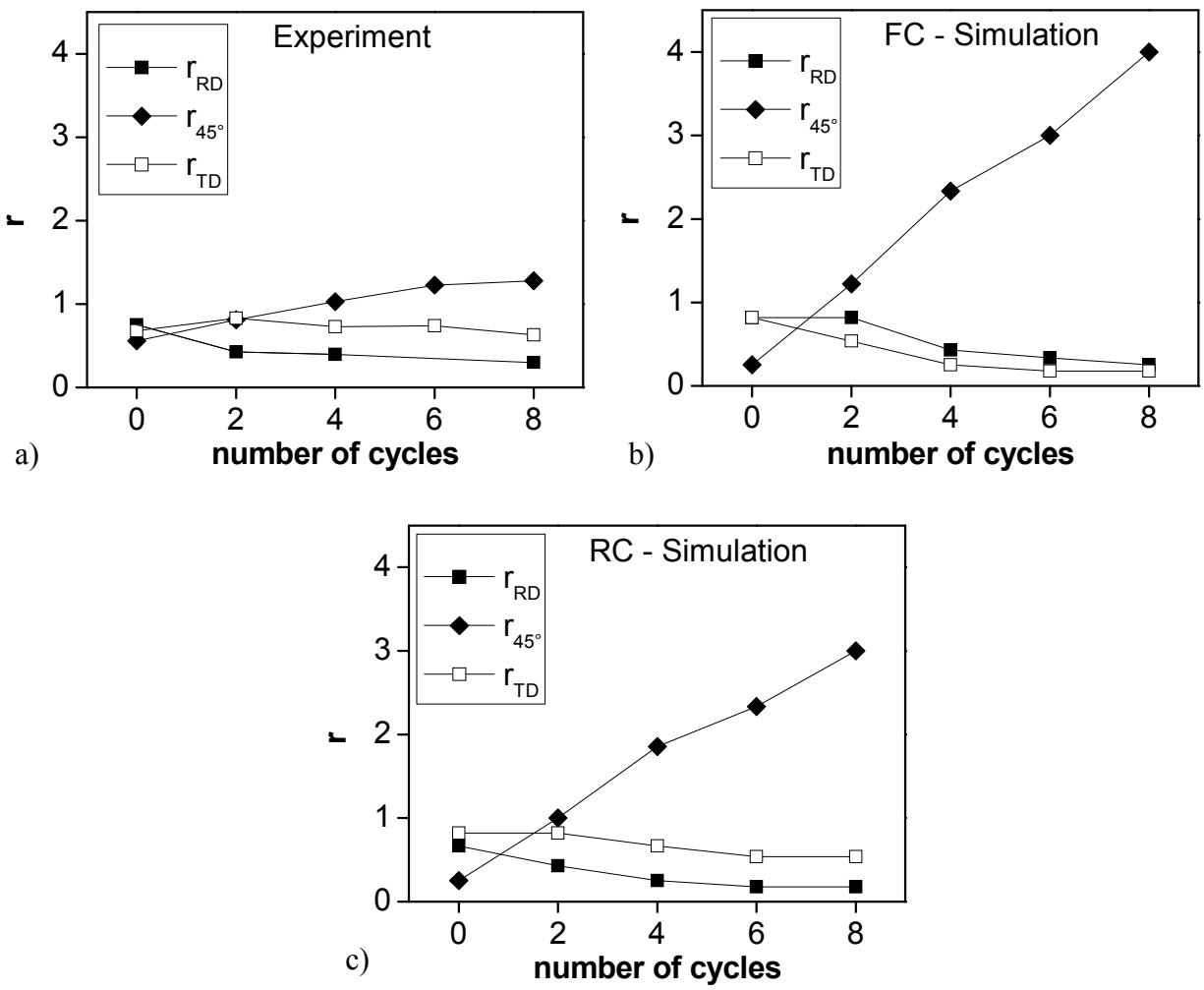


Fig. 3: Lankford parameter *r* calculated for tensile deformation in different directions as a function of the number of ARB cycles, a) experiment, b) FC and c) RC Taylor model

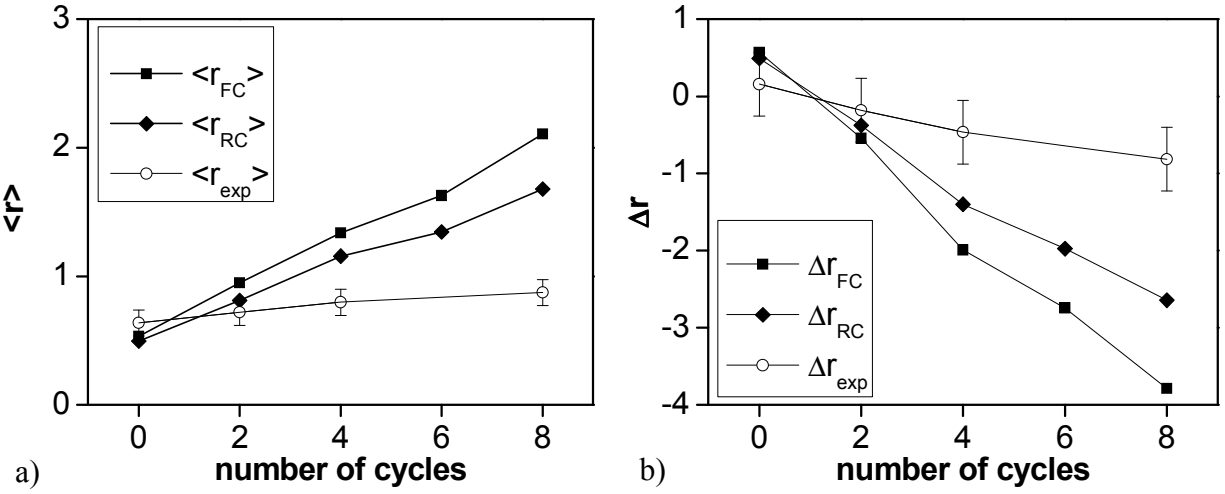


Fig. 4: Measured and simulated normal anisotropy <*r*> (a) and planar anisotropy *Δr* (b) as a function of the number of ARB cycles

Conclusions

Measurements of the Lankford parameter show that the plastic anisotropy of the ultrafine grained Al alloy AA6016 increases with the number of ARB cycles. This trend can be simulated with the Taylor model taking the texture into account. Increasing differences in the plastic anisotropy between experiment and theory with increasing ARB cycles may be attributed to the highly oriented microstructural features.

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