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Effect of back pressure on material flow and texture in **ECAP of aluminum**

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Abstract. Large billets $(5 \times 5 \times 30)$ cm³ of technically pure aluminum (AA 1050) taken from thick rolled sheets were deformed at room temperature by single pass equal-channel angular pressing (ECAP). ECAP was done at different back pressures (0 - 60 MPa) using a square die with channels intersecting at 90° in sharp corners. The normal direction of rolling was taken parallel to the transverse direction of ECAP. The flow pattern was visualized by marker lines on split billets. The initial texture of the coarse-grained rolled sheet was measured by neutron diffraction. After ECAP, X-ray diffraction was used to measure the texture gradient from top to bottom of the billets. The results show, that with increasing back pressure the corner gap is closed and the flow line pattern becomes more symmetric. The flow line exponent increases strongly from top to bottom of the billets. Moreover, the inhomogeneous deformed zone at the bottom of the billets becomes smaller. The texture changes from a typical rolling texture to a typical shear texture with the intensity of the different shear texture components changing with back pressure. For the A₁*component splitting is observed. The texture changes are discussed considering Toth's flow line model and grain refinement.

1. Introduction

To improve the mechanical properties of metals with regard to strength and ductility, nowadays, severe plastic deformation (SPD) is often employed through various processes [1, 2]. One of such SPD processes, which has been studied extensively in the literature, is equal channel angular pressing (ECAP) [3]. In ECAP a billet is pressed repetitively through two equal channels which are connected at a certain angle. In this process SPD is produced mainly by simple shear on the plane of intersection of the two channels and this promotes considerable grain refinement.

The actual deformation mode during ECAP depends on die geometry (die angle, corner roundness), processing conditions (friction, back pressure (BP), temperature and pressing speed) and plastic properties of the material itself [3]. Applying BP offers several advantages: (i) BP enhances the workability of the material and therefore is especially useful for less ductile materials [4]. Porosity usually developing during ECAP is suppressed by BP leading to

ductile fracture of the material during tensile testing [5, 6]. (ii) As shown by an analysis of finite element method (FEM), BP changes the flow behavior in the die [7]. For strain hardening metals, like technically pure aluminum AA 1100, with

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increasing BP the outer asymmetric corner gap is closed and above a certain level of BP (about 100 MPa) a dead metal zone is produced. Accordingly, the plastic deformation zone (PDZ) around the intersection plane of the die channels first decreases and then increases again. With decreasing PDZ the overall strain rate along the intersection plane increases and the strain rate distribution becomes more uniform and symmetric. The equivalent plastic strain in the billet is almost constant at 1.0 in a range of 0.1 to 0.7 of the relative distance from the top surface. In the upper section it is slightly smaller, while in the lower section it is much lower and increases with increasing BP. In contrast, in nearly non-hardening metals, like the peak-aged aluminum alloy AA 6061-T6, already without PB no corner gap is formed and with increasing BP the PDZ increases, while the strain rate distribution does not change too much. The equivalent plastic strain is constant at 1.0 within a range of 0.1 to 0.8 of the relative distance from the top surface. In the upper section it is slightly smaller, while in the lower section it drastically increases for all BPs applied. The broadening of the PDZ with BP has been shown by scribed grids on furnace-cooled aluminum alloy AA 6016-O [8].

(iii) With increasing BP there is a decrease in average cell size, increase in cell wall thickness and increase of dislocation density within the cell and cell walls. Moreover, the formation of high angle boundaries is faster with strain. This has been shown for AA 6016-O [9, 10] by applying a BP of 200 MPa. If the material is deformed at temperatures, where dynamic recrystallization takes place (AA 5024, 300°C, 100 MPa BP), it has been found that recrystallization is enhanced by BP [11].

(iv) As the shear deformation during ECAP is quite large, there is pronounced texture formation [12]. Due to non-uniform strain rate distribution in the PDZ and hence heterogeneous strain distribution in the billet (see above) texture development is not homogeneous throughout the billet. There exists a gradient from top to bottom in the deformed billet [13, 14] and consequently this affects the overall mechanical properties.

The effect of BP on the overall texture formation has been shown for AA 6016-O [15]. Application of a BP of 200 MPa results in a positive rotation of the typical shear texture components about the transverse direction. This translation reduces in magnitude with increasing number of ECAP passes until no translation exists after eight and more passes. As BP leads to enhanced grain refinement and increase in dislocation density and, consequently, to earlier age-hardening, the decrease in microhardness and increase in ductility may be attributed to the change in texture.

Although the effect of back pressure on ECAP has been demonstrated in experiment and FEM modeling for various aluminum alloys, understanding of the flow behavior and texture development is far from complete. Therefore, in the present study one ECAP pass has been performed on technically pure aluminum alloy AA 1050 under different BPs. The sophisticated large-scale ECAP tool used with moving outer walls and sliding bottom was especially designed for low friction [16]. The flow pattern was made visible by a grid scribed on the transverse section of a billet split in the middle. Texture measurements were done on the normal plane as a function of distance from the top of the billet. Special care was also taken to characterize the initial microstructure and texture. Based on the flow line pattern the texture was simulated with Toth's flow line model [17] and compared with experiment.

2. Experimental

A technically pure aluminum bar (AA 1050, 2N+) was rolled down to a thickness of 50 mm and large billets were cut from the sheet with a cross-section of (50×50) mm² and a length of 300 mm. The billets were deformed by one ECAP pass at room temperature at different back pressures (0 MPa, 30 MPa, 60 MPa) in a 90° die with sharp corners and almost square cross-section (input channel: (52×51) mm², exit channel: (51×51) mm²). The ECAP die material is made up of classical tool steel (H13 quenched and tempered). The pressing speed was 20mm/min. Friction was minimized by using MoS₂ as lubricant and with the help of moving walls and a bottom slider [16]. To have a homogeneous microstructure and texture in the

IOP Conf. Series: Materials Science and Engineering **63** (2014) 012153 doi:10.1088/1757-899X/63/1/012153 transverse direction plane of ECAP, the normal direction in rolling (ND)_r before extrusion was parallel to the transverse direction (TD)_E in ECAP.

For neutron texture measurements cubes of $(5 \times 5 \times 5)$ mm³ were cut in (ND)_r of the rolled plate with an electro discharge cutting machine. Similarly, for X-ray texture measurements 10 samples of $(18 \times 18 \times 4.45)$ mm³ were cut in normal direction of ECAP (ND)_E and then additionally mechanically polished with wet SiC papers (grit 220 to 2400) with Struers Labopol-21. Samples for EBSD were mechanically ground on wet SiC paper (grit 220 to 4000) followed by electropolishing in an electrolyte (91% ethanol + 9% perchloric acid) at a temperature of about -17°C and a polishing voltage of 42V using Struers Lectropol-5. The electropolishing was repeated four times for intervals of 8s.

Because of the large grain size neutron diffraction was used to measure the initial texture. To capture the texture gradient along (ND)_E, X-ray diffraction in reflection mode was used in a HZG-4 goniometer (GE Sensing & Inspection Technologies GmbH) by applying Cu K_a radiation (λ =0.154nm) on a sample area of about (8 × 8) mm². The defocusing error was corrected using an aluminium powder specimen with random texture. With neutron and X-ray diffraction the {111}, {200} and {220} pole figures were measured. For calculation of the orientation distribution function from these pole figures LaboTex software [18] was used. The Euler angles given are in the Bunge notation [19] with crystal and sample reference systems defined as x || extrusion direction ED, y || ECAP normal (ND)_E and z || ECAP transverse direction (TD)_E yielding an ODF representation appropriate for simple shear [17] rotated anticlockwise by 45°. The textures are represented by $\varphi_2 = 0^\circ$ and $\varphi_2 = 45^\circ$ ODF sections, which for face-centred cubic (fcc) metals contain all major shear components transferred into the ECAP reference system.

For microstructure investigation of the samples, EBSD measurements were carried out in a field emission gun (FEG) SEM (Zeiss Ultra 55) using 15 kV as acceleration voltage and orientation analyses were performed with Channel 5 software produced by HKL technology.

Texture simulations were done with Toth's flow line model [20] developed for ECAP using the viscoplastic polycrystal self consistent (VPSC) code. The values of the flow line exponent n were varied between 2 and 20. The experimental texture was represented by 10,000 grains, where each grain orientation was described by a set of Euler angles. The strain rate sensitivity index m and the parameter α in the interaction equation of the VPSC model were chosen as 0.1 and 0.6, respectively. The slip systems used were the octahedral ({111}<110>) as well as additionally non-octahedral systems ({100}<110>) of fcc metals [21].

3. Results and Discussion

The general flow characteristics in ECAP are demonstrated in Fig. 1 on a sample deformed without BP and etched after deformation. It is clearly seen, that during ECAP without BP an asymmetric corner gap is formed which limits the PDZ marked by the white pointed lines.

To ensure a save ejection of the billet from the die, the punch was driven in the input channel just below the top wall of the exit channel. (It should be noted, that this is not an interrupted test. The strain situation and the flow lines can be different when the stationary deformed part of the sample is passing through the deformation zone. Looking at the flow with a punch being so near to the PDZ, the boundary condition for the flow is different. Namely, there is a strictly horizontal part of the sample where it is in contact with the die and this is not the case when that part of the sample is deformed in which the deformation is stationary. Then the horizontal part is far from the PDZ, see for example [7].) Quantitative evaluation of the flow pattern was made possible from the deformed grid scribed on split extra samples of shorter length (Fig. 2), neglecting a minor effect of the punch on the flow line shape at larger distance from the inner die corner (see Fig. 9a).

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Fig. 1: Flow characteristics in ECAP for a sample deformed without BP and etched after deformation with the PDZ marked by the pointed lines.



Fig. 2: Change of flow line pattern with BP: The PDZ, zone of inhomogeneous shear strain and region of texture measurement are marked. The shear angle is about 64°.

In the tail section of the billet the area of the corner gap decreases with increasing BP. Similarly, the area of the asymmetric fan-like PDZ decreases. The only border point staying fixed is the upper channel corner which is intersected by the lower border line. In the steady region the grid is homogeneously sheared yielding an angle of the line, which initially - before deformation - was a horizontal line, with ED of about $\alpha = 64^{\circ}$, which is in agreement with the theoretical shear angle given by $\alpha = \arctan 2 = 63.4^{\circ}$. It should be noted that it looks like that the shear is taking place in the (ND)_E plane but actually it is on the intersection plane. Writing the strain gradient tensor it becomes obvious that an initial horizontal line is transformed into a line with this angle [12]. The inhomogeneous deformed bottom part decreases with increasing BP from 10 mm at 0 MPa BP over 5 mm at 30 MPa to 2.5 mm at 60 MPa BP. It is also shown that with increasing BP the head region approaches an ideally undeformed triangle. These results agree well with those found by FEM analysis [7].

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Fig. 3: Microstructure and texture of the initial samples (assuming orthorhombic sample symmetry) displayed in the rolling coordinate system.

The initial microstructure and texture in the central layer of the rolled sheet is shown in Fig. 3. The microstructure is a typical rolling microstructure consisting of grains flattened in the rolling plane. Using the line intercept method and taking a critical disorientation angle of 15° for high angle grain boundaries (HAGBs), the coarse grains have approximate dimensions in ND, TD and RD of 20 μ m, \geq 50 μ m and \geq 50 μ m, respectively. The texture is a typical rolling texture of fcc metals with a strong copper (Cu) and brass (Bs) component, a minor Goss and very weak cube component. The few bands that are close to the cube orientation have a lower spacing between HAGBs.



Fig. 4: Grain structure before and after ECAP with the shear angle marked by solid line and the trace of the channel intersection plane marked by dashed line.

The microstructure of the ECAP deformed samples on the TD plane is shown in Fig. 4. ECAP leads to grain refinement which becomes more pronounced with increasing BP, compare

IOP Conf. Series: Materials Science and Engineering **63** (2014) 012153 doi:10.1088/1757-899X/63/1/012153 [10]. The size and aspect ratio of the newly formed grains is about 2.5 μ m and 2.6, respectively, for a BP of 60 MPa. There exists a preferred extension of the (initial) grain structure at the shear angle $\alpha = 64^{\circ}$. Moreover, shear features exist along the trace of the channel intersection plane. The texture of the ECAP sample deformed without back pressure is shown in Fig. 5. The texture is a typical shear texture with the ideal components given in the key figure and defined in Tab. 1. The initial texture is also given in the ECAP reference system, i.e. rotated by $\varphi_1 = 90^{\circ}$, to show the texture change during ECAP. It is seen that the initial Bs and Goss components are already close to A₁* and C, while the initial Cu component is close to A/ \overline{A} .



Fig. 5: Texture gradient after ECAP from top to bottom of the billet for the sample deformed without BP

As generally observed [13, 14], there is a change of texture from the top to the bottom of the billet with regard to intensity and displacement from the ideal position of the components. These two parameters are quantitatively displayed for all samples in Figs. 6 and 7.

According to these figures three zones may be distinguished from top to bottom of the billet:

- Upper zone I of 10 mm with strong intensity variations and strong deviations of the components from their ideal positions,
- a rather homogeneous zone II from 10 to 30mm with respect to intensity and very small deviation (±5°) from ideal position and
- a zone III above 30 mm, in which the A₁* component is split. Here, in general, the intensities of the components decrease and stronger deviations exist from the ideal positions. The zone of inhomogeneous shear strain defined in Fig. 2 can only be correlated with texture for the sample deformed without back pressure. In this zone there is a general decrease in intensity and increase in deviation.

IOP Conf. Series: Materials Science and Engineering **63** (2014) 012153 doi:10.1088/1757-899X/63/1/012153 Zones I and III may be related to the zones found by FEM analysis, in which the equivalent plastic strain rate along the channel intersection plane is significantly higher than in zone II [7].

Component	Miller indices	Euler angles [°]		
designation	{shear plane } <shear direction=""></shear>	φ1	Φ	φ2
A	$\{1\overline{1}\overline{1}\} < 110 >$	0	35.26	45
\overline{A}	$\{\overline{1}11\}{<}\overline{1}\overline{1}0>$	180	35.26	45
A_{1}^{*}	$\{\bar{1}\bar{1}1\} < 112 >$	35.37	45	0
		125.37	90	45
A_2^*	$\{11\overline{1}\} < 112 >$	144.74	45	0
		54.74	90	45
В	$\{\bar{1}12\} < 110 >$	0	54.74	45
		120	54.74	45
\overline{B}	$\{1\overline{1}\overline{2}\} < \overline{1}\overline{1}0 >$	60	54.74	45
		180	54.74	45
C	$\{001\} < 110 >$	90	45	0
		0	90	45
<111> or A fibre	$\{111\}{<_{{\it uvw}}}{>}$			
<110> or B fibre	$\{ hkl \} < 110 >$			

Tab. 1: Typical ideal shear texture components with the corresponding Euler angles



Fig. 6: Intensity of texture components from top to bottom of the billet: Zones of inhomogeneous shear strain, strong variation of intensity of texture components and splitting of A_1^* component are marked by black, red and green lines, respectively.



Fig. 7: Deviation of texture components from ideal shear position: Zones of inhomogeneous shear strain, strong variation of intensity of texture components and splitting of A₁* component are marked by black, red and green lines, respectively.



Fig. 8: Texture change with BP in the rather homogeneous zone II from 10 to 30mm from top of the billets.

The change of the intensities of the components with BP in the rather homogeneous zone II is shown in Fig. 8. With increasing BP there is a relative increase of the intensity of the components except that of C which goes over a maximum. As a result the maximum component at 0, 30 and 60 MPa BP is A_1^* , C and \overline{A} , respectively. The texture results differ from those reported by [15]. The reason may be the smaller die, higher BP and different Al alloy in Ref. [15].

To quantify the flow behavior during ECAP the symmetric flow line function defined in the flow line model of Toth [20] has been fitted to the deformed grids shown in Fig. 2. This was only possible for BPs of 30 and 60 MPa, where the flow pattern is quite symmetric. The quality of the fit is demonstrated for 60 MPa BP in Fig. 9a; the change of the flow line

IOP Conf. Series: Materials Science and Engineering **63** (2014) 012153 doi:10.1088/1757-899X/63/1/012153 exponent *n* describing the rounding of the flow line in the PDZ, from top to bottom of the billet is shown in Fig. 9b. The flow line exponent increases almost linearly from top to bottom with the slope being larger in the bottom part above 30 mm. There is practically no change from 30 to 60 MPa BP.



Fig. 9: Flow line fit (a) and flow line exponent *n* from top to bottom of the billet (b).

Taking the flow line exponents derived from experiment the ECAP textures for the BPs of 30 and 60 MPa have been simulated. The results are shown in Figs. 10 and 11. There is quite good agreement between experiment and simulation for 30 MPa BP when using octahedral and non-octahedral slip with equal CRSSs. Even some characteristic features of the ODF can be reproduced. As the flow lines do not change from 30 to 60 MPa BP the change of the experimental texture with BP cannot be explained by Toth's flow line model alone. Moreover, the splitting of the A_1^* component cannot be reproduced.

It is generally accepted that BP enhances friction of the billet at the channel walls, this effect being strongest at the bottom wall. The interrelated effect of friction and back pressure on flow in ECAP has been shown by Bowen [22]. Therefore, both influences are hard to separate. By using a friction-reduced tool, as done here, BP on the one hand leads to narrowing of the PDZ by this approaching the simple shear mode. On the other hand the microstructure is more refined. This seems to be a clear hydrostatic pressure effect. Hydrostatic pressure reduces the diffusivity of the material and hence dynamic recovery. As a result the microstructure is more refined. Evidently, this effect leads to a texture change. To check this hypothesis, simulations with Toth's grain refinement model [23] are planned.



Fig. 10: Comparison of texture between experiment (a) and simulation (b) (30 MPa BP, octahedral and non-octahedral slip).



Fig. 11: Comparison of texture between experiment (a) and simulation (b) (60 MPa BP, octahedral and non-octahedral slip).

4. Conclusions

Investigations of the flow behavior and development of microstructure and texture as well as texture simulations on aluminum ECAP deformed at different BPs with a friction-reduced tool leads to new insight into the role of BP on ECAP:

(1) As generally observed, BP leads to narrowing of the PDZ accompanied by filling of the corner gap.

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- (2) Different zones of homogeneity can be distinguished with regard to strain and texture. While strain is homogeneous over 0.8 of the height of the billet from top and this range increases with BP, the texture only is homogeneous within a zone of 0.1 0.3 independent of BP. This indicates that not only the total strain is important in ECAP, but also the strain mode in the PDZ which changes along the channel intersection plane.
- (3) The texture can be modeled well with Toth's flow line model only for a BP of 30 MPa. It is assumed that for higher BPs the more intense grain refinement has to be taken into account.

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