Texture dependent lattice strains and texture gradient in Al7020

Z Y Zhong1,2, H-G Brokmeier1,2, E Maawad2 and N Schell2
1Technische Universität Clausthal, IWW-TEXMAT, Agricolstraße 6, 38678 Clausthal-Zellerfeld, Germany
2Helmholtz-Zentrum Geesthacht, GEMS Outstation at DESY, Notkestraße 85, 22607 Hamburg, Germany
3Helmholtz-Zentrum Geesthacht, Max-Planck-Straße 1, 21502 Geesthacht, Germany
E-mail: zhengye.zhong@hzg.de

Abstract. Firstly, an Al7020 block was characterized by the texture gradient, which was remarkably strong. Texture sharpness in the center with about 30 mrd (multiple random distribution) shows typical plain strain texture components. On the surface and close to the surface the texture sharpness is much weaker showing also shear components. Strongest shear was not directly at the surface but 4 mm deeper. The texture analysis at HEMS Beamline (Petra III/DESY-Hamburg) was done with continuous scanning mode to include all grains to improve the grain statistics. Secondly, with an in situ synchrotron experiment the texture dependent lattice strain behavior was investigated using flat tensile samples oriented 0°, 45° and 90° to the rolling direction (RD). Texture induced anisotropy influenced on the lattice dependent yield strength and the lattice dependent stress-strain behavior, which will be discussed in detail. Due to the high energy synchrotron beam complete Debye-Scherrer rings were obtained so that the patterns, parallel and perpendicular to loading direction (LD), were obtained simultaneously.

1. Introduction
The rolling texture of fcc metals with high stacking fault energy, such as aluminum alloys, exhibits orientations along β fiber at large degrees of rolling under plane strain state, where the plastic deformation is realized by slips on the (111)<110> slip systems, without presence of twining. However, due to the friction between rolls and workpiece and roll gap geometry, texture gradient through the thickness will be formed. Investigations revealed that the friction influenced on the thin surface layer, whereas the roll gap geometry may cause shear deformation through the thickness [1, 2]. Besides, in the present study, the texture induced anisotropic behaviors of the highly textured center layer are characterized by the lattice strain evolution during uniaxial tension along 0°, 45° and 90° to RD, respectively.

2. Experimental procedure
The as-received Al7020 block has a thickness of 29.7 mm, from which the texture-gradient sample was cut along the normal direction with dimensions of 7.09 × 6.36 × 29.7 mm³. The investigated layers are described by the parameter s = 2t/t₀ (t is the distance from the center and t₀ is the plate thickness). Five layers were investigated, corresponding to the s values of 0.97, 0.73, 0.49, 0.26 and 0, respectively. Pole figure measurements were carried out at the high energy X-ray beamline HEMS Po7B at PETRA III (DESY, Hamburg), with X-ray wavelength of 0.1422 Å, beam size of 0.5 × 0.5 mm², sample detector distance of 1111 mm and mar345 detector. The ω range for pole figure measurement was from -92.5° to 92.5° with 5° per step using continuous scanning mode. Complete orientation distribution function (ODF) was calculated from the measured (111), (200) and (220) pole figures by iterative series expansion method with an expansion degree of Lmax = 35.

The flat tensile samples for lattice strain evolution were cut from the center layer (s = 0) along 0°, 45° and 90° to RD, respectively, with gauge volume of 3 × 3.4 × 18 mm³ (thickness × width × length). In situ tensile test was carried out at HEMS Po7B, with X-ray wavelength of 0.1420 Å, beam size of 0.5 × 0.5 mm², sample detector distance of 1119 mm and PerkinElmer XRD 1622 detector, on a universal tensile machine with loading speed of 5 × 10⁻⁴
mm/s till UTS at room temperature. In order to get lattice spacing \( d_{hkl} \) in both parallel and perpendicular to LD, the intensity-\( 2\theta \) spectra were integrated from complete Debye-Scherrer ring within 10° segment in \( \gamma \) along the two directions. Lattice strains under different loads were obtained by \( \varepsilon = (d_{hkl} - d_{o,hkl})/ d_{o,hkl} \), where \( d_{o,hkl} \) is the starting lattice spacing of stable elastic deformation. The misalignment of detector was calibrated by LaB\(_6\) powder.

3. Results and discussion

3.1. Texture gradient along the normal direction of the Al7020 block

The complete ODF analysis results at \( \varphi_2 \) of 45°, 65° and 90° sections are shown in Fig. 1 for the above mentioned 5 layers. Table 1 shows the main ideal orientations observed in Fig. 1. In the surface layer (\( s = 0.97 \)), the texture is consisted of the orientations along the \( \beta \) fiber and weak shear components. But the Bs component scatters in the vertical direction in the \( \varphi_2 = 90° \) section, while the Copper component shifts to the Dillamore component which is at the lower \( \Phi \) angle in the \( \varphi_2 = 45° \) section and S component shifts to the lower \( \Phi \) angle in the \( \varphi_2 = 65° \) section. Besides, the rotated cube component scatters towards \( \{112\}<110> \) shear orientation. In the subsurface layer (\( s = 0.73 \)), rotated cube component becomes stronger and the orientations along the \( \beta \) fiber get weaker than the surface layer. Furthermore, the scattering of the \( \beta \) fiber orientations grow larger. In the quarter layer (\( s = 0.49 \)), the orientations along the \( \beta \) fiber become stronger and tend to shift towards their ideal positions. The scattering of the Copper, Bs and S components also get smaller. The rotated cube component gets very weak. Moreover, there is a weak Goss component. Further towards the center (\( s = 0.26 \) and \( s = 0 \)), the texture is composed of the typical plain strain rolling components which concentrate along the \( \beta \) fiber, and the shear components totally disappear.

Fig. 1: ODF results of different layers of the Al 7020 plate
Table 1: Miller indices and Euler angles of the main ideal orientations observed in Fig.1.

| Designation | Miller indices | Euler angles | Designation | Miller indices | Euler angles |
|-------------|----------------|--------------|-------------|----------------|--------------|
| Copper      | {112}<111>    | 90 30 45     | Goss        | {011}<100>    | 0 45 0/90    |
| Dillamore   | {4411}<11118> | 90 27 45     | Cube        | {001}<100>    | 0 0 0/90     |
| S           | {123}<634>    | 59 34 65     | Rotated cube| {001}<110>    | 45 0 0/90    |
| Bs          | {011}<211>    | 35 45 0/90   | Shear       | {112}<110>    | 0 35 45      |

Deviation from plain strain deformation state where \( \varepsilon_{11} = -\varepsilon_{33} \) and \( \varepsilon_{12} = \varepsilon_{13} = \varepsilon_{22} = \varepsilon_{23} = 0 \) leads to shear texture \( 1, 2, 3 \) stand for RD, TD and ND of the as-received block, respectively) [3]. Relaxation of any of the shear components \( (\varepsilon_{12}, \varepsilon_{13}, \varepsilon_{23}) \) could be achieved by rolling, resulting in different texture changes with respect to the plain strain deformation [4]. In the s=0.97 and s = 0.73 layers, at \( \phi_2 = 45^\circ \) section, the scattering of Dillamore towards the rotated cube component, especially at \( s = 0.73 \) layer, can be attributed to the relaxation of \( \varepsilon_{13} \). The increase of rotated cube component, Dillamore component scattering to the lower and lower \( \Phi \) angle, and Bs and S components at \( \phi_2 = 65^\circ \) and \( \phi_2 = 90^\circ \) sections scattering further towards the rotated cube component, indicate \( \varepsilon_{13} \) value increasing from surface to subsurface. In the s = 0.49 layer, Dillamore component shifts to the higher \( \Phi \) angle where it corresponds to the Copper component at \( \phi_2 = 45^\circ \) section, indicating the \( \varepsilon_{13} \) value gets smaller. In \( \phi_2 = 90^\circ \) section, besides the scattering towards the rotated cube component, Bs component also scatters towards the Goss component owing to the relaxation of \( \varepsilon_{13} \). From \( s = 0.26 \) to \( s = 0 \) layer, the texture sharpness gets stronger and stronger and plain strain deformation prevails, making the Copper, Bs and S components tend to locate at their ideal positions and the scattering of these components get smaller.

3.2. Lattice strain evolution during uniaxial tension

The lattice strain evolution along \( 0^\circ, 45^\circ \) and \( 90^\circ \) to RD during uniaxial tension is shown in Fig. 2. The differences in lattice strain evolution along these three directions directly show the anisotropic behavior. In the elastic region, all results show the expected behavior related to less single crystal elastic anisotropy, which is expressed as \( 2C_{44}/(C_{11}-C_{12}) \) with a value equal to 1.22 [5]. Means, the texture dependent lattice strain evolution in elastic region is not evident. The lattice dependent yield strengths of individual planes are shown in Table 2. As one can see the lattice dependent yield strength varies due to the orientation of the tensile direction with respect to the rolling geometry, because texture induced anisotropy makes the shape of yield surface deviate from the isotropic state. Therefore, different yield strengths can be obtained through tensile loading in different directions. In the plastic region, much information can be obtained, but in the present article, only the orientation dependent work hardening behaviors of individual lattice planes and the abnormal behaviors of \{200\} planes are discussed. When plastic deformation starts, the grain oriented work hardening behavior (see the single crystal investigations of Kocks [6]) dominates the lattice behavior, as shown in Fig. 2. For all the three samples, the work hardening behaviors of individual lattice planes can be divided into two groups. The first group shows a flat work hardening curve after yield while the second group shows an increasing work hardening curve. The different work hardening behaviors are due to the different stress states. The stress state of the first group is dominant by the \{100\} tension, whereas that of the second group is dominant by \{111\} tension (see Bishop [7] for the different stress states for polyslip). However, the lattice strain of \{200\} planes exhibits a dramatic change after yield in both parallel and perpendicular to the LD of the \( 45^\circ \) and \( 90^\circ \) to RD samples. The change is mainly related to the stress state of the \(<110>\) directions of the \{200\} planes [5, 8, 9]. When the \(<110>\) of the \{200\} is stressed, the active slip systems are \((111)[10-1], (111)[01-1], (11-1)[101] \) and \((11-1)[011] \). If the amount of slip on the
4 active slip systems is the same, the deformation is asymmetric and it will cause large contraction in the [001] direction. When the contraction is opposite to the LD, it will cause a compressive stress. If the contraction is parallel to LD, a tensile stress will be induced. For the {200} lattice strain perpendicular to the LD, the contraction is much larger than the matrix, leading to tensile stress in this direction, as shown in Fig. 2 (b).

![Graphs showing lattice strain](image)

(a) RD  (b) 45° to RD  (c) 90° to RD

Fig. 2: Lattice evolution along different directions during uniaxial tension

Table 2: Lattice dependent yield strength (MPa)

| Lattice plane | 111 | 200 | 220 | 311 | 222 | 331 | 420 | 422 |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|
| RD            | 315.40 | 314.07 | --- | 312.37 | 314.63 | --- | 331 | 422.24 |
| 45° to RD     | 293.65 | 290.25 | 298.62 | 296.13 | 291.17 | 304.77 | 299.81 | --- |
| 90° to RD     | 298.49 | 295.86 | 312.75 | 311.48 | 295.51 | 308.86 | --- | --- |

4. Conclusions
Texture gradient is found in the as-received Al7020 block. From the surface to subsurface, the deformation mode is shear plus plain strain. From subsurface to center, plain strain deformation prevails. Besides, texture induced anisotropy is characterized by lattice strain evolution during uniaxial tension along the 0°, 45° and 90° to RD directions. The results show that lattice dependent stress-strain behaviors are strongly related to the stress states, which are caused by both external load and the interactions between neighboring grains.

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