

# Quantifying texture evolution during hot rolling of AZ31 Twin Roll Cast strip

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**Abstract.** Multi-pass rolling experiments with an AZ31 Twin Roll Cast (TRC) alloy were performed on an industrial scaled four-high rolling mill. Within the rolling with an intermediate annealing the evolution of texture was investigated. To quantify the extent of preferred crystallographic orientation experimental X-ray pole figures were measured after different process steps and analyzed using the free and open Matlab® toolbox MTEX for texture analysis. The development of the fiber texture was observed and analyzed in dependence on rolling conditions. In the initial state the specimen exhibits a texture composed of a weak basal texture and a cast texture with {0001}-planes oriented across the rolling direction. During the following rolling process a fiber texture was developed. The expected strength increment of the fiber texture was quantitatively confirmed in terms of volume portions of the orientation density function around the fiber and in terms of the canonical parameters of fitted pseudo Bingham distributions. On the results of this work a model for prediction of the texture evolution during the strip rolling of magnesium in the examined parameter range was developed.

## 1. Introduction

The reducing of mass plays an important role in a development of modern construction technologies. Magnesium is the lightest metal among the construction materials because of its low density. The disadvantage of this material is its low formability at room temperature due to a limited number of effective deformation systems. Basal slip is the dominant slip system during the deformation, resulting in the formation of a basal texture during deformation and reducing the resulting mechanical properties. At the Institute of Metal Forming of TU Bergakademie Freiberg a new technology process chain of Twin Roll Casting (TRC) with subsequent rolling of Mg-alloys has been developed [1]. The TRC-plant with a subsequent four-high reverse strip rolling mill in an industrial scale allows us to investigate the material properties in a production like process.

In this paper the texture evolution of the rolled TRC AZ31 strip aiming at a quantification of the evolving fiber texture were investigated. Understanding of the texture and microstructure evolution is essential to predict and control it during rolling of TRC strips of Mg alloys in the future.

Definitions, conventions, and the notation with respect to texture analysis closely follow the publication introducing MTEX [2].

All computations were done with the free and open source Matlab® toolbox MTEX 3.3.2 for texture analysis, which can be downloaded from <http://mtex.googlecode.com>. It employs fast Fourier transforms for  $S^2$ ,  $S^2 \times S^2$ , and SO (3) as encoded in the public domain software NFFT, cf. <http://www-user.tu-chemnitz.de/~potts/nfft/>.



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## 2. Problem

The subject of this paper is the hypothesized systematically increasing extent of preferred orientation of a fiber texture during rolling of TRC-material in a production like process. The laboratory experiments cannot always be transferred to production processes, therefore, the first objective of the investigation is to demonstrate the texture evolution in the production like process. The second objective is to quantify the texture evolution. The texture was represented in terms of orientation density functions (ODFs) derived from the experimental diffraction pole figures, and the hypothesized evolution of a fiber component due to progressive deformation was analyzed in terms of characteristics of the ODFs and in particular in terms of the canonical parameters of the fitted pseudo Bingham orientation density functions.

## 3. Experiments

The initial material was Twin-Roll Cast strip of AZ31 (3% Al, 1% Zn, Mg) alloy with a thickness of 5 mm. The Twin Roll casted coil with a width of 600 mm was used for the rolling experiment. Before rolling the TRC coil was homogenized above 400 °C in a circulation air furnace and roughed down in two passes to a thickness of 2.45 mm. Then it was intermediately annealed at 360 °C and finish-rolled in two passes to the final thickness of 1.5 mm. The rolling speed was 80–120 m/min with a rolling temperature in the range of 270–360 °C. The deformation degree for every pass was 20–35% for rough down and for finish-rolling steps. The roughed and finish-rolling steps were carried out on coil material. The coil was set on the coiler and reversibly rolled on the four-high rolling mill. The texture evolution was investigated in the chosen process conditions because of importance and relevancy for the safety of reversing rolling. It provides the favorable combination of rolling temperature, rolling speed, deformation degree and its effect of the microstructure and geometrical properties of the final strip, which is important for the product quality [1, 3].

The texture was measured at the Institute of Materials Science (TU Bergakademie Freiberg) with X-ray goniometry at the middle layer on RD-TD cross sections of the rolled specimens. Due to the coarse grained microstructure of initial stage stack of four ND-RD cross sections were measured to improve the statistics. The measured data was analyzed with the free and open Matlab® MTEX for texture analysis [2].

## 4. Descriptive texture analysis

The fitted pole figures from the experiment are shown in Fig. 1. The pole figures of the texture of initial material are shown in Fig. 1a. The {0001}-pole figures have two different maximums, indicating a weak basal texture within the deformed parts with the other maximum transversal to the rolling direction, showing the undeformed parts of the material cast state [4]. During roughing down the basal texture increased due to an increase in deformation (see Fig. 1b and c). {10-10}-pole figures show beginning of a fiber texture development along the (0001)-axis, which is more pronounced with a higher deformation degree.

During deformation the dislocation slips along the basal slip systems primarily, although other slip systems are activated at this temperature [5]. It leads to evolution of basal texture with the increasing of deformation degree. The effect is shown on the pole figures after the 1<sup>st</sup> and 2<sup>nd</sup> passes. After the 2<sup>nd</sup> pass the coil was intermediately annealed. During this process static recrystallization was activated. After the heat treatment the basal texture is more distinct with the increase of the fiber portion. This sharpening depends on the incomplete dynamic recrystallization after two roughing passes. Some not recrystallized grains saved a dislocation portion after the deformation. The activation of the static recrystallization during the intermediate annealing leads to the initial grain growth and to rotation and coalescence of new grains with subgrains [6, 7]. It provides more intensive maximum of basal texture after heat treatment (see Fig. 1d). The same mechanism of the evolution of the basal texture with increasing of fiber portion was activated during 3<sup>rd</sup> and 4<sup>th</sup> finish-rolling passes (see Fig. 1e and f). It provides more intensive basal texture with homogeneous fiber distribution.

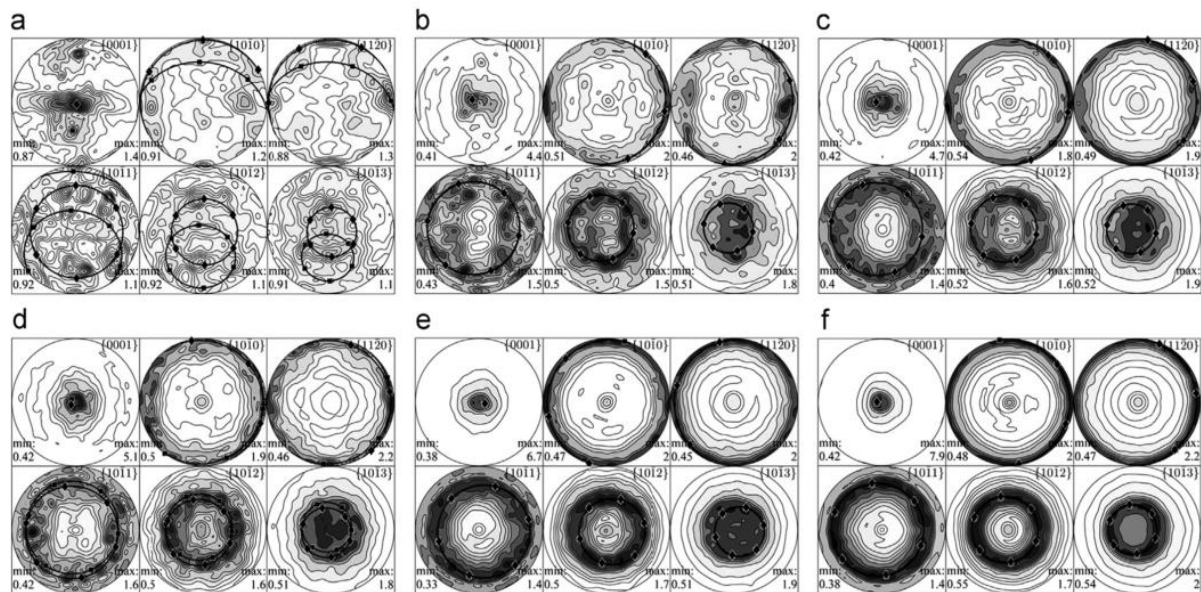


Figure 1 : Fitted X-ray pole figures of six crystal forms  $h=\{0001\}$ ,  $\{10-10\}$ ,  $\{11-20\}$ ,  $\{10-11\}$ ,  $\{10-12\}$ ,  $\{10-13\}$  displaying (a) texture in homogenized TRC-strip; (b) texture after the 1<sup>st</sup> pass; (c) texture after the 2<sup>nd</sup> pass; (d) texture after the intermediate annealing; (e) texture after the 3<sup>rd</sup> pass; (f) texture after the 4<sup>th</sup> pass.

## 5. Quantitative texture analysis

The experimental X-ray pole figures of the six specimens reveal the systematically increasing strength of a fiber texture as to be expected from the successive deformation steps in this process window. Next, the texture evolution, in particular the increasing strength of the fiber portion, is confirmed by means of quantitative texture analysis with MTEX. First, an orientation density function (ODF) is estimated from the experimental pole figures and characterized by a few quantities like uniform portion, texture index and entropy. The extent of an increasingly strong fiber texture is measured in terms of volume portions of the ODF around the fitted fiber. Then a model ODF, here a fiber pseudo Bingham orientation density, is fitted. The pseudo Bingham distribution is the most versatile model distribution, which is able to present several different patterns of preferred orientation including asymmetric unimodal textures and incomplete and asymmetric fiber textures. Its four canonical shape parameters measure the extent of anisotropy  $\kappa$ , and of a bipolar  $B$ , of a fiber  $C$ , and of a spherical proportion  $S$ , respectively. The absolute extent of a fiber texture is captured by  $2\kappa C$  and confirms again the increasing strength of a fiber texture along the successive deformation.

### 5.3. Practical application to rolled AZ31 TRC strip

The fitted canonical Bingham parameters  $\kappa$ ,  $B$ ,  $C$ ,  $S$  for the six sets of experimental pole figures are shown in Table 1. Their systematic evolution, especially the systematic increasing of  $2\kappa C = k_3 - k_2$  capturing the extent of a fiber texture, is consistent with the increasing volume portions around the fibers with respect to both the orientation density estimated with the experimental pole intensities and the fitted pseudo Bingham orientation density for all sizes of neighborhoods from  $2^\circ$  to  $32^\circ$ . The quantitative texture analysis as summarized in Table 1 is consistent in all its figures and clearly confirms the initial hypothesis of a fiber texture of increasing strength. The fitted pole figures are shown in Fig. 2.

The details for canonical parametrization of the Bingham orientation density and fitting a pseudo Bingham ODF are described in [8].

All calculations were done with MTEX's defaults wherever they apply.

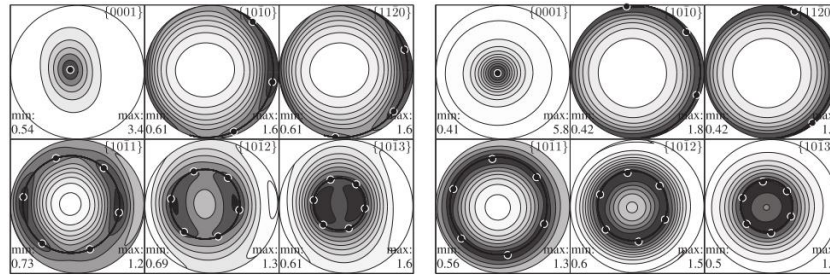


Figure 2 : Pseudo Bingham fitted h-pole densities of specimen 1<sup>st</sup> pass (left) and of specimen 4<sup>th</sup> pass (right) augmented with their modal directions (black dots) and the fitted ((0001),  $r_{\text{mode}((0001))}$ )-fiber (black circle).

| Quantitative texture analysis in terms of fitted Bingham parameters and volume portions |                       |                       |                       |                        |                       |                       |
|---|-----------------------|-----------------------|-----------------------|------------------------|-----------------------|-----------------------|
| process stage   | homogenized TRC-strip | 1 <sup>st</sup> pass  | 2 <sup>nd</sup> pass  | intermediate annealing | 3 <sup>rd</sup> pass  | 4 <sup>th</sup> pass  |
| anisotropy $\kappa$   | 7.4129444e+000        | 8.6070332e+000        | 1.1570152e+001        | 1.0603488e+001         | 1.4995928e+001        | 2.2429046e+001        |
| bimodal $B$   | 1.8575467e-003        | 2.0642562e-003        | 5.6262756e-003        | 1.1471018e-002         | 2.7158914e-003        | 1.6682365e-003        |
| fiber $C$   | 2.2812029e-003        | 1.4202273e-001        | 1.4013803e-001        | 1.6351103e-001         | 1.3179895e-001        | 1.0482021e-001        |
| spherical $S$   | 9.9586125e-001        | 8.5591302e-001        | 8.5423570e-001        | 8.2501796e-001         | 8.6548515e-001        | 8.9351156e-001        |
| <b><math>2\kappa C = \kappa_3 - \kappa_2</math></b>                                     | <b>3.3820860e-002</b> | <b>2.4447886e+000</b> | <b>3.2428365e+000</b> | <b>3.4675745e+000</b>  | <b>3.9528952e+000</b> | <b>4.7020344e+000</b> |
| vol( $\mathcal{U}_2(\mathbf{c}, \mathbf{r})$ ) epf-fit                                  | 8.5897016e-004        | 2.6038779e-003        | 2.8832333e-003        | 3.0296859e-003         | 3.9655463e-003        | 4.7405316e-003        |
| vol( $\mathcal{U}_2(\mathbf{c}, \mathbf{r})$ ) Bingham-fit                              | 7.6937037e-004        | 2.0062491e-003        | 2.5932498e-003        | 2.5872391e-003         | 3.3573408e-003        | 4.3855930e-003        |
| vol( $\mathcal{U}_4(\mathbf{c}, \mathbf{r})$ ) epf-fit                                  | 3.5288945e-003        | 1.0371037e-002        | 1.1574777e-002        | 1.2061598e-002         | 1.5784445e-002        | 1.8985669e-002        |
| vol( $\mathcal{U}_4(\mathbf{c}, \mathbf{r})$ ) Bingham-fit                              | 3.1914850e-003        | 8.2812889e-003        | 1.0674593e-002        | 1.0658407e-002         | 1.3774106e-002        | 1.7873499e-002        |
| vol( $\mathcal{U}_8(\mathbf{c}, \mathbf{r})$ ) epf-fit                                  | 1.3085129e-002        | 3.5107493e-002        | 4.0336222e-002        | 4.1352302e-002         | 5.3651277e-002        | 6.5375058e-002        |
| vol( $\mathcal{U}_8(\mathbf{c}, \mathbf{r})$ ) Bingham-fit                              | 1.2179298e-002        | 3.1032508e-002        | 3.9602588e-002        | 3.9655117e-002         | 5.0502181e-002        | 6.4041872e-002        |
| vol( $\mathcal{U}_{16}(\mathbf{c}, \mathbf{r})$ ) epf-fit                               | 4.9241187e-002        | 1.1603805e-001        | 1.4264877e-001        | 1.4132609e-001         | 1.7682212e-001        | 2.0248692e-001        |
| vol( $\mathcal{U}_{16}(\mathbf{c}, \mathbf{r})$ ) Bingham-fit                           | 4.8781337e-002        | 1.1553517e-001        | 1.4215937e-001        | 1.4371419e-001         | 1.7400054e-001        | 2.0555045e-001        |
| vol( $\mathcal{U}_{32}(\mathbf{c}, \mathbf{r})$ ) epf-fit                               | 1.6883367e-001        | 3.1859113e-001        | 3.8515509e-001        | 3.9087263e-001         | 4.3814811e-001        | 4.4050111e-001        |
| vol( $\mathcal{U}_{32}(\mathbf{c}, \mathbf{r})$ ) Bingham-fit                           | 1.7161651e-001        | 3.2756035e-001        | 3.7287372e-001        | 3.8191330e-001         | 4.2306807e-001        | 4.5791790e-001        |
| uniform portion   | 8.2317539e-001        | 3.4492614e-001        | 3.4154289e-001        | 3.3959066e-001         | 2.9149666e-001        | 3.2342474e-001        |
| texture index epf-fit   | 1.0157083e+000        | 1.5029599e+000        | 1.7064079e+000        | 1.7536885e+000         | 2.0234547e+000        | 2.1647929e+000        |
| texture index Bingham-fit   | 1.0051204e+000        | 1.3282550e+000        | 1.5303073e+000        | 1.5689386e+000         | 1.8269390e+000        | 2.0691460e+000        |
| entropy epf-fit   | -6.3188062e-003       | -1.9561308e-001       | -2.5222319e-001       | -2.6416862e-001        | -3.3428893e-001       | -3.4637583e-001       |
| entropy Bingham-fit   | -2.4223380e-003       | -1.2991566e-001       | -1.9599677e-001       | -2.1148514e-001        | -2.8447396e-001       | -3.7027462e-001       |

Table 1 : Summary of texture analysis of specimens homogenized TRC strip, 1<sup>st</sup> pass, 2<sup>nd</sup> pass, intermediate annealing, 3<sup>rd</sup> pass, and 4<sup>th</sup> pass, comprising the  $L^1$ -fitted canonical parameters (i) extent of anisotropy  $\kappa$ , and proportional (ii) bimodal  $B$ , (iii) fiber  $C$ , and (iv) spherical  $S$ , and, most instructively, the extent of a fiber preferred orientation  $2\kappa C$  (bold) of the pseudo Bingham orientation density function, and then for both the orientation density function estimated from the experimental pole figures (epf-fit) and the fitted pseudo Bingham orientation density function (Bingham-fit) volume proportions around the  $(\mathbf{c}, r_{\text{mode}(\mathbf{c})})$ -fiber, and uniform portion, texture index and entropy.

## 6. Conclusions

The evolution of texture was investigated and quantified during the rolling of TRC AZ31 strip in the production-like process. The rolling process resulted in an increasingly strong  $(\mathbf{c}, \mathbf{r}_0)$ -fiber texture with  $\mathbf{r}_0 \approx \mathbf{z}$ . Texture analysis of six sets of experimental X-ray pole figures referring to consecutive rolling passes actually reveals systematically increasing volume portions around the  $(\mathbf{c}, \mathbf{r}_0)$ -fiber with respect to the orientation densities estimated with the sets of experimental pole intensities. Moreover, fitting pseudo Bingham orientation densities the systematic evolution of their canonical parameters  $\kappa$ ,  $B$ ,  $C$ ,  $S$  and especially of  $2\kappa C = \kappa_3 - \kappa_2$  is consistent with the evolution of the volume portions around the  $(\mathbf{c}, \mathbf{r}_0)$ -fiber. Thus the initially hypothesized evolution towards an increasingly pronounced  $(\mathbf{c}, \mathbf{r}_0)$ -fiber texture is confirmed twofold, (i) by the volume portions about the  $(\mathbf{c}, \mathbf{r}_0)$ -fiber of the orientation density functions fitted to the six sets of experimental pole figures as well as the fitted pseudo Bingham orientation densities, and (ii) by the extent  $2\kappa C = \kappa_3 - \kappa_2$  of preferred crystallographic fiber orientation quantified in terms of canonical parameters  $\kappa$ ,  $B$ ,  $C$ ,  $S$  of the fitted pseudo

Bingham orientation distribution. Thus, beyond visualization the method enables us to define and characterize a fiber texture quantitatively in terms of its parameters. The achieved knowledge enables the prediction of the texture evolution in the production-like process, which is important for the optimization of the rolling process in the future.

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