

# Texture effect on mechanical properties anisotropy of products from Zr-based alloys

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**Abstract.** Technique of the macroscopic yield stress anisotropy calculation of Zr alloys based on texture  $f$ -parameters was validated in the frame of this work. In order to compare experimental and calculated anisotropy of products, samples cut out from rolled slabs of Zr-1%Nb alloy along three directions (rolling, transversal and normal) were subjected to uniaxial tension and compression up to different deformation degrees. Investigation of texture evolution under loading was implemented by measuring of several direct pole figures by means of X-ray diffractometric methods for samples in the initial state as well as after their deformation. Using obtained texture data three normalized yield stresses for orthogonal directions of studied samples were estimated and compared with experimental values measured by initial loading curves.

## 1. Introduction

Construction elements of the nuclear reactor core from Zr-based alloys are characterized with anisotropy of different mechanical properties. Degree of such anisotropy is mainly determined in the initial state of products and is based on static tensile or compressive tests along different directions, what requires labor-intensive sample preparation. At the same time various authors have developed mathematical algorithms, based on crystallographic texture data, which allow to calculate anisotropy of properties as well as modeling of its evolution under external loading [1-3]. Along with complicated models for calculation of the texture evolution there exists a simple technique for the express evaluation of the products anisotropy for materials having HCP crystalline structure based on well known integral Kearns  $f$ -parameters [4]. In this context, the aim of presented study is to validate such technique for products from Zr-based alloys.

## 2. Estimation of the yield stress anisotropy by the texture data

Simple method of the physical-mechanical properties averaging is known for materials having HCP crystalline structure. The method is based on integral Kearns  $f$ -parameters being the sum of volume fraction projection of basal normals [0001] on different directions of sample [4, 5]. In case of HCP materials with orthotropic sample symmetry the Mises yield criterion for the triaxial stress state, taking texture  $f$ -parameters into account, has the following form [4, 6]:

$$\sigma_e^2 = \frac{3}{2} \left[ f_1(\sigma_2 - \sigma_3)^2 + f_2(\sigma_3 - \sigma_1)^2 + f_3(\sigma_1 - \sigma_2)^2 \right],$$

where  $\sigma_e$  – effective stress, 1, 2, 3 – orthotropic axes, i.e. RD, TD and ND for rolled products. The initiation of the plastic flow during uniaxial loading along one of the directions ( $i$ ) occurs under condition  $\sigma_e^2 = \frac{3}{2}(1 - f_i)(\sigma_{0,2}^i)^2$ , where  $\sigma_{0,2}^i$  – material's yield stress measured in the  $i$ -th direction in course of uniaxial test. Thereby for determination of the yield anisotropy one can reduce the general equation to the dimensionless form by normalization to the  $\sigma_{0,2}^i$  in any direction. Thus construction of the yield locus for any type of stress state can be conducted by determination of  $f$ -parameters and the yield stress for one of product's directions.

## 3. Experimental results

Samples, cut out from rolled products of Zr-1%Nb alloys along different directions, were subjected to uniaxial compression and tension up to different deformation degrees in order



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to study texture evolution under simple loadings. Tension tests were conducted using plane samples, cut out from the sheet of 2 mm thickness along rolling (RD) and transversal directions (TD), with test portion length equal to 20 mm and cross section area equal to 20 mm<sup>2</sup>. Samples were strained prior to the moment of the neck initiation and after that probes from the central part along the sample's length were cut for the texture investigation. Compression tests were conducted on cylindrical samples cut out from hot-rolled slab along RD, TD (∅10×15mm) and normal direction (ND) (∅8×12mm). After the deformation samples were cut parallel to the base of the cylinder at the mid-height for further studies. Test surfaces of all samples were subjected to grinding and fine polishing for removing of the work-hardened layer.

Investigation of the texture evolution under loading was carried out by means of X-ray diffractometric measurement of several incomplete pole figures (PF) for samples in the initial condition as well as after their deformation [5]. These PFs were used for ODF restoration followed by the complete PFs construction and calculation of *f*-parameters by the LaboTex program [7]. Using obtained *f*-parameters, normalized yield stresses for three orthogonal directions of samples were calculated. Anisotropy of these yield stresses was compared with experimental one measured by uniaxial loading curves.

**Tension test**

Obtained tensile loading curves are presented in fig. 1 together with PF (0001) and {11 2̄ 0} for initial state as well as after tension along RD and TD. Moreover variation of normalized to  $\sigma_{0.2}^{RD}$  yield locus of the sheet during its tension along different directions is presented in fig. 1-*b* while calculated anisotropy coefficient  $R = \sigma_{0.2}^{TD} / \sigma_{0.2}^{RD}$  in table 1.

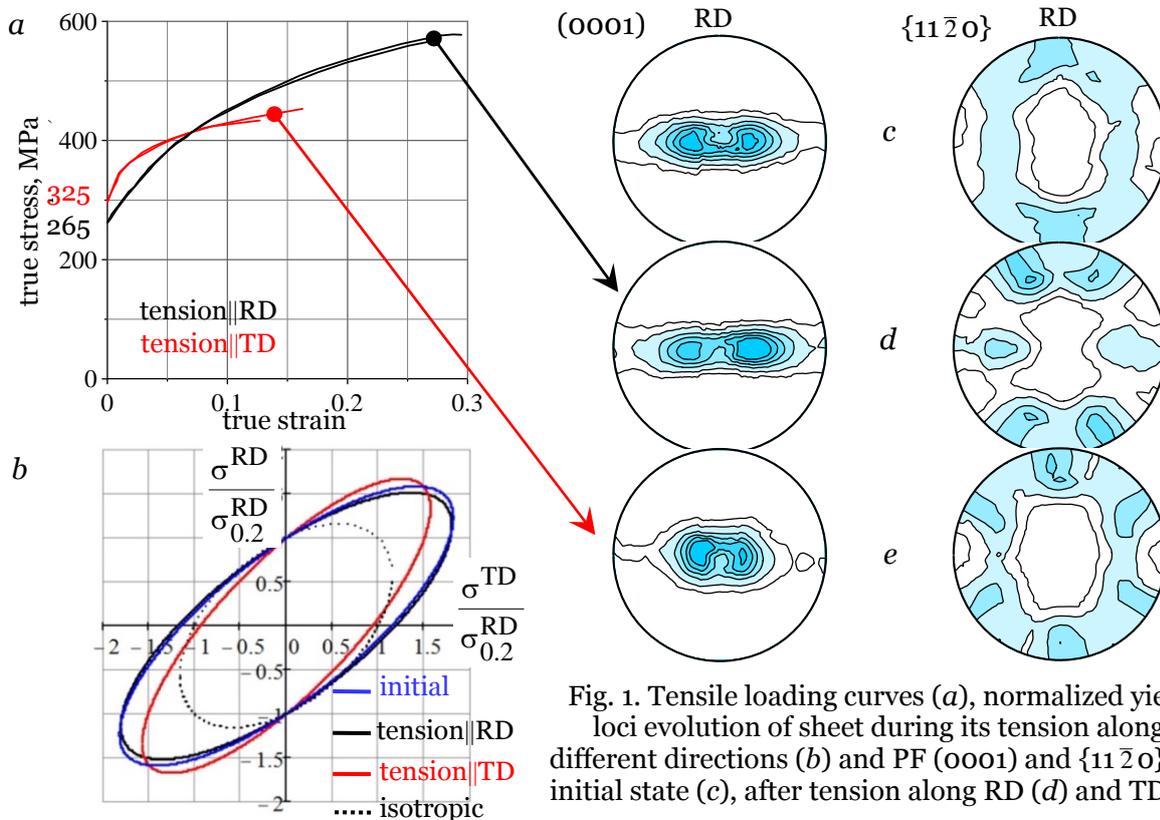


Fig. 1. Tensile loading curves (a), normalized yield loci evolution of sheet during its tension along different directions (b) and PF (0001) and {11 2̄ 0} for initial state (c), after tension along RD (d) and TD (e)

It's seen from fig. 1-*a* that material's yield stress for tension along TD is higher than for tension along RD while elongation, which characterizes plasticity, is lower. In case of uniaxial tension along RD basal normals position is stable what is seen on PF (0001) as well as by *f*-parameters values (table 1). Rotation of prismatic normals observed by PF {11 2̄ 0} for this

case (fig. 1-d) testifies that deformation takes place at the expense of the prismatic slip operation as confirmed by modeling in [8].

In case of uniaxial tension along TD the basal normals distribution changes (fig. 1-e),  $f$ -parameter for tensile direction ( $f_{TD}$ ) decreases and  $f_{RD}$  increases at the expense of the twinning activation by planes  $\{10\bar{1}2\}$  in grains having the TD-orientation [9]. This fact explains the higher yield stress under tension along TD because critical resolved shear stress is higher for twinning than for prismatic slip. There is no prismatic normals rotation in this case and basal normals reorientate towards the ND due to the basal slip activation.

Texture evolution under loading along RD results in the increasing of the calculated yield anisotropy coefficient  $R_{calc}$  in the sheet plane and under tension along TD anisotropy changes to the inverse value (table 1, fig. 1-b). On the basis of the obtained data one can see that, if strain direction during tensile test coincides with strain direction under preceding mechanical treatment, then product anisotropy intensifies and, if strain direction reverses, then degree of anisotropy decreases or changes to the inverse value.

Difference between the experimental and calculated anisotropy coefficient of the initial sheet takes place because the used calculation algorithm doesn't involve any information about various operating deformation mechanisms and difference of their critical resolved shear stresses. Despite this fact it quite applicable for express evaluation of anisotropy degree and its evolution under subsequent loading.

### Compression test

Results for samples after compression tests are presented in figure 2. Due to the intermediate behavior of the deformation diagramm for compression along TD it will not be considered further in detail. Thus anisotropy coefficient  $R = \sigma_{0.2}^{ND} / \sigma_{0.2}^{RD}$  is used in this case. Two stages of material's hardening can be found on compression curves for samples cut out along RD. This is connected with the drastic reorientation due to activation of twinning by  $\{10\bar{1}2\}$  planes at the initial stage of the compression along to the direction, which was the tension direction under preceding mechanical treatment – RD. Basal slip having higher critical resolved shear stresses is involved during further deformation, what causes an increase of flow stress. Compression along the initial compressive direction under rolling (ND) doesn't have such features. This can be explained by lower critical resolved shear stress for twinning activated during compression along RD, than for basal slip activated during compression along ND. Thus the texture under compression along ND of slab is more stable and under compression along RD drastic reorientation of basal normals takes place.

Initial experimental anisotropy coefficient of the slab  $R = 1.31$ . Calculated coefficients obtained by measured PF and their variation under uniaxial loading are presented in the table 2. On the basis of the obtained data one can see that, as in the case of uniaxial tension, coincidence of the strain direction during test with the strain direction under preceding mechanical treatment (RD is tensile direction and ND is compressive during rolling) results in anisotropy intensification and reversing of strain direction results in anisotropy decreasing or changing to the inverse value.

Table 1. Tension anisotropy of sheet from Zr-based alloy.

$R_{exp} = \sigma_{0.2}^{TD} / \sigma_{0.2}^{RD} = 1.23$			
Sample	$f_{RD}$	$f_{TD}$	$R_{calc}$
initial state	0.08	0.29	1.15
tension    RD	0.07	0.28	1.19
tension    TD	0.11	0.22	0.94

Table 2. Compression anisotropy of Zr-slab.

$R_{exp} = \sigma_{0.2}^{ND} / \sigma_{0.2}^{RD} = 1.31$							
compression    ND				compression    RD			
true strain	$f$ -parameters		$R_{calc}$	true strain	$f$ -parameters		$R_{calc}$
	RD	ND			RD	ND	
0	0.16	0.48	1.27	0	0.14	0.38	1.29
0.11	0.15	0.54	1.36	0.11	0.28	0.27	1.14
0.18	0.18	0.57	1.39	0.18	0.31	0.29	1.07
0.38	0.14	0.65	1.58	0.50	0.49	0.21	0.86

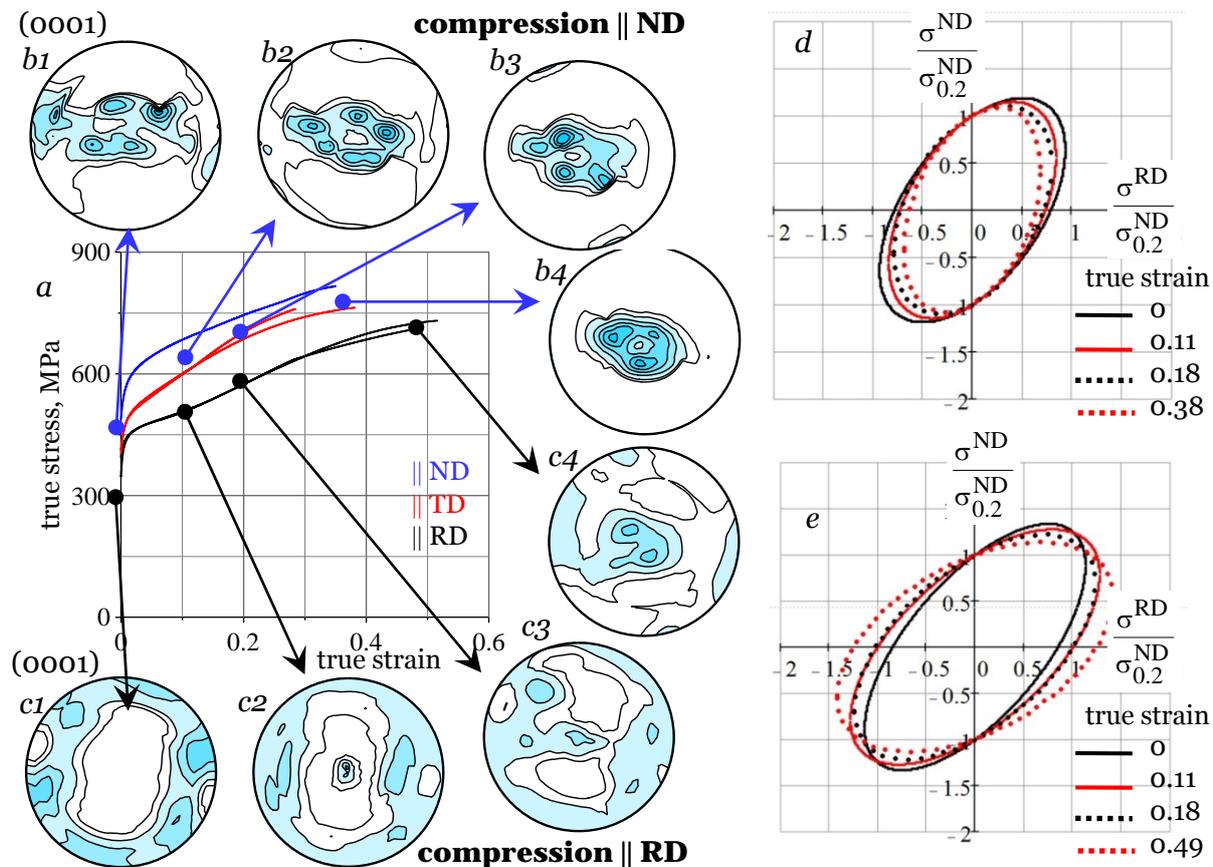


Fig. 2. Compression loading curves (a), PF (0001) for samples deformed along ND (b1-b4) and RD (c1-c4) up to different deformation degrees and yield loci evolution of slab after its compression along ND (d) and RD (e).

#### 4. Conclusions

Interrelation between the crystallographic texture evolution of products from Zr-based alloys during uniaxial loading along different directions and their yield stress anisotropy is established.

Contributions of different plastic deformation mechanisms, activated during uniaxial tension and compression along different directions, are compared.

It was shown that technique of calculation mechanical properties anisotropy, based on integral texture parameters, allows to evaluate degree of anisotropy of products from Zr-based alloys.

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