

## Conference Paper

# Features of Formation of Crystallographic Texture in Cells of Spacing Grid at their Stamping

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## Abstract

The structural and textural heterogeneity of thin-walled tubes of Zr-1% Nb alloy used for stamping of the cells of the spacing grid (SG) was studied. It was found, that structure and texture of thin-walled tubes corresponds to incomplete recrystallization. During the increasing of recrystallization degree, the variation of crystal structure parameters of Nb solid solution in  $\alpha$ -Zr is marked. The observable fluctuations of structure parameters can influence on the mechanical properties of tubes. The processes of texture formation in the cells of SG were studied at their stamping out of thin-walled tubes. It was shown that, as a result of plastic deformation of the tube, a significant layered texture heterogeneity is formed in different parts of the cell, due to the stress distribution features during stamping. Wherein the integral texture parameters of different cell areas are varied in a wide range. The following annealing of SG cells not remove of inhomogeneity, formed on the previous stage of plastic deformation.

**Keywords:** Zr-1%Nb alloy, tube, cell of spacing grid, stamping, crystallographic texture, deformation mechanisms.

## 1. INTRODUCTION

The spacing grid (SG) is used in fuel assemblies of nuclear reactors and is an important element of the design, experiencing significant alternating-sign loads [1-2]. Thereby high requirements to the properties of SG cells are put forward, which are determined by its structure and phase state and crystallographic texture. The structure and texture formation in cells during the stamping is due to using deformation scheme and initial state of thin-walled Zr-1%Nb alloy tubes from which the cells are manufactured. The distinguishing feature of zirconium products is anisotropy of physical and mechanical properties; therefore, the layerwise inhomogeneity of crystallographic texture can lead

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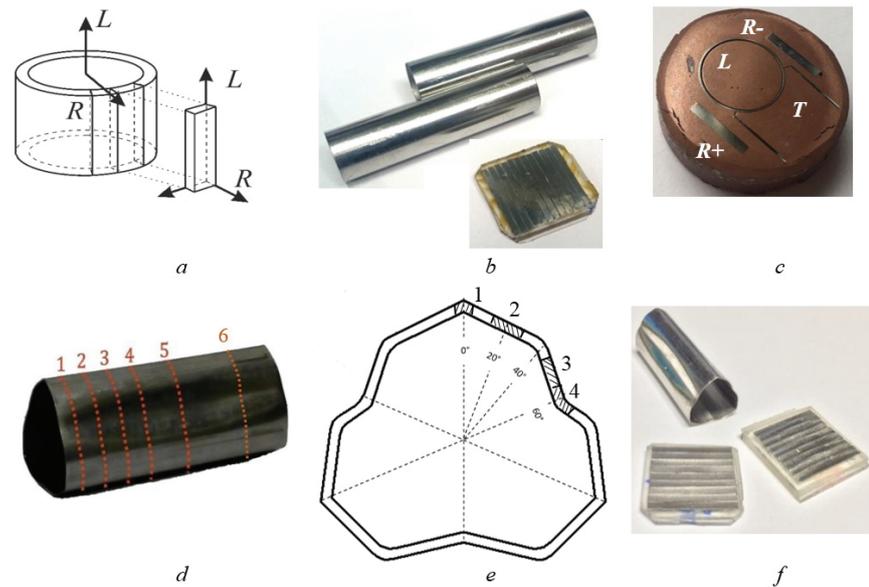
the appearance of high stresses between layers, for example, due to difference of linear expansion coefficients [3]. As a result of cell manufacturing, its various sections are undergone significant plastic deformation, which is accompanied by a reorientation of grains that persists during subsequent recrystallization annealing [4]. The purpose of this research was the obtaining of systematic information about changes of structure, properties and crystallographic texture of the SG cells during their stamping. It will allow to extend the understanding of regularities of the texture and structure formation and their influence at the operational properties of the SG cells.

## 2. SAMPLES AND METHODS

The structure and properties of SG cells are due to the structure of thin-walled tubes from the alloy Zr-1% Nb, as well as the regularities of their formation at the stage of stamping and subsequent annealing. In this paper, structure, texture and mechanical properties of tubes are studied, as well as the processes of their change in different areas of the stamped SG cells. To carry out the described complex of researches, the samples, the surface of which was perpendicular to one of the main external directions in the tube or cell, were prepared as shown in Fig. 1-a, where  $R$  – radial direction,  $T$  – tangential direction and  $L$  – axial (longitudinal) or rolling direction. For preparing of  $L$ -sample, it is sufficient to prepare the grinded and then etched surface of a branch tube or a cell perpendicular to the axis of the product. For texture research, tubes were cut into segments according to the scheme, shown in the Fig. 1-a. The studied sample of necessary size shown in Fig. 1-b was composed from these segments.

To study the structure and properties of the  $L$ -samples, the cell was cut according to the scheme shown in Fig. 1-d, in order to allocate the characteristic areas with different deformations and stresses, realizing during the stamping process. To study the texture in the vicinity of the area 5, characteristic segments (corner, dent, flat surface), perpendicular to the  $R$ -direction, were cut out along the  $L$ -axis of the cell, as shown in Fig. 1-e and f. Samples of necessary size were composed from these segments shown in Fig. 1-f.

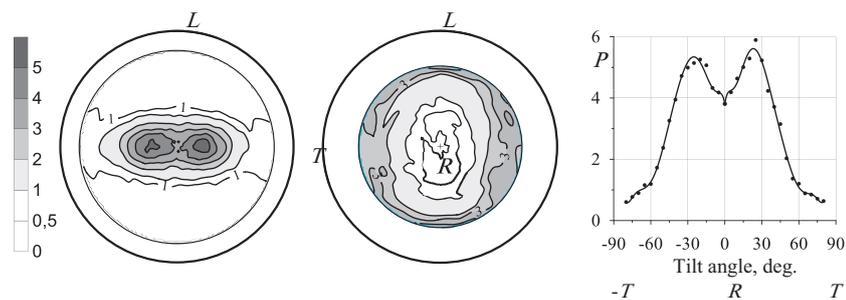
Precision cutting of all described samples was carried out by an electro-erosion machine using a goniometric attachment, which allows to align the necessary surface in the plane of movement of the cutting wire with an accuracy of 0.5 degrees. For X-ray studies, all prepared surfaces were subjected to preliminary grinding, polishing and subsequent etching in a mixture of dilute nitric and hydrofluoric acids. Grinding and polishing of tube and cell sections were carried out by using of grinding-polishing machine "POLILAB". Sanding paper No. 2400 was used for grinding, cloth and colloidal



**Figure 1:** Samples of the SG cells preparing for the X-ray diffraction and indentation: a – the scheme of cutting tube segments; b – the external view of tubes and their composed *R*-sample, c – *R*-, *T*-, *L*-samples for the indentation from the different directions, d – location of studied sections along a cell length, e – location of characteristic areas along perimeter of the cell for studying the texture of *R*-sections; f – the external view of cell and the composed *R*-samples of different surfaces of corner area 1.

suspension with a decrease in its dispersion (9, 3, 1  $\mu\text{m}$ ) and silicon suspension with a dispersion of 0.05  $\mu\text{m}$  with the addition of 50% hydrogen peroxide were used for polishing.

To study the structural state of tubes and SG cells, methods for evaluating the material structure perfection by means of X-ray line profile and the ratio of the line intensities ( $10\bar{1}0$ ) and ( $11\bar{2}0$ ) recorded for the *L*-section of the investigated products. Research of texture features of tubes and different areas of SG cells was carried out by direct pole figures (DPF) for *R*-sections of product. Based on the results of the X-ray survey, DPF ( $0001$ ),  $\{11\bar{2}0\}$ ,  $\{10\bar{1}2\}$   $\{11\bar{2}2\}$  were constructed. These DPF were used for calculation of the integral texture Kearns parameters, basic axes distribution in *R*-*T*-section of tubes and cells and orientation distribution function (ODF section  $\phi_1 = 0^\circ$ ). Integral texture Kearns parameters, representing the projection of basic axes to the three main mutually orthogonal directions of a product, were calculated by complete pole figures ( $0001$ ) [5]. X-ray measurements and calculation of DPF were realized by means of the programs, developed in the texture analysis laboratory of NRNU MEPhI [5-6]. The ODF was restored by X-ray texture data with the help of the LABOTEX software [7]. The analysis of the results was carried out using the characteristic section ODF for hexagonal materials in the Euler space at  $\phi_1 = 0^\circ$ . The measurement of residual elastic macrostresses in axial and tangential directions was made on the uncut samples using the standard X-ray  $\sin^2\psi$ -method [8-9]. X-ray diffraction measurements



**Figure 2:** DPF (0001) (a) and  $\{11\bar{2}0\}$  (b) and the distribution of basal axes in  $R$ - $T$ - section of thin-walled tube.

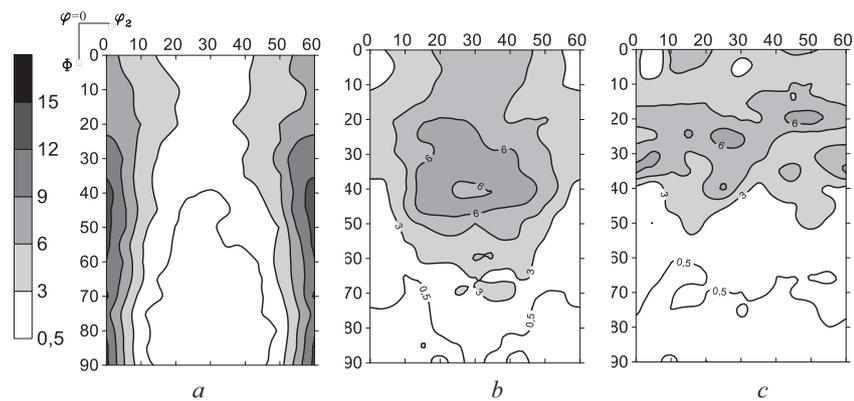
were carried out by diffractometers named DRON-3, DRON-3M and D8 DISCOVER using different anodes of X-ray tubes (Cu and Cr).

### 3. RESULTS AND DISCUSSION

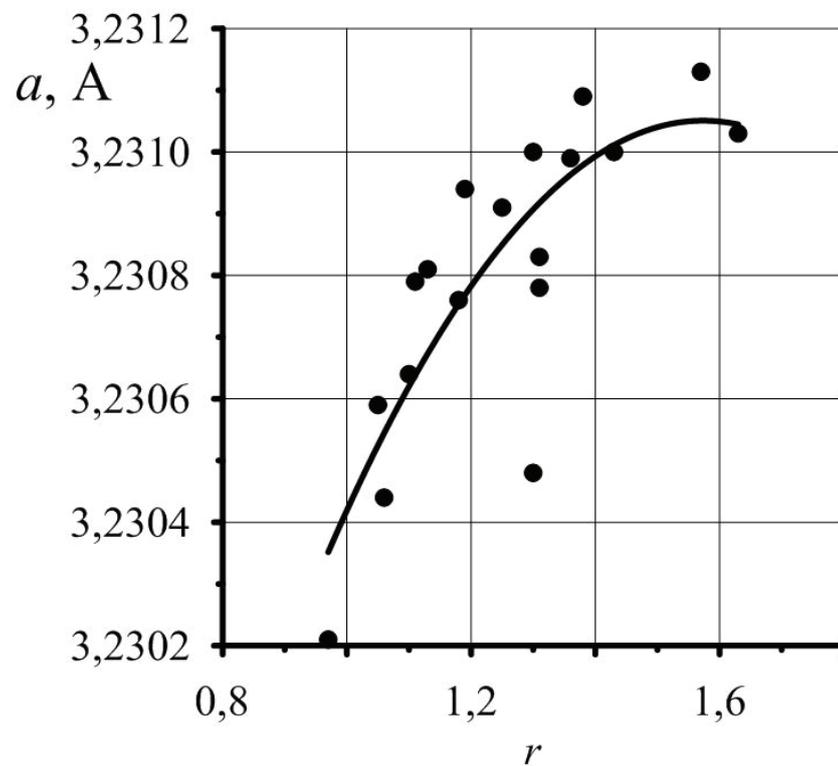
The X-ray phase analysis of studied products showed, that the main phase in the Zr-1%Nb alloy tubes is Nb solid solution in  $\alpha$ -Zr, characterized by hexagonal close-packed (hcp) structure, and the additional phase is Zr solid solution in body-centered cubic (bcc) structure of Nb, with Nb concentration from 10 to 12 weight percents. According to the equilibrium phase diagram, this alloy composition is characteristic for annealing near the recrystallization temperature of 540-580°C.

Crystallographic texture analysis of studied Zr-1%Nb alloy tubes, which was evaluated by DPF (0001) and  $\{11\bar{2}0\}$ , and by ODF section ( $\phi_1 = 0^\circ$ ), shown in a Fig. 2, indicates partial recrystallization initial thin-walled tubes. In papers [10-13] it was shown the redistribution ODF as a result of recrystallization of deformed tube. ODF sections ( $\phi_1 = 0^\circ$ ) of deformed (Fig. 3-a) and recrystallized (Fig. 3-b) cladding Zr-1%Nb alloy tubes and studied thin-walled tube (fig.3c) are shown in Fig. 3. Presented results indicate, that texture of considered thin-walled tubes is characterized by scattering of texture maximums to the meridional direction of PF  $\{11\bar{2}0\}$  and corresponding scattering in ODF section ( $\phi_1 = 0^\circ$ ) along  $\phi_2 = 0^\circ$  direction. It is the evidence of incomplete (partial) recrystallization of the product.

The Fig. 4 shows the correlation dependence of  $\alpha$ -Zr lattice parameter  $a$  determined by the content of Nb in  $\alpha$ -phase solid solution, on recrystallization degree of  $\alpha$ -Zr, calculated by intensity ratio of X-ray lines (11.0) and (10.0). Observable correlation confirms choice correctness of recrystallization degree evaluation to consider the processes of crystalline structure development of Zr based alloys.

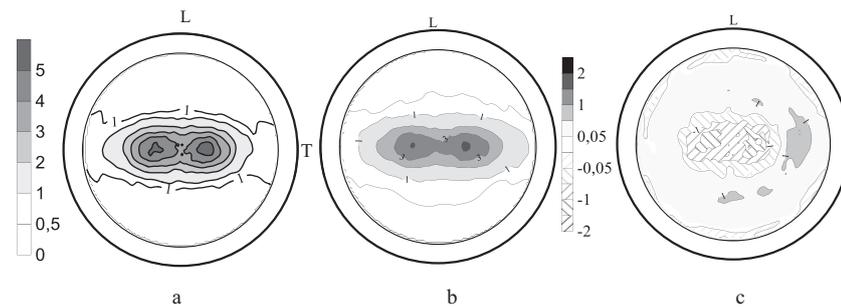


**Figure 3:** ODF-section ( $\phi_1 = 0^\circ$ ) of deformed (a) and fully recrystallized (b) cladding tubes, and studied thin-walled tube (c).



**Figure 4:** Variation of  $\alpha$ -Zr lattice parameter  $a$  with the increasing recrystallization degree.

According to the texture analysis of the investigated tubes and the microhardness measurement on samples of three different orientations cut from 18 pipes, a correlation of the microhardness with the Kearns integral parameters was established. For studied tubes, it is shown, that the microhardness of samples depend on direction of indentation. With the increasing of basic normal concentration along the direction of measurement, i.e. with increasing of the texture integral parameter, the microhardness essentially rises. It is due to the difficulties of activation of slip systems under the action



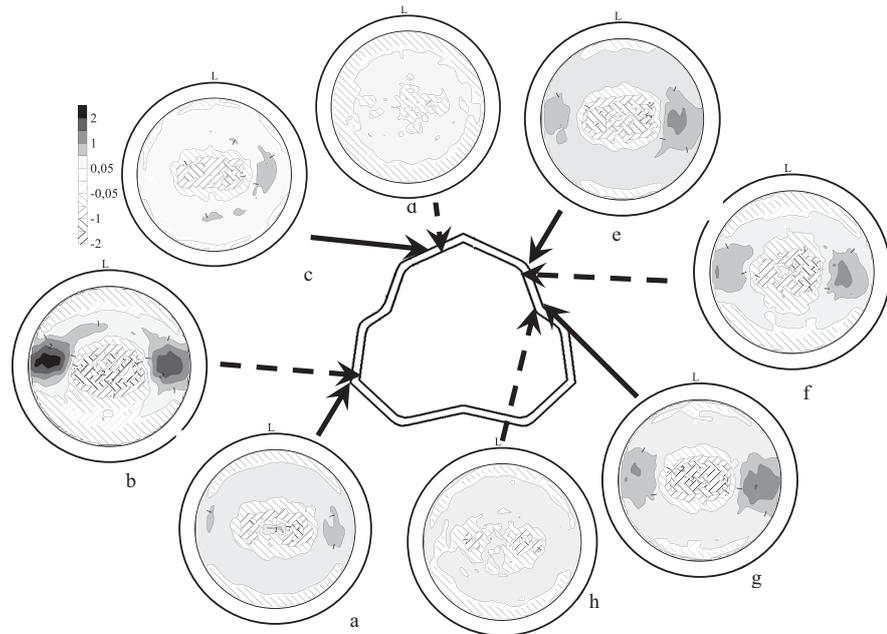
**Figure 5:** DPF (0001) of initial tube (a), deformed segment 2 (fig.1-e) of cell (b) and diagram of difference of pole densities for the first DPF (c):  $(PF(0001)_{cell} - PF(0001)_{tube})$ .

of compressive forces along the basic axes. The twinning begins to act at essentially higher critical shear stresses. It should be noted, that the indentation was carried out by Berkovich pyramid with slope angles  $65,3^\circ$ .

Crystallographic texture is a sensitive indicator of grains reorientation during the plastic deformation. Therefore, it is used for the analysis of stressed state, realizing in cell during its stamping. For the analysis of texture changes in different areas of cell the method of calculation of difference diagrams was used, the principle of which is shown in the Fig. 5. The value corresponding to the difference between pole densities on PF (0001) of one of researched cell areas and initial tube, i.e.  $\Delta P(\psi, \phi) = P_{cell}(\psi, \phi) - P_{tube}(\psi, \phi)$ , put in corresponding points  $(\psi, \phi)$  of a stereographic projection of product. The difference diagrams for various cell areas are presented in Fig. 6. These diagrams permit to estimate the change of PF (0001), as a result of plastic deformation of tube during the stamping.

Using the results of texture analysis the integral texture parameters were calculated and are presented in the table 1. Following recrystallization annealing at the temperature  $580^\circ\text{C}$  during 2.5 hours doesn't remove texture inhomogeneity of different SG cells areas, which was formed during the stamping.

The most important part of the SG, of course, are the welded joints and the dents of the SG cell, the last of which are directly in contact with the fuel element. According to the works [3, 14], when the  $f_T$ -parameters of different layers change by 0.05 in cladding tubes, during heating and cooling the development of tangential tensile stresses is observed, due to differences in the linear thermal expansion coefficients of interacting layers. These tangential stresses are sufficient for hydride reorientation perpendicular to the acting tensile stresses. In our case, the difference of  $f_T$ -parameters of inner and outer layers of annealed cell reaches 0.15 in the dent (see Tabl. 1).



**Figure 6:** Diagrams of difference of pole densities ( $PF(0001)_{cell} - PF(0001)_{pipe}$ ) in the various areas of the SG cell through its perimeter along the outer and inner surfaces.

From the obtained difference diagrams (Fig. 6), it follows that during the stamping in the all layers along the wall thickness compressive stresses are realized, and its magnitudes are approximately equal in different directions in a plane perpendicular to the radial direction, i.e. in the  $L$ - $T$ -plane. It follows from the difference diagrams, which are consistent with the regularities of basal axes reorientations in case of twinning under compression [15].

In the outer layers of the stamped cells, the dominance of compression in tangential direction compared with axial direction is noted. It ensures a preferential reorientation of the basal axes from the radial direction towards the tangential one (Fig. 6). According to Fig. 6, the maximum changes of crystallographic texture are observed for the inner surface of area 1 and the outer surface of area 4, which characterizes the cell corner and dents, correspondingly. According to the data of table 1, maximum layerwise changes of  $f$ -parameters are observed in the cell corners.

The results of residual elastic macrostresses analysis of different areas of uncut cells, averaged from the measurement results for all symmetrically located cell areas are shown in Fig. 7. According to the obtained data all of researched cell sections (3, 5, 6 of Fig.1-d) are characterized by predominantly compressive axial and tangential residual stresses, and value of residual axial macrostresses exceeds the value of tangential stresses 1,5-2 times. Obtained data are correlate with the conclusions about stresses acting during the cells stamping process, which were made earlier.

TABLE 1: Integral texture parameters of different cell areas.

Number of cell segment	<i>f</i> -parameters			$ \Delta f  =  f_{cell} - f_{tube} $		
	<i>R</i>	<i>T</i>	<i>L</i>	<i>R</i>	<i>T</i>	<i>L</i>
tube	0,64	0,27	0,09	-	-	-
tube'	0,68	0,24	0,08	-	-	-
1	0,60	0,30	0,09	0,04	0,05	0,01
1'	0,52	0,40	0,08	0,16	0,16	0,00
2	0,58	0,30	0,12	0,07	0,02	0,03
2'	0,67	0,26	0,08	0,02	0,01	0,01
3	0,54	0,35	0,12	0,10	0,03	0,03
3'	0,58	0,35	0,08	0,11	0,11	0,00
4	0,51	0,39	0,11	0,13	0,11	0,02
4'	0,63	0,28	0,09	0,06	0,04	0,02
4*	0,48	0,41	0,11	0,16	0,14	0,02
4'*	0,65	0,26	0,09	0,03	0,02	0,01

' – the inner surface of cell  
\* – after recrystallization annealing

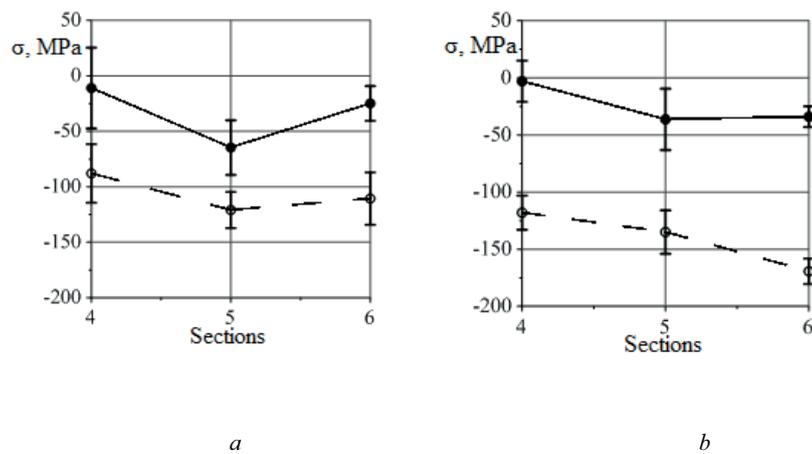


Figure 7: Distribution of residual macrostresses along a cell length: for area 1 of cell (corner) (a) and for flat area 2 of cell (b) (see Fig.1-e) – tangential stresses; – axial stresses.

## 4. CONCLUSIONS

- Based on the results of the investigation of the texture inhomogeneity of thin-walled tubes and the character of the crystallographic texture, it is shown, that the structural state of the tube corresponds to partial recrystallization.
- It is discovered that the period of the crystal structure of  $\alpha$ -Zr, which depends on Nb concentration in the solid solution of  $\alpha$ -phase, correlates with the degree of recrystallization calculated from the intensity ratio of X-ray lines ( $11\bar{2}0$ ) and ( $10\bar{1}0$ ).
- Microhardness of studied samples depends on the measuring direction: with the increasing of basal normal concentration along the direction of indentation essentially increase the microhardness.
- Crystallographic texture of different cell areas varies widely, for which, for example, the  $f_R$ -parameter of stamped cells varies from 0.52 to 0.67 in the inner surface layers and from 0.51 to 0.60 in its outer surface layers. In some segments of the cell, a layerwise texture heterogeneity is noted, for example, the dent  $f_T$ -parameter varies from 0.26 in the outer cell surface to 0.41 in the inner surface.
- The change in the crystallographic texture of the tube during the stamping of the cell characterizes the presence of significant compressive stresses during the plastic deformation of the product acting in the  $L$ - $T$  plane, which causes the preservation of high residual elastic macro-stresses in the deformed cell.
- Maximal changes in texture and layerwise texture heterogeneity during the stamping are observed in two cell areas: the angle and the dent, which are retained after recrystallization annealing.

## ACKNOWLEDGMENT

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