Adaptation of the pole figure measurement to the irradiated items from zirconium alloys

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Under strain of any metal resulted from the effect of sliding and twining, the grain crystalline lattice turns expectedly to the orientations being stable relative to the applied strain scheme. It leads to the appearance of the predominant crystallographic orientation of either grain or texture. Under the further thermal treatment of the material its strain texture may become of either recrystallization type or phase transformation one. The presence of the crystallographic texture in the material results in the anisotropy of its properties, especially significant for metals and alloys with HCP crystalline lattice characterized by high anisotropy. Zirconium is among such metals. At a room temperature Zr-based alloys contain, mainly, α-phase with HCP crystalline lattice.

Items from zirconium alloys are widely used in the nuclear engineering. The operating characteristics of materials with HCP are greatly affected by the texture peculiarities that control their irradiation-induced growth. This fact is of great importance when investigating the texture changes under irradiation. During the operation under reactor irradiation different types of texture can lead to different irradiation deformation due to the irradiation growth and creep. To predict the deformation of Zr-based items under irradiation, this or that type of texture is created during their fabrication. Nevertheless, specialists dealing with the examination of power reactor fuel assemblies reveal very often the variation in their heights and difference in diameters of certain fuel rods irradiated in one and the same fuel assembly, Fig.1 [1].

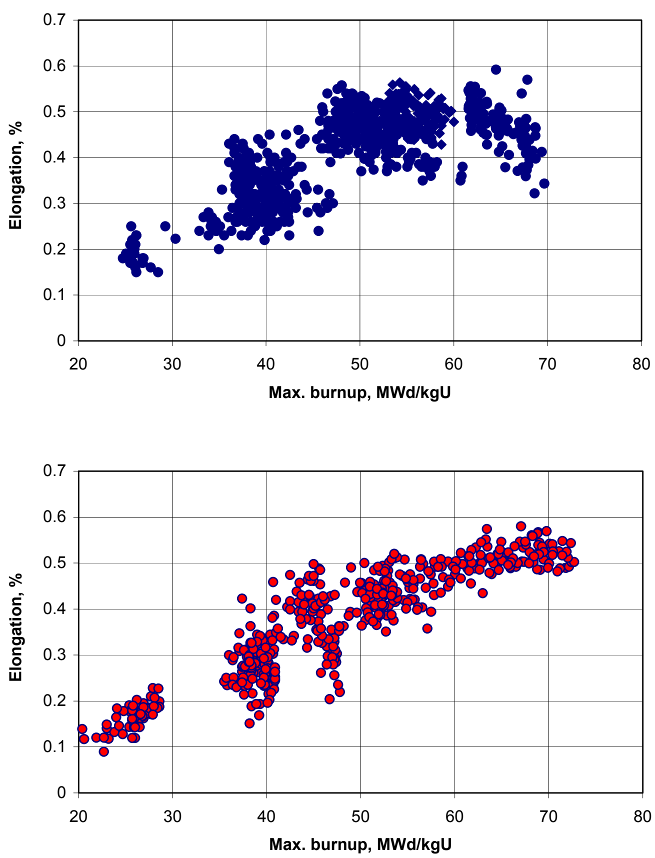

Fig.1. Length of the VVER-440 (top) and VVER- 1000 (bottom) fuel rods versus the maximal fuel burn up [1]

Either direct or inverse pole figures are used to determine the texture characteristics. A direct pole figure (DPF) is a stereographic projection of normals to certain planes (hkl) for all crystallites of the given material. DPFs are plotted in the coordinates of the sample.

An inverse pole figure (IPF) is a standard stereographic triangle, on which a so-called pole density (P_{hkl}) is indicated near projections of different crystallographic directions (or poles) of a standard monocrystal projection. The pole density is determined as a probable coincidence of the given crystallographic direction with the set physical direction of the sample. The measuring algorithm for these figures is known well [2]. The most significant drawback of the IPF analysis is an impossibility to analyze P_{hkl} for a large amount of poles. Thus, the most preferable way is to determine the texture characteristics when the direct pole figures are registered.

The X-ray examination allows us to reveal the presence of the predominating grain orientation in the polycrystalline material as well as to describe qualitatively the statistic scattering of the grain orientations using a quantitative analysis of diffracted ray distribution in space and plotting of direct pole figures.

It is known that surface layers of the sample take part in the formation of the diffraction picture. Their thickness depends on the linear coefficient of X-ray absorption and is of an order of several microns. The texture determined by the X-ray analysis describes the grain orientation in the corresponding layer. Since the degree and, sometimes, the texture of the strained material can change in depth as getting far from the strained surface, the samples used for texture examinations should be prepared rather careful selecting certain areas to be examined. For instance, when transmitting the texture we cannot examine the outer surface of the sample and when performing the reflection examination of the texture we cannot examine a thin sample obtained by polishing and etching of the massive sample. So we cannot consider the obtained pole figures complementing one another and characterizing the texture in one and the same sample volume.

The necessity to measure the texture of the irradiated samples can be related both to the absence of data on the texture of some items in the unirradiated state and to the possible change of the texture after irradiation of Zr-based items up to high neutron fluence.

An approach is known based on the phenomenon of the anisotropic re-distribution of atoms occurring under irradiation of the Zr-based items and their dimensional changes (volume being preserved) characterized by the following relation [3]:

$$\varepsilon_d = S \cdot G_d \cdot F,$$

where ε_d – distortion in direction **d**; S – coefficient determined by the material structure and depending on the irradiation conditions; G_d – texture growth coefficient determined on the basis of X-ray data by expression $(1-3f_d)$, where f_d – quantitative portion of α - zirconium grains, of which normals to epipolar planes coincide to the selected direction; F – neutron fluence (damage dose). Usually, this approach supposes the texture growth coefficient G_d to be a constant. Some papers related to the investigation of the radiation damageability of zirconium alloys and effect of irradiation on the structural parameters of zirconium alloys (characterized by coefficient S) show significant structural changes under high-dose irradiation [4-7]:

- specific dislocation structure appears in the form of dislocation loops and linear dislocations, of which type and morphology depend both on the initial structural state and on the irradiation parameters;
- irradiation-induced fine-dispersed secondary phase particles appear;
- change of the size distribution of the secondary phase precipitates presented in the material before irradiation;
- crystalline structure of some phase precipitates transforms into another type of lattice ;
- some precipitates become amorphous;
- redistribution of elements occurs between precipitates and solid zirconium matrix solution.

Such significant changes of the inter-grain structure under high-dose irradiation have to influence the orientation of crystalline lattice grains, i.e. they should be related to the change of texture peculiarities of the material.

Up to now the effect of irradiation on the polycrystalline material texture has not been investigated because of the following factors:

- methodical difficulties in high-level samples treatment;
- absence of specialized texture goniometric devices at the X-ray diffactometers used to measure pole figures of irradiated samples;
- limited number of specialists with required knowledge on the X-ray texture analysis;
- common opinion that under irradiation the Zr-based alloy texture either changes insignificantly or does not change at all;
- isolation of scientific disciplines dealing with the effect of irradiation on materials and processes of plastic strain.

Specialists from the Moscow Physical and Engineering Institute (MEPhI, Russia) have investigated the regularities of texture formation in Zr-based alloys under plastic strain [12], recrystallization [13] and phase transformation [14] based on the developed devices and software for the X-ray analysis of texture and structural peculiarities of Zr-based items [8-11]. Fine examinations have been performed during the above investigation to reveal the texture changes in Zr alloys related to lowered hydride cracking [15] and ion irradiation [16-17].

Thus, the methodical base has been developed to examine the texture of Zr-based alloys, data on the formation and change of the texture have been accumulated and experience in the X-ray examination of different aspects of Zr alloys behavior under process treatment and operation has been gained.

The specific peculiarities of the measurement of pole figures of irradiated materials are related to their radioactivity that limits the dimensions of the objects to be examined. The shape and dimensions of items are also of great importance when preparing objects for texture examination. So, one of the stages to try out the measurement of direct pole figures of irradiated materials is to master the method for preparing small-size samples and determining the minimal sample size required for measurements.

RIAR has a chain of remote diffractometers located in the hot cells and general-purpose diffactometers for non-active samples located in the rooms intended for work with low-level samples. Also RIAR has large experience in cutting and preparing different sections from structural materials. All this makes it possible to prepare samples necessary for examination and to perform measurements using equipment modernized by the MEPhI specialists.

On the whole, there are some backgrounds to implement work on the examination of the texture of Zr-based alloys after high-dose irradiation.

The implementation of such work will allow a quantitative estimation of the texture of Zr-based alloys irradiated up to ~(10^{25}-$5 \cdot 10^{26}$) m^{-2} (E>0.1 MeV), thus proving or disproving the supposition about the significance of these changes for irradiation deformation and hardening of Zr alloys. We will get information necessary to modify models of these phenomena that were verified experimentally. It will also allow a creation of a methodical X-ray complex to measure texture and calculate texture and structural parameters using irradiated Zr-based items.

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