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Texture and hydride orientation relationship of Zircaloy-4 fuel clad tube during its fabrication for pressurized heavy water reactors

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A B S T R A C T

Zircaloy-4 material is used for cladding tube in pressurized heavy water reactors (PHWRs) of 220 MWe and 540 MWe capacity in India. These tubes are fabricated by using various combinations of thermo-mechanical processes to achieve desired mechanical and corrosion properties. Cladding tube develops crystallographic texture during its fabrication, which has significant influence on its in-reactor performance. Due to radiolytic decomposition of water Zircaloy-4 picks-up hydrogen. This hydrogen in excess of its maximum solubility in reactor operating condition (~300 °C), precipitates as zirconium hydrides causing embrittlement of cladding tube. Hydride orientation in the radial direction of the tube limits the service life and lowers the fuel burn-up in reactor. The orientation of the hydride primarily depends on texture developed during fabrication. A correlation between hydride orientation (F_n) with the texture in the tube during its fabrication has been developed using a second order polynomial. The present work is aimed at quantification and correlation of texture evolved in Zircaloy-4 cladding tube using Kearn's *f*-parameter during its fabrication process.

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1. General introduction

Fuel clad due to its critical applications has stringent specification for mechanical, physical and chemical properties. The mechanical and corrosion properties of Zr–Fe–Sn alloys are attributed to the complete solubility of alloying elements and presence of intermetallic compound. Anisotropy in Zircaloy-4 due to hexagonal crystal structure leads to the development of texture after thermo-mechanical processing. The final texture of this thin wall tube has an influence on the hydride orientation, irradiation growth, mechanical properties etc. The hydride orientation factor measured as F_n is specified in fuel clad specification as a measure of texture. There is no quantitative texture parameter for clad tube specification. Several approaches have been attempted to characterize the texture in a given sample for example, Rittenhouse and Picklcsimer [1] used microhardness measurement to construct pole figures. Larson and Picklesimer [2] tried polarized light to determine the tilt of the basal poles from the surface normal. Texture determination by ultrasonic has also been attempted [3]. The hydride test [4] is still widely used to obtain an approximate texture measurement. Texture measurement by XRD gives the exact quantification of crystallographic orientation. There are two methods for interpretation of texture namely, calculation of quantitative texture (Kearn's '*f*') parameter from powder diffraction data and the pole figures obtained from X-ray goniometer technique. Kearn's '*f*' parameter gives an idea of the distribution of the basal poles in terms of fractions in sample co-ordinate system, i.e., longitudinal or rolling direction (LD), transverse direction (TD) and normal or radial direction (RD). This technique gives a partial view of the orientation distribution in the material, whereas the full representation is obtained by using X-ray goniometer to obtain the pole figures, which are the two dimensional representation of crystallographic orientations. The present work is based on the calculation of Kearn's '*f*'-parameter for quantitative determination of Zircaloy-4 fuel tube texture developed during its fabrication route.

2. Experimental procedure

2.1. Thermo-mechanical processing

Zircaloy-4 clad tube for 220 MWe Pressurized Heavy Water Reactors (PHWRs) was manufactured using a process route given in Fig. 1. β-Quenched billets were mechanically jacketed with seamless copper tubes, preheated in a resistance heating furnace at 800 °C and extruded in a 3780T Horizontal Extrusion Press (HEP) maintaining an extrusion ratio 14:1 and speed of 25–30 mm/s. Copper jacketing of billet prevents oxidation of Zircaloy billet and also copper acts as an additional lubricant with oil based graphite. Since Zircaloy has galling property, it sticks with extrusion tooling surfaces such as container and die during extrusion. The copper cover on the billet surface prevents any direct contact of the Zircaloy with tooling surface whereas oil based graphite reduces the friction and thereby load requirement for extrusion.

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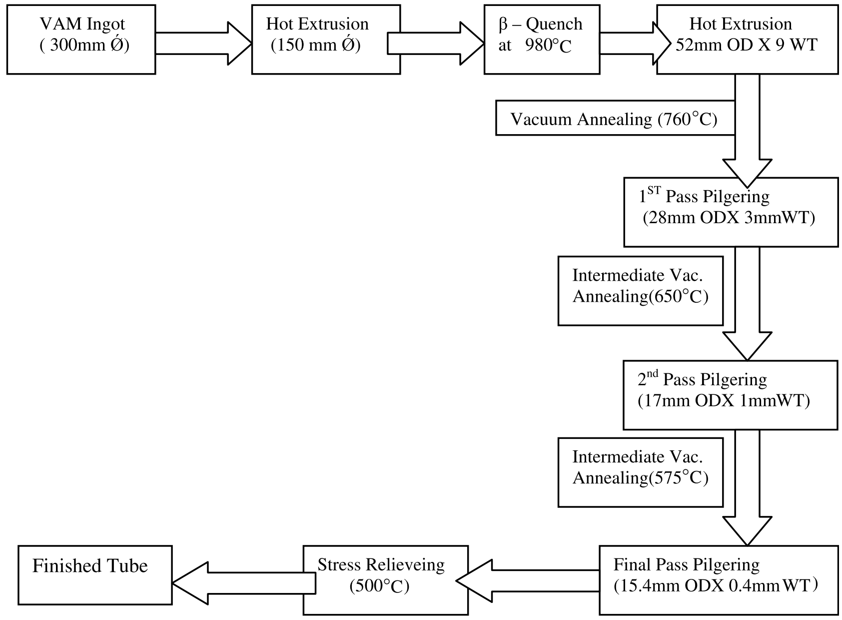

Fig. 1. Flow sheet used for Zircaloy-4 fuel clad tube manufacturing.

Copper jacketing remains on the blank after extrusion which is removed by dissolution using a bath containing 5% HF, 45% HNO_3 and 50% H_2O solution. Hot extruded and annealed blanks were cold pilgered to lower outer diameter and thinner wall in gradual passes. Tubing deformed by a high wall thickness and a low diameter reduction leads to a texture with the normal to a basal plane primarily aligned parallel to the radial direction. Each stage of reduction was followed by an intermediate vacuum annealing to restore ductility of the Zircaloy-4 tube. Table 1 shows the amount of cross sectional reduction (CSA) and *Q*-ratio maintained during three stages of pilgering of the tube to the final size. *Q*-ratio is given by

$$Q = \ln[w_f/w_o]/\ln[MD_f/MD_o],$$

where, w_o, w_f = wall thickness before and after pilgering, respectively; MD_o, MD_f = mid wall diameter before and after pilgering, respectively; MD = OD–WT.

Tube samples were collected for a set of three lots processed at all four stages of tube manufacturing starting from hot extrusion to 52 mm OD × 9 mm WT Tube. Now, from these tube samples further pieces were cut into longitudinal or rolling direction (LD), transverse direction (TD) and normal or radial direction (RD) for texture measurement by XRD technique. One sample at each stage of fabrication was also hydrided for hydride orientation factor (F_n) determination by using image analysis technique. Table 2 gives in brief the overall sampling plan for characterization of texture and hydride orientation.

Table 1
Tube reduction parameter for Zircaloy-4 pilgering

Pilgering schedule	%CSA	*Q*-Ratio
1st pass	80.6	2.0
2nd pass	78.7	2.4
Final pass	62.5	14.2

2.2. Texture analysis by X-ray diffraction technique

X-ray diffraction is an important tool for determination of preferred orientation or texture in the Zircaloy. Texture determination has been performed predominantly by powder X-ray diffraction technique for calculating Kearn's '*f*'-parameter for all samples.

2.2.1. Determination of texture by Kearns's '*f*'-parameter

The Kearn's '*f*'-parameter is the fraction of basal poles oriented in the three principal directions, i.e. longitudinal, transverse and radial (f_l, f_t and f_r) in the sample [5].

$$\text{Such that} \quad f_l + f_t + f_r = 1. \tag{1}$$

Fractions of basal poles in the longitudinal, transverse and radial directions are denoted as f_l, f_t and f_r, respectively. The number for any reference direction, say f_l, is arrived at by summation of the volume fraction (V_i) of crystals having basal poles inclined at angle (ϕ_i) to longitudinal direction, multiplied by cosine^2(ϕ_i) as projection of this quantity (V_i) in the reference longitudinal direction.

$$\text{Thus} \quad f = \sum_{\phi_i=0}^{\phi_i=\pi/2} V_i \cos^2 \phi_i. \tag{2}$$

Table 2
Sampling plan

Sl. no.	Tube fab. stage	Lot no.	Texture measurement				Hydriding
			Sample direction			Total	
1	Extruded and ann. 52 mm × 9 mm	Lot 1	RD	TD	LD	3	1
		Lot 2	RD	TD	LD	3	1
		Lot 3	RD	TD	LD	3	1
2	Pilgered and ann. 28 mm × 3 mm	Lot 1	RD	TD	LD	3	1
		Lot 2	RD	TD	LD	3	1
		Lot 3	RD	TD	LD	3	1
3	Pilgered and ann. 17 mm × 1 mm	Lot 1	RD	TD	LD	3	1
		Lot 2	RD	TD	LD	3	1
		Lot 3	RD	TD	LD	3	1
4	CWSR 15.4 mm × 0.4 mm	Lot 1	RD	TD	LD	3	1
		Lot 2	RD	TD	LD	3	1
		Lot 3	RD	TD	LD	3	1
Total						36	12

The volume fraction of crystals having inclination ϕ_1–ϕ_2 with the reference direction is given by

$$V_i = \frac{\int_{\phi_1}^{\phi_2} I(\phi)\sin(\phi)\mathrm{d}\phi}{\int_0^{\pi/2} I(\phi)\sin(\phi)\mathrm{d}\phi}, \quad (3)$$

where $I(\phi)$ is the average intensity of poles at an angle ϕ,

$$I(\phi) = \int_0^{2\pi} I(\phi,\beta)\cdot \mathrm{d}\beta \quad (4)$$

From Eqs. (2) and (3) we get

$$f = \frac{\int_0^{\frac{\pi}{2}} I(\phi)\cdot\sin\phi\cdot\cos^2\phi\cdot\mathrm{d}\phi}{\int_0^{\frac{\pi}{2}} I(\phi)\cdot\sin\phi\cdot\mathrm{d}\phi} \quad (5)$$

2.2.2. Measurement of Kearn's 'f'-parameter using powder diffraction data

This method uses the X-ray diffraction data for the samples taken from the tube in LD, TD and RD directions. However, this method will not evaluate all the preferred orientations, since only those discrete orientations corresponding to the $(hkil)$ diffraction planes of Zircaloy are measurable. These orientations are shown elsewhere [5] by the points of the (0001) standard projection of Zircaloy. The angle ϕ shows the tilt of a diffraction plane's pole from the basal pole $[0001]$. The angle β indicates a plane's rotation about the basal pole.

From the diffraction data corresponding to the three sets of planes $(10\bar{1}l)$, $(21\bar{3}l)$ and $(11\bar{2}l)$ in the samples taken for a reference direction, the texture coefficient $\mathrm{TC}_{(hkil)}$ for each $(hkil)$ plane can be calculated using the following formula [6,7]:

$$\mathrm{TC}_{(hkil)} = \frac{\frac{I_{(hkil)}}{I_{o(hkil)}}}{\left[\frac{1}{N}\right]\sum\left(\frac{I_{(hkil)}}{I_{o(hkil)}}\right)}, \quad (6)$$

where $I_{(hkil)}$ and $I_{o(hkil)}$ are the measured and the random intensities, for $(hkil)$ reflections, N is the total number of allowed reflections. The intensity I was determined as a function of ϕ, the tilt angle with respect to reference direction for the three sets of planes $(10\bar{1}l)$, $(21\bar{3}l)$ and $(11\bar{2}l)$, where ϕ is varying from 0 to $\pi/2$ for each set. The average Intensity $I_{\mathrm{av}}(\phi)$ is calculated using the following formula [5]:

$$I(\phi)_{\mathrm{av}} = \frac{I}{30}\left[19.1\left(\frac{I_1+I_2}{2}\right) + 10.9\left(\frac{I_{21}+I_3}{2}\right)\right], \quad (7)$$

where, I_1, I_2 and I_3 are the intensities at a given value of ϕ for the three sets of lines $(10\bar{1}l)$, $(21\bar{3}l)$ and $(11\bar{2}l)$, respectively. Finally 'f' is obtained from Eqs. (5)–(7).

Composite specimens for the longitudinal, transverse and radial directions (LD, TD and RD) were prepared with cut pieces of the tubings stacked together as shown in Fig. 2. In figure the longitudinal direction corresponds to the rolling direction whereas normal direction represents the radial or through thickness direction of the tube. These composite specimens were metallographically polished up to 600 grit emery paper before final polishing at 1000 grit emery paper. Specimens were immediately cleaned with 45% H_2O + 45% HNO_3 + 10% HF solution to remove the surface cold work induced by polishing.

2.2.3. X-ray diffraction procedure

For texture measurement, Rigaku Dmax 2000 X-ray diffractometer fitted with a vertical goniometer was used. XRD was carried out by applying 30 kV and 30 mA and Cu K_α radiation (λ = 1.54 Å) radiation was used as the X-ray source. Scanning speed of 1°/min was maintained between the 2θ range of 20–140° in the scan step of 0.01°/step. The three basic steps involved in the raw data processing are curve smoothening, background removal and stripping of $K_{\alpha 2}$ radiation by software. Monochromatic $K_{\alpha 1}$ for diffraction was obtained by separation of K_β radiation using crystal monochromator. A software programme was developed which requires diffraction data as input and directly gives the Kearns's f-parameter.

2.3. Hydride orientation factor (F_n) determination using image analysis

F_n is defined as the fraction of hydrides within a certain range of angles from a reference direction as observed in the microstructure. F_n number in the samples were determined as per the ASTM B-353. Zircaloy-4 tube samples of each size were charged with 100–125 ppm of hydrogen using a Sievert's Apparatus. Samples were heated up to 350 °C while charging, whereas post absorption heating ranged between 1 h and 15 h for 0.4 mm thin sample to 9 mm thick sample. Hydrided specimens were hot mounted and

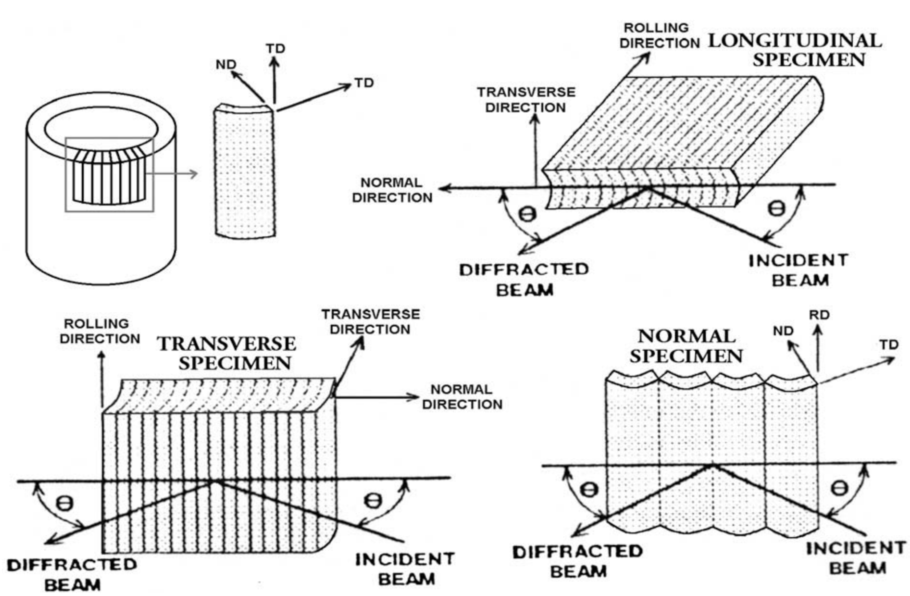

Fig. 2. Schematic of composite specimen preparation in three orthogonal directions for texture evaluation.

metallographically polished starting from 80 grit to 600 grit emery papers. Finally samples were polished to mirror finish on 1000 grit emery paper. Polished samples were then swab etched with 45% HNO_3 + 45% H_2O + 10% HF aqueous solution for 30 s, immediately rinsed in water, washed in ethyl alcohol and dried. A second swab was carried out in an aqueous solution containing 50% H_2O_2 + 25% ethyl alcohol + 10% HNO_3 + 1% HF to enhance the contrast of the hydride morphology when observed in polarized light.

Hydrided specimens were observed under the optical microscope and suitable micrographs were recorded at the magnification of 400×. Microstructures were recorded such that the reference direction, i.e. radial direction is perpendicular to circumferential hydride. Hydride orientation factor, F_n was obtained using a Soft Imaging System GmbH Analysis® software. The major steps of the image analysis consisted of calibration of images, 8 bits image conversion, shading correction (for intensity variation over the image) and marking of hydride and matrix phases based on contrast. Finally, images were converted to grey scale. Hydride dimension was defined between 5 and 250 μm^2 and aspect ratio greater than 1.8. Finally total number of hydrides in the micrographs as well as hydrides oriented lying in the range of ±40° angle with the radial reference direction was determined from the analysis.

3. Results and discussion

3.1. X-ray diffraction analysis using Kearn's *f*-parameter

X-ray diffraction patterns were obtained for all the 36 samples in three orthogonal directions of the tube viz; RD, TD and LD and the corresponding texture coefficients (TC) and the *f*-parameter in the RD, TD and LD of the tubes are presented in Table 3. The texture coefficients are tabulated for the (0002) basal plane and $\{10\bar{1}0\}$ prismatic plane whereas *f*-factor has been determined for (0002) basal plane. From the table it can be observed that there is a consistency in the TC data obtained for both (0002) and $10\bar{1}0$ planes in all the specimens of three lots under examination. A comparison of the basal texture coefficients $TC_{(0002)}$ indicates that in all the lots of as extruded & annealed condition of the tubing, values are highest in the transverse direction (TD), i.e. the basal poles are oriented closer to TD than to the radial and longitudinal directions (RD and LD). The values for $TC(10\bar{1}0)$ at as extruded and annealed stage of tube are highest in the longitudinal or rolling direction (LD). Hence, the prismatic poles shall be closer to the LD of the tube samples. The *f*-parameter determined for all the samples at four stages and its average value for three lots at each stage of fabrication has been further tabulated in Table 4. The table indicates that there are average 36% of the basal poles along the RD, 50% and 11% along the TD and LD, respectively, in as extruded and annealed blank. Maintaining a *Q*-Ratio of 2.0 (R_w/R_D) of 1.44 during the tube fabrication in the 1st pass of pilgering (Table 3) it is observed that there are about 53% basal poles in radial direction, 40% and 5% along TD and LD respectively after 1st pass. Also $TC(10\bar{1}0)$ value has been found to be reduced in RD. Further with the 78.7% cross sectional reduction in 2nd pass pilgering average values of evaluated *f*-parameter for the pilgered and annealed tubes of 17 mm OD × 1 mm WT indicates that about 63.5% of the basal poles are along RD, 36% and 5% are along the TD and LD.

Table 3
(0002) and $(10\bar{1}0)$ texture coefficient data and Kearns's *f*-parameter for (0002) planes of Zircaloy-4 tube at four stages of fabrication

Sl. no.	Tube fab. stage (OD × WT)	Lot no.	Tube direction	Basal TC(0002)	Prismatic $TC(10\bar{1}0)$	Basal *f*-parameter
1	Extruded and ann. 52 mm × 9 mm	Lot 1	RD	2.337155	2.548973	0.3495
			TD	6.079089	0.234089	0.5
			LD	1.577879	4.788494	0.115
		Lot 2	RD	2.471944	2.075143	0.373
			TD	6.39912	0.266126	0.51
			LD	1.442151	4.828071	0.112
		Lot 3	RD	2.094417	2.384239	0.359
			TD	6.966407	0.27216	0.51
			LD	1.476988	4.817912	0.113
2	Pilgered and ann. 28 mm × 3 mm	Lot 1	RD	5.803222	1.304108	0.53
			TD	3.4212491	3.422491	0.399
			LD	0.051184	3.190564	0.05
		Lot 2	RD	6.259162	1.328936	0.5398
			TD	3.357755	1.750606	0.382
			LD	0.020579	2.857925	0.05
		Lot 3	RD	5.55471	1.297656	0.526
			TD	3.677173	1.753313	0.4043
			LD	0.039991	2.640732	0.057
3	Pilgered and ann. 17 mm × 1 mm	Lot 1	RD	7.339536	0.485844	0.65
			TD	2.731046	2.258991	0.369
			LD	0.048982	3.994068	0.051
		Lot 2	RD	6.855501	0.687979	0.626
			TD	2.291633	1.664151	0.356
			LD	0.04394	3.344937	0.056
		Lot 3	RD	5.75715	0.532062	0.63
			TD	3.946617	1.894906	0.381
			LD	0.038494	5.00281	0.05
4	CWSR 15 mm × 0.4 mm	Lot 1	RD	7.610783	0.071936	0.76
			TD	1.577216	2.253866	0.255
			LD	0.045634	5.930705	0.029
		Lot 2	RD	7.629767	0.06416	0.72
			TD	1.568127	2.828542	0.237
			LD	0.022784	8.723513	0.044
		Lot 3	RD	8.536761	0.082158	0.747
			TD	1.226586	2.287185	0.215
			LD	0.118641	8.852064	0.049

Table 4
(0002) basal pole Kearn's *f*-parameter and hydride orientation factor data for Zircaloy-4 tube at four stages of fabrication

Sl. no.	Tube fab. stage (OD × WT)	Lot no.	Basal plane *f*-parameter				F_n
			RD (f_r)	TD (f_t)	LD (f_l)	$f_r + f_t + f_l$	
1	Extruded and ann. 52 mm × 9 mm	Lot 1	0.35	0.5	0.115	0.965	0.3
		Lot 2	0.372	0.51	0.112	0.994	0.3
		Lot 3	0.36	0.51	0.113	0.983	0.32
		Average	0.361	0.507	0.113	0.981	0.306
2	Pilgered and ann. 28 mm × 3 mm	Lot 1	0.53	0.399	0.05	0.979	0.27
		Lot 2	0.54	0.382	0.05	0.972	0.26
		Lot 3	0.526	0.416	0.057	0.999	0.28
		Average	0.532	0.399	0.052	0.983	0.27
3	Pilgered & ann. 17 mm × 1 mm	Lot 1	0.65	0.36	0.05	1.06	0.17
		Lot 2	0.62	0.35	0.056	1.026	0.21
		Lot 3	0.63	0.38	0.051	1.061	0.2
		Average	0.635	0.363	0.053	1.043	0.193
4	CWSR 15 mm × 0.4 mm	Lot 1	0.758	0.255	0.0359	1.0489	0.03
		Lot 2	0.72	0.237	0.044	1.001	0.05
		Lot 3	0.747	0.214	0.049	1.01	0.03
		Average	0.742	0.235	0.0429	1.02	0.037

Final tube dimension of 15.4 mm OD × 0.4 mm WT were achieved by the 3rd pass pilgering schedule with a very large Q-Ratio of 14.2 employing a predominant reduction in wall thickness due to stronger compressive forces in the radial direction of the tube than that in tangential direction during pilgering. Table 3 indicates that the peak values of $TC_{(0002)}$ has been reached in the radial direction where as peak values of $TC\left(10\bar{1}0\right)$ can be observed in the longitudinal or rolling direction of the tubes. With the completion of the fourth and final stage of fabrication the average values of *f*-parameter for the basal poles (f_r) are 74%, 23.5% and 4% along the RD, TD and LD, respectively.

The average values of the sum of f_r, f_t and f_l has also been calculated and presented in Table 4. At all stages of examination maximum variation in the sum total f (=$f_r + f_t + f_l$) is within 0.98–1.04.

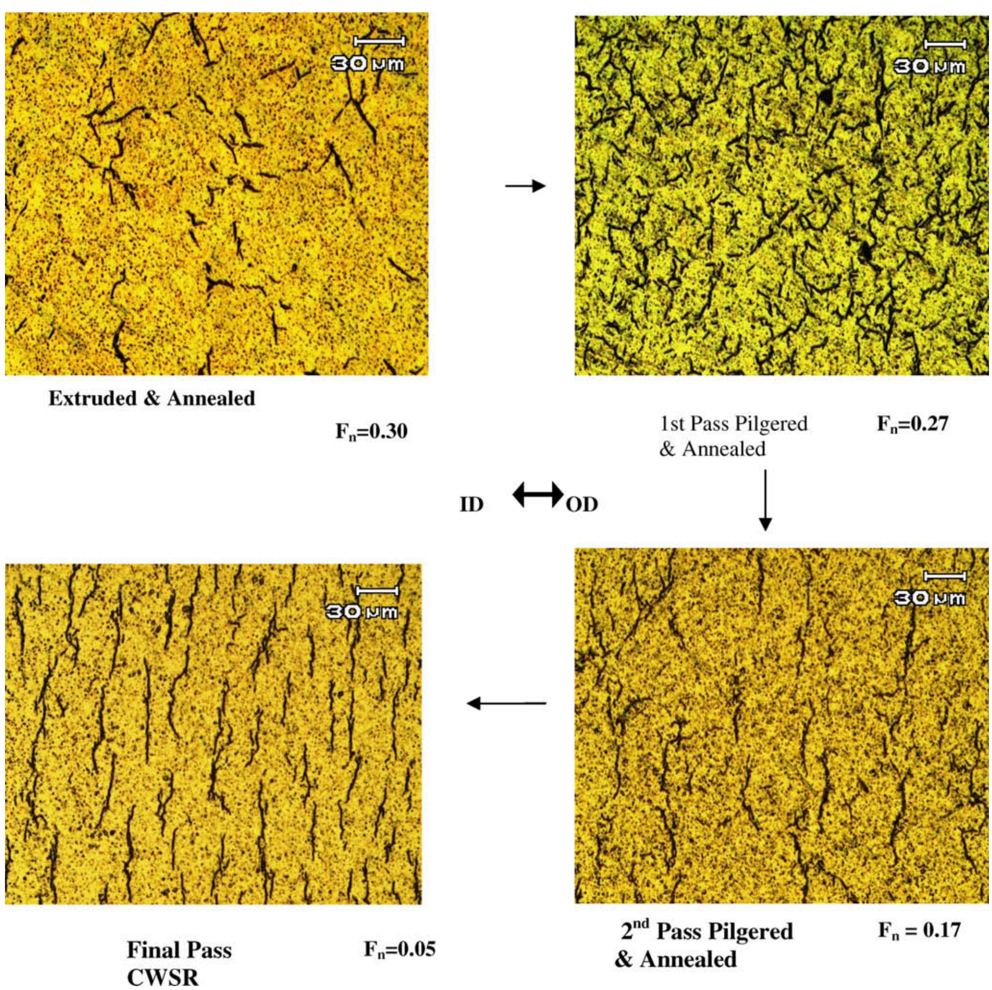

Fig. 3. Micrographs of hydrided samples of Zircaloy-4 tubes at four stages of fabrication.

The maximum variation has been observed for 17 mm OD × 1 mm WT tube samples. These variations are normally expected due to possible texture gradient through wall thickness of the tube and normally acceptable [8].

3.2. Hydride orientation (F_n number) analysis

An average of 100–125 ppm of hydrogen was charged into the samples taken from tubes after each stage of fabrication. The optical micrographs of hydrided specimens for each lot at four stages of fabrications were recorded and presented in Fig. 3. The precipitation of zirconium hydrides with given texture condition of the tube can be observed. The micrographs of the specimens under the condition of slow furnace cooling show characteristic precipitates in the form of single platelets or elongated group of platelets. The F_n number has been tabulated along (0002) basal plane Kearns *f*-parameter in Table 4. F_n *number* results show a clear consistency in a particular stage of fabrication for three different Zircaloy-4 tube lots under examination. As can be seen in Fig. 3, the hydride density is very less in the as extruded and annealed condition of tube samples also they are having random in orientation. This observation is in agreement with highest F_n values obtained in this stage (Table 4). The randomness of hydride precipitates gradually appear to be reduced and hydride platelets are found to be aligned in vertical, i.e. the circumferential directions of the tubing after each stage of fabrication. The gradual decrease in the F_n values from 52 mm OD × 9 mm WT tube sample to the final 15.4 mm × 0.4 mm WT tube is the quantitative indication of the texture development. In final cold work stress relieved condition of Zircaloy-4 fuel clad tube F_n number was found to be drastically reduced ranging between 0.03 and 0.05 (Table 4).

The orientation of the hydride platelets in the Zircaloy-4 is a function of crystallographic texture, stress distribution within the component and grain shape [9,10]. There exist a definite crystallographic relationship between the hydride platelets and the HCP-α in Zircaloy-4. The Zircaloy-4 has only habit plane $(10\bar{1}7)$ for hydride [9]. In the present study the precipitation of hydrides in the samples of the first three stages of fabrication takes in annealed condition where residual stress were negligible at the same time the single phase α- grains are equiaxed in shape. Hence the crystallographic texture would be the most affecting factor during the orientation of hydrides. Therefore in the absence of stress and the influence of grain boundaries the hydrides are oriented on the $(10\bar{1}7)$ habit plane closest to the (0002) basal plane at an angle of 14°. From Tables 3 and 4, it is observed that the Kearns *f*-parameter the basal pole gradually orient more and more in radial direction (RD), i.e. basal planes along the circumferential direction. Therefore the precipitated hydrides orient along the basal plane in the absence of any residual stress. After the final stage of cold working the Zircaloy-4 clad tubes have been stress relieved at 500 °C and the grains remain elongated in rolling direction. Accordingly hydrides tend to orient along the grain boundaries.

3.3. Relationship between basal pole f-parameter and hydride orientation factor (F_n)

The basal pole Kearns *f*-parameter in radial and transverse directions (f_r and f_t) at four different stages have been plotted

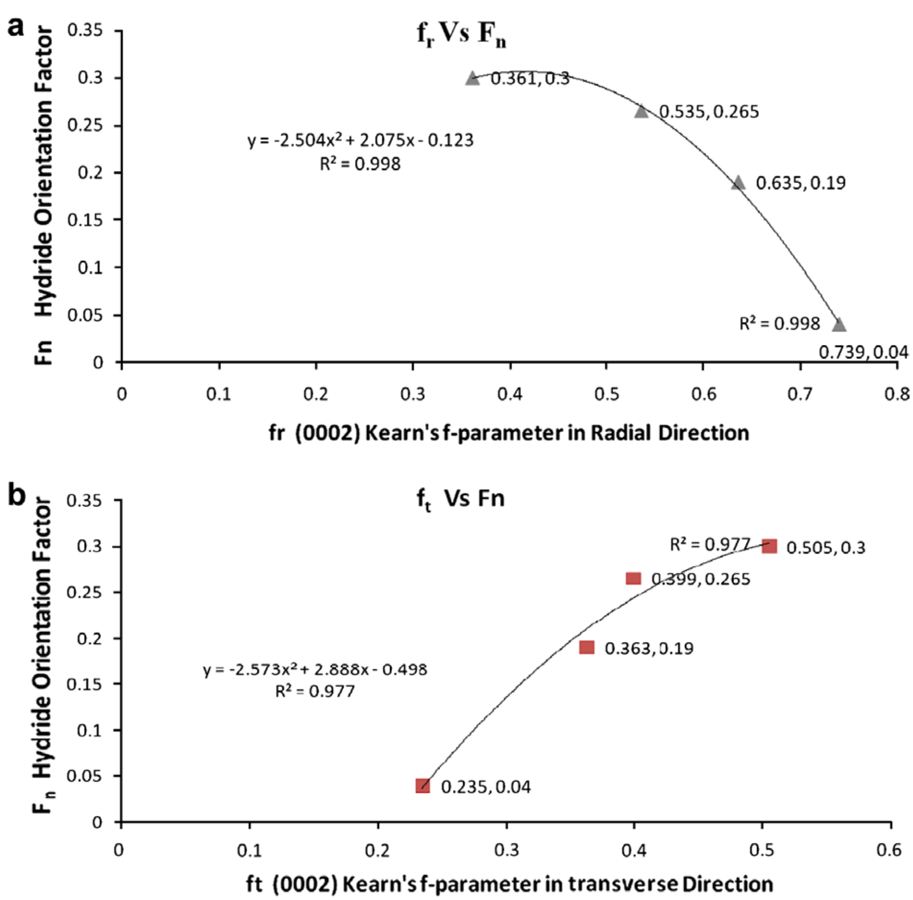

Fig. 4. (a) Graph between (0002) *f*-factor in radial direction and hydride orientation factor. (b) Graph between (0002) *f*-factor in transverse direction and hydride orientation factor.

Table 5
f_r, f_t, f_l and F_n values listed as the average of two lots nos. 1 and 2

Fab. stage	f_r	f_t	f_l	F_n
1	0.361	0.505	0.113	0.3
2	0.535	0.399	0.050	0.265
3	0.635	0.363	0.053	0.19
4	0.739	0.235	0.039	0.04

Table 6
Comparison between calculated F_n and experimental F_n for validation of empirical relations (8) and (9) for *f*-parameter and F_n number

Fab. stage	f_r (lot 3) Experimental	$F_{n\,\text{calculated}}$ (f_r vs F_n)	f_t (lot 3) Experimental	$F_{n\,\text{calculated}}$ (f_t vs F_n)	F_n Experimental
1	0.36	0.298809	0.51	0.304691	0.32
2	0.526	0.274915	0.416	0.2572	0.28
3	.63	0.189607	0.38	0.22697	0.20
4	0.747	0.028867	0.214	0.00129	0.03

against the corresponding values of hydride orientation factor, F_n. The data used in this plot (Fig. 4(a) and (b)) is an average of lot 1 and 2 (Table 5). Fig. 4(a) and (b) shows the (0002) basal pole *f*-parameters along the *X*-axis and F_n values along *Y*-axis. The variation between f_r and F_n (Fig. 4(a)) indicates the decreasing values of F_n with the increase in f_r This variation is correlated with a second order polynomial, given by

$$F_n = -2.504(f_r)^2 + 2.075(f_r) - 0.213 \quad [R^2 = 0.998]. \tag{8}$$

The correlation between f_t and F_n is shown in Fig. 4(b). This figure indicates the increasing values of F_n with the increase in f_t. The correlation is established using second order polynomial, given by

$$F_n = -2.5732(f_t)^2 + 2.888(f_t) - 0.498 \quad [R^2 = 0.977]. \tag{9}$$

The experimental values obtained for lot 3 was used for validation using Eqs. (8) and (9). Data in Table 6 can be observed to compare the calculated F_n values for lot 3 obtained using above relations with the experimental F_n values of the same lot 3. This is quite evident that the values are in close agreement and validates the variations between Kearn's *f*-parameter and hydride orientation factor for Zircaloy-4 clad tube. These relations can be of great significance during the industrial Production of Zircaloy-4 fuel clad tube for the process route. With this relationship, hydride orientation factor can be directly calculated using Kearns's *f*-parameter data. This relationship can be used in maintaining the optimum processing parameters for the fabrication of Zircaloy-4 fuel clad tube.

4. Conclusions

(1) The 15.4 mm OD × 0.4 mm WT Zircaloy-4 fuel clad tube for 220 MWe pressurized heavy water reactors (PHWRs) is manufactured with a combination of thermo-mechanical processing. The basal pole texture coefficient value $TC_{(0002)}$ and (0002) basal pole Kearns's *f*-parameter increases consistently in the radial direction (RD) of the tubing during the course of its fabrication from extruded and annealed condition to final cold work stress relieved condition.

(2) The prismatic pole texture coefficient $TC\left(10\bar{1}0\right)$ value increases consistently in the longitudinal or rolling direction (LD).

(3) The hydride orientation measured in terms of F_n number is dependent on the extent of basal poles orientations along the radial and transverse directions. A second order polynomial relationship between basal pole *f*-parameter and hydride orientation factor F_n has been developed.

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