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Influence of temperature on threshold stress for reorientation of hydrides and residual stress variation across thickness of Zr–2.5Nb alloy pressure tube

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Abstract

Threshold stress, σ_{th}, for reorientation of hydrides in cold worked and stress-relieved (CWSR) Zr–2.5Nb pressure tube material was determined in the temperature range of 523–673 K. Using tapered gage tensile specimen, mean value of σ_{th} was experimentally determined by two methods, half thickness method and area compensation method. The difference between local values of σ_{th} measured across the thickness of the tube and the mean σ_{th} values yielded the residual stress variation across the tube thickness. It was observed that both the mean threshold stress and residual stress decrease with increase in reorientation temperature. Also, the maximum value of residual stresses was observed near the midsection of the tube.

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1. Introduction

Due to low neutron absorption cross-section, high melting point, adequate high temperature strength, acceptable corrosion resistance in aqueous media, excellent compatibility with both metallic uranium and uranium dioxide fuel, good fabricability and weldability, and microstructural and irradiation stability dilute Zr-alloys find application as core structural material [1–4] in water-cooled nuclear reactors. These advantages are partially offset by difficulties in the fabrication and mechanical behaviour due to crystallographic anisotropy of the hexagonal close packed α-Zr phase, limited creep strength above the reactor operating temperature of 573 K, enhanced corrosion rate in water and steam under accidental conditions, susceptibility to hydrogen/hydride induced embrittlement and high cost. These difficulties are being overcome by involved and

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mature fabrication technology, control of alloy and coolant chemistry and detailed understanding of in-service degradation processes [5–7].

Hydrogen/hydride induced degradation of mechanical properties of Zr-alloys has been identified as a life limiting factor for Zr-alloy pressure tubes of pressurized heavy water reactors (PHWR). Though, the initial hydrogen content of the pressure tubes is kept as low as possible by controlling manufacturing process parameters [6], part of the hydrogen/deuterium evolved during service can be picked up by the pressure tube. The maximum hydrogen concentration which can be retained in solution without forming hydride precipitate, is called terminal solid solubility (TSS) [8,9]. Hydrogen present in excess of solid solubility precipitates out as hydride phase. Depending upon the hydrogen content, cooling rate and temperature of hydride precipitation, either metastable γ or stable δ and/or ε-hydrides can form in dilute zirconium alloys [7]. However, due to the cooling rate encountered by the pressure tubes under reactor operating conditions, only δ-hydride forms [7] in in-pile pressure tubes. Due to misfit strains associated with the accommodation of δ-hydride in α-Zr matrix [10,11], the former acquires platelet morphology. Being a brittle constituent, the hydride platelets make the tubes susceptible to embrittlement.

The severity of the embrittlement is strongly influenced by the orientation of the plates [7,12] as the hydride plates oriented normal to the tensile stress provide an easy crack propagation path. It is observed that the degree of embrittlement depends on the hydrogen concentration, hydride volume fraction, its size, distribution and orientation. The factors affecting δ-hydride platelet orientation in Zr–2.5Nb pressure tube material are reported [7] to be:

i. Crystallographic texture – hydride precipitation within a grain exhibits a habit plane, which makes an angle of ∼14 ° with the basal plane. The habit plane is $\{10\bar{1}7\}$ [13].
ii. Prior strain – hydride precipitation occurs on planes which are parallel to the direction of compressive strain [7].
iii. Stress – hydride precipitation occurs on planes, which are normal to the applied or residual tensile stresses [7].

During fabrication of cold worked and stress-relieved (CWSR) Zr–2.5Nb pressure tube, majority of the α-Zr grains acquire an orientation with their basal poles along the circumferential or radial direction. Thus, the texture of the pressure tube material is such that in the as fabricated condition, crystallographically only two orientations are permissible. These are along the circumferential–axial plane and along the radial–axial plane [7]. Hydride platelets oriented along the circumferential–axial plane are called circumferential hydrides and those oriented along radial–axial plane are called radial hydrides. These orientations of hydrides have been illustrated by the schematics in Fig. 1. Under unstressed condition, only circumferential hydrides form in Zr–2.5Nb pressure tubes [7,14–16]. However, due to stress reorientation phenomenon, radial hydrides may precipitate and being oriented normal to hoop stress direction [14–16] of the pressure tubes, can significantly increase the latter's susceptibility to failure [7,12].

The phenomenon of reprecipitation of hydrides with a different orientation, when cooled under stress from solution annealing temperature, than in the unstressed condition is known as stress-reorientation of hydrides [7,14–16]. For dilute Zr-alloy pressure tubes this translates to precipitation of radial hydrides under hoop stress as compared to the precipitation of circumferential hydrides in the unstressed condition. This is usually associated with a critical stress called threshold stress below which no reorientation occurs [7,12,14–16]. Though, threshold stress is reported to increase with material strength, it is reported to decrease with increasing solution annealing temperature [7]. The role of solution annealing temperature is two fold. Firstly, to control the dissolved amount of hydrogen at the reorientation temperature and secondly to anneal the dislocation debris around the pre-existing hydrides, which is reported to impart memory effect to subsequent hydride precipitation [7]. It is felt that the pre-existing hydrides and/or the dislocation debris around the pre-existing hydride plates during the reorientation process will influence the threshold stress and hence the degree of reorientation.

The objective of the present investigation was to determine the threshold stress for cold worked and stress relieved Zr–2.5 wt%Nb pressure tube material, charged with controlled hydrogen concentration and under controlled solution annealing and reorientation temperature. Leger and Donner [14] based on their observation of the existence of a marked boundary between the radial and circumferential hydrides across the thickness of the pressure

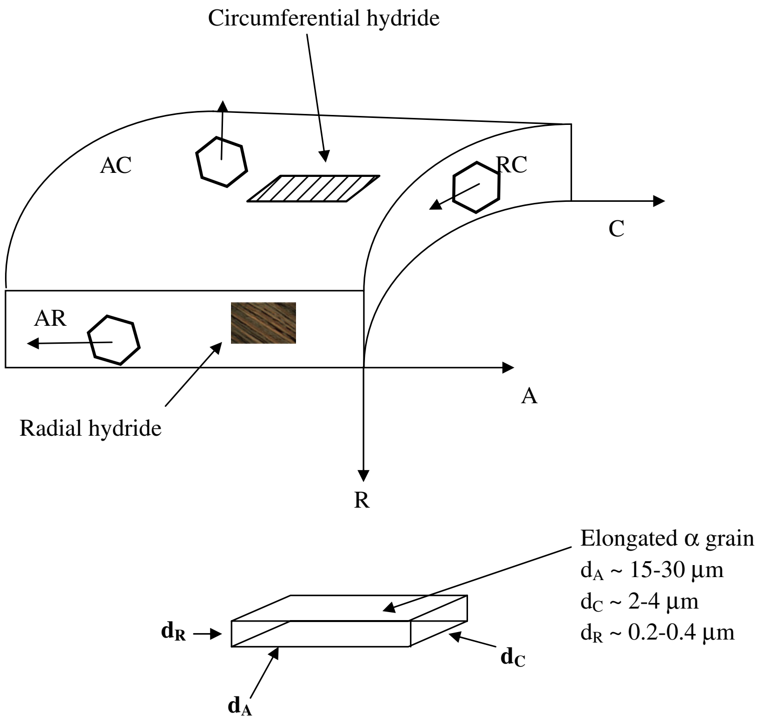

Fig. 1. Schematic of a section of pressure tube showing the orientation of circumferential and radial hydrides [7] and typical α phase grain dimensions [18] observed in Zr–2.5Nb pressure tube alloy. A – axial, C – circumferential and R – radial directions. AR – axial–radial, RC – radial–circumferential and AC – axial–circumferential planes. Both circumferential and radial hydride orientations are also illustrated in this figure. d_A, d_R and d_C are dimensions of α-Zr grains along axial, radial and circumferential directions, respectively.

tubes reported the variation in threshold stress across the pressure tube thickness and have attributed it to the residual stresses in these materials [17]. The difference between the mean threshold stress value and the local threshold stress across the thickness yielded the residual stress variation across the pressure tube thickness.

2. Experimental

2.1. Material

The Zr–2.5Nb pressure tubes of Indian 500 MWe PHWRs, are manufactured by a fabrication route similar to the modified route II followed by AECL [18,19]. The material was received from Nuclear Fuel Complex, Hyderabad, in the form of tubes of length 130 mm, diameter 103 mm and wall thickness 4.5 mm. Composition analysis indicated niobium and oxygen content to be 2.54 wt% and 0.1175 wt%, respectively. Hundred millimeter wide sections were slit from these tubes, cold flattened by continuous bending and stress-relieved at 400 °C for 24 h. For determination of threshold stress for reorientation, tensile specimens with tapered gage and with specimen axis along the circumferential direction of the tube were fabricated as per the drawing given in Fig. 2. The taper angle yielded a stress ratio of three between the maximum

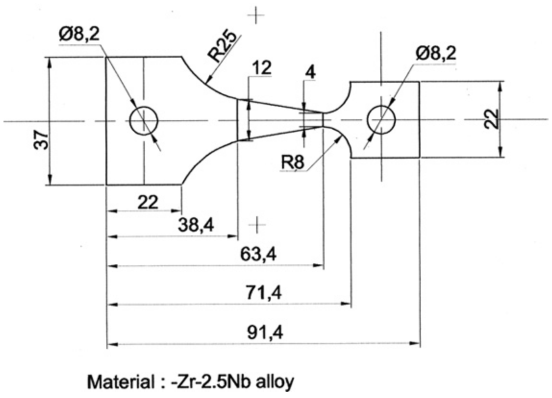

Fig. 2. Sketch of the tapered gage tensile specimens used in the present investigation for determination of threshold stress associated with the reorientation of hydrides (all dimensions are in mm).

and minimum stresses. These specimens were successively polished up to 1200 grit silicon carbide abrasive paper to obtain a fresh, contamination free surface. Subsequently the specimens were gaseously charged with about 32 or 73 wt ppm of hydrogen in a modified Sievert's apparatus. The average hydrogen content of the samples was estimated from the difference between the initial and the final pressure readings recorded during hydrogen charging process. However, small samples were obtained from the tapered gage tensile specimens subjected to reorientation treatment and analysed for hydrogen content by inert gas fusion (IGF) technique. Through out this manuscript, the values of hydrogen content shown in parenthesis are those obtained from IGF technique and the number before parenthesis are the mean hydrogen content estimated from modified Sievert's apparatus.

2.2. Stress reorientation treatment

The tapered gage specimens were subjected to stress reorientation treatment in a single arm lever type, creep-testing machine under a constant load. The lever advantage was 1:17. The reorientation treatment consisted of solution annealing at a predetermined temperature (to take all the hydrogen in solution and to anneal out the dislocation network around hydrides [7]), cooling from solution annealing temperature to reorientation temperature (to have maximum amount of hydrogen in solution during reorientation process [8,9]), soaking at reorientation temperature (to allow for thermal equilibrium) and cooling under load from the reorientation temperature to ambient temperature (to facilitate reorientation of hydrides). The solution annealing temperatures were 573, 673 and 723 K and the reorientation temperatures were 423, 473, 523, 573, 623 and 673 K. For reorientation tests at 423–523 K, the specimens were solution annealed at 573 K, for reorientation treatment at 573 and 623 K, specimens were solution annealed at 673 K and for reorientation test at 673 K the specimen was solution annealed at 723 K. For all the tests, the specimens were soaked for an hour at the solution annealing temperature, cooled to the reorientation temperature at a cooling rate of 1 K/min, soaked at the reorientation temperature for an hour, reorientation load was applied for half an hour at that temperature and the specimens were furnace cooled (less than 1 K/min) under load to the room temperature. For temperature measurement, two number of K-type thermocouples were placed in contact with the top and lower shoulder of the specimens.

2.3. Microstructure

The as-received pressure tube microstructure was examined under transmission electron microscope (TEM). The samples for TEM examination were prepared by electro-jet polishing. TEM samples were jet polished using 20% perchloric acid in methyl alcohol at 243 K and at an operating voltage of 20 V. The faces of the TEM foils of as-received material were parallel to the axial–radial (AR), radial–circumferential (RC) and circumferential–axial (CA) planes of the pressure tube. Standard metallographic technique was followed to reveal the hydride microstructure, its morphology and distribution using optical microscopy with the specimens etched in a solution of HF:HNO_3:H_2O: 2:9:9 for 15 s. In order to observe the hydride morphology its size and distribution, the samples were prepared with faces parallel to the radial–circumferential and radial–axial plane of the pressure tube. Both the radial and the circumferential hydrides were examined under SEM in secondary electron and back scattered modes to observe their detailed features. The specimens used for optical microscopy were also examined under scanning electron microscope (SEM) in secondary electron mode. These samples were repolished and etched lightly before SEM examination in back scattered mode. For determining the threshold stress for reorientation [12,14] of hydrides, the tapered gage tensile specimens, subjected to reorientation treatment were sectioned along its axis (i.e. along the circumferential direction of the pressure tube). A montage was prepared for the cross-section (radial–circumferential plane of the tube) of tapered specimens by taking photographs at a magnification of 30. The boundary between the circumferential and radial hydrides was identified to determine the threshold stress for reorientation of hydrides.

2.4. Threshold and residual stress determination

Ideally one would expect a point transition from circumferential orientation of hydrides to the radial ones for the Zr-alloy pressure tube materials. However, due to crystallographic and thermal anisotropy and also due to heavy cold work, large residual stresses are observed in the Zr-alloy pressure tube material [17]. One of the consequences of the large residual stress is that there exists a range of stresses at which both circumferential and radial hydrides co-exist across the thickness of the tube. Thus there exist two threshold stresses – a lower threshold and upper threshold [20]. The regions having tensile residual stress exhibit a lower threshold stress whereas the regions having compressive residual stresses show upper threshold stress for the reorientation of hydrides. A unique value of the threshold stress called mean threshold stress for reorientation of hydrides in dilute zirconium alloys is determined by two methods, viz. half thickness methods and area compensation method [14]. The half thickness method suggests mean threshold stress as the stress corresponding to which 50% of the thickness of the specimen contains radial hydrides. The half thickness method is simple and provides quick estimation of the mean threshold stress for reorientation of hydrides. The area compensation method is more scientific and rigorous [14]. The determination of mean threshold stress by area compensation method requires drawing a tie line along the thickness of the specimen and identification of a transition curve defined as the boundary between the regions containing circumferential and radial hydrides. The area compensation method is based on the principle that the areas under the tensile and compressive stress regions are equal. The area compensation takes threshold stress as the stress corresponding to a tie line for which the areas (bound by the transition curve and the tie line) on both sides of the tie line are equal [14].

In this study mean threshold stress was determined by both the methods. The externally applied stress variation was computed for the montage (prepared for the cross-section of tapered specimens). In an earlier study on the stress reorientation of hydrides in this alloy by Singh et al. [12], the thickness of cold flattened plates were reduced to obtain flat specimen. However for this study, the stock thickness of the pressure tube material was retained to facilitate mean threshold stress determination by area compensation method. The residual stress was taken as the difference between the threshold stress across the thickness and mean threshold stress obtained by area compensation method.

3. Results

3.1. Microstructure

The current fabrication route of the pressure tubes imparts a duplex microstructure of elongated, hcp α phase grains and a nearly continuous grain-boundary network of bcc β phase [18,19]. Fig. 3 depicts the microstructure of the Zr–2.5Nb pressure tube material for three orthogonal planes (a) AR, (b) CA and (c) RC as illustrated by schematic in Fig. 1. As can be seen from Fig. 3, the α grains are highly elongated along axial direction. Typical grain dimensions are 15–30 μm along axial, 2–4 μm along circumferential and 0.2–0.4 μm along

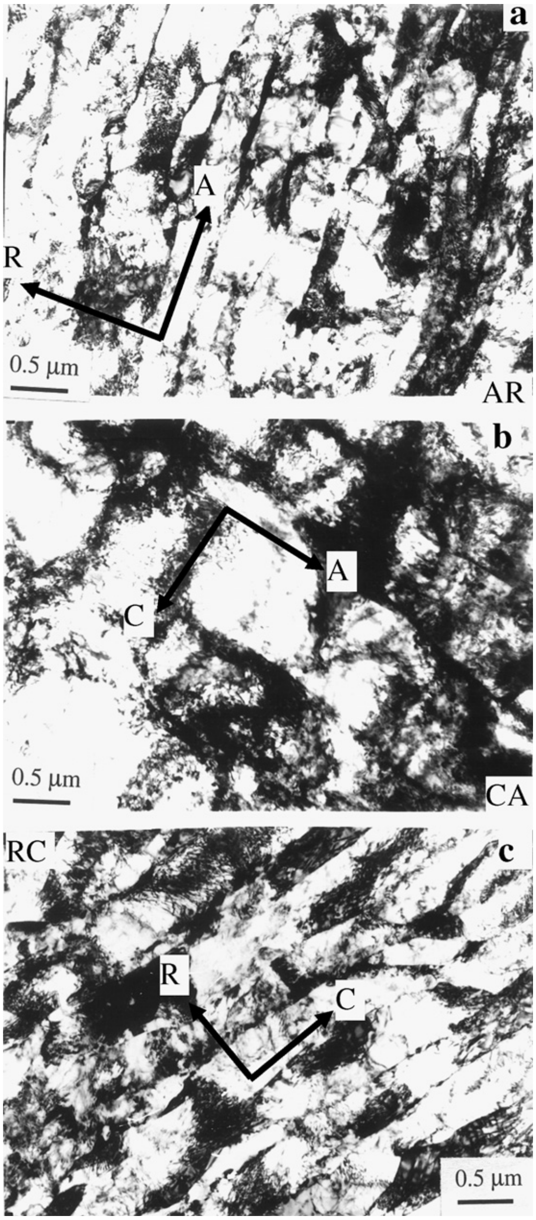

Fig. 3. Transmission electron micrographs representing the as-received microstructure of the pressure tube along (a) AR, (b) CA and (c) RC plane.

radial direction [18]. The α grains are highly textured with basal poles predominantly oriented either along circumferential direction (about 54%) or along radial direction (about 43%) [21] of the tube.

The microstructural features of hydrides observed under optical microscope on two orthogonal planes (AR and RC planes) of the Zr–2.5Nb pressure tube material, which were charged with about (a) 32 (41) and (b) 73 (60) ppm by wt of hydrogen, are shown in Fig. 4. This figure shows that in the as-hydrided condition, hydride plates (dark lines) are oriented along the circumferential–axial plane only. These hydrides are called circumferential hydrides [7]. The trace of the hydride plate along the axial direction is relatively straight as compared to that along circumferential direction.

Fig. 5 shows the montage of the micrograph obtained from the specimen subjected to reorientation treatment at 673 K. The variation in applied stress (MPa) across the specimen axis is also shown in this figure. It may be noted in this figure that hydride platelet exhibit only two orientations. Such a preferential precipitation of hydride orientation is attributed to the microstructural features of the pressure tubes such as grain-boundary orientation and nature of residual stresses [7].

Fig. 6 shows the radial (a, b) and circumferential (c, d) hydride plates as seen under scanning electron microscope in secondary electron mode (a, c) and in backscattered mode (b, d). It is evident from this figure that the hydride plates which appear as single continuous line under optical microscope comprises of several smaller platelets. Also, the radial hydride appears to be comprising of smaller platelets as compared to circumferential hydrides.

3.2. Threshold and residual stress

The stress reorientation treatment details such as hydrogen content estimated from Sievert's apparatus (hydrogen content estimated by IGF technique are shown in parenthesis), solution annealing temperature, reorientation temperature and mean value

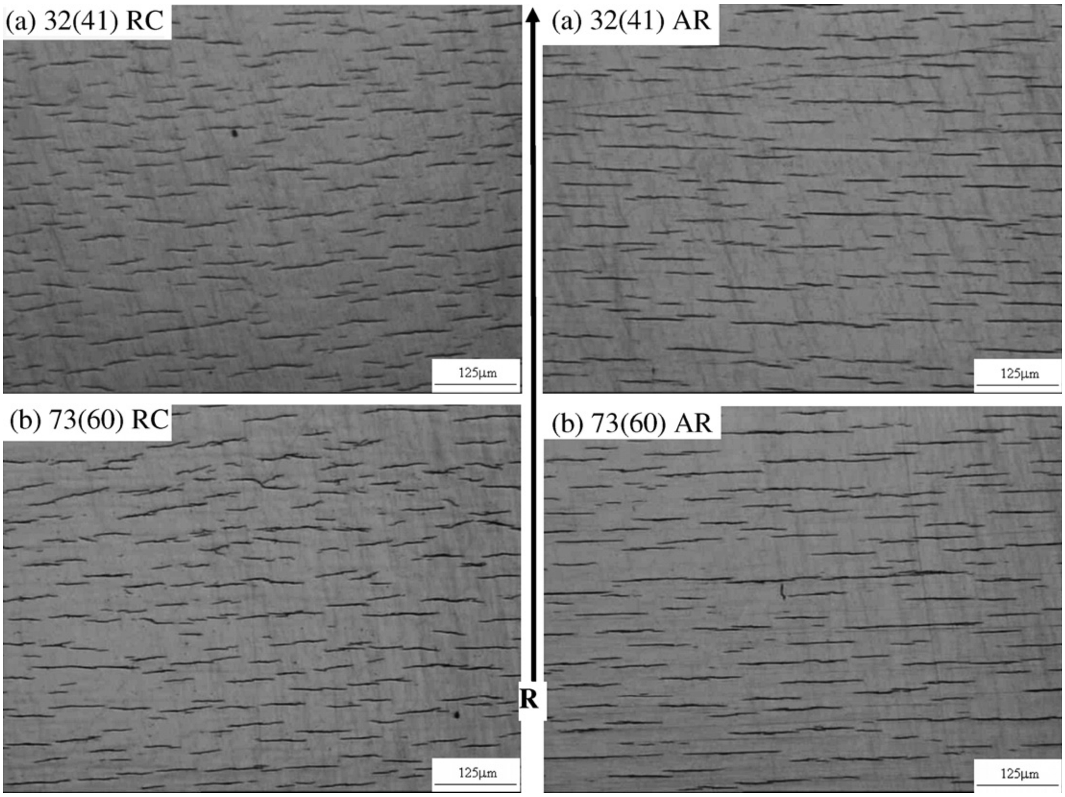

Fig. 4. The microstructural features of traces of hydrides on two orthogonal planes (AR and RC) of Zr–2.5Nb pressure tube alloy charged with (a) 32 (41) and (b) 73 (60) ppm of hydrogen. The orthogonal planes are defined in Fig. 1. For higher hydrogen concentration the hydride platelets become longer and thicker. Arrow shows the radial direction and axial or circumferential direction in these micrographs is normal to it.

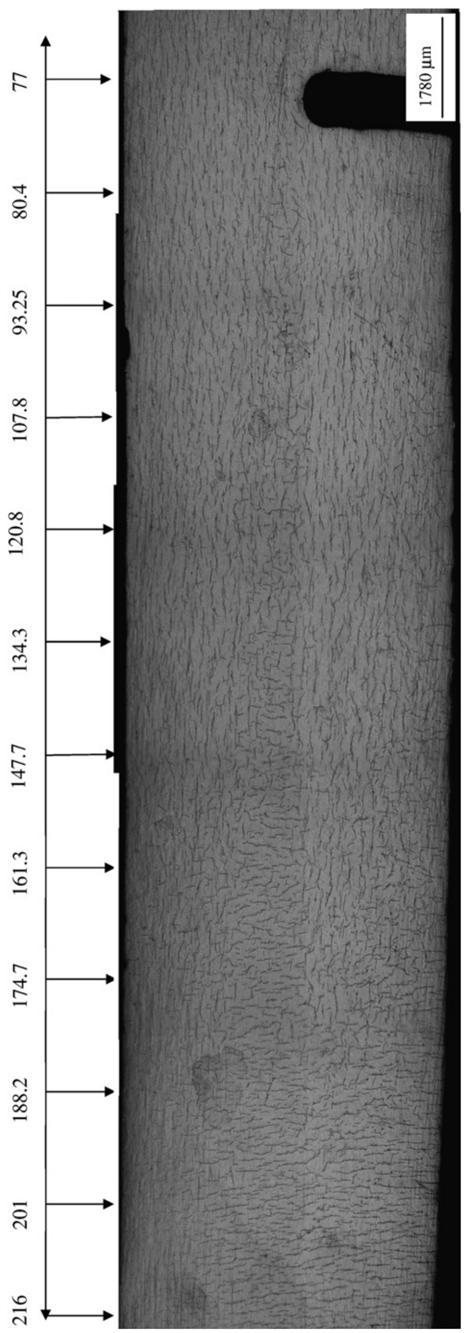

Fig. 5. Montage of the hydride micrographs showing the variation in hydride orientation across the gage length of tapered gage tensile specimen subjected to reorientation treatment at 673 K. The numbers above the montage represent the externally applied stress in MPa during the reorientation treatment.

of threshold stress obtained from half thickness and area compensation method are shown in Table 1. Fig. 7 shows the variation of the mean threshold stress with reorientation temperature and is observed to decrease with increase in reorientation temperature. Also plotted in this figure for comparison is the mean threshold stress value for this alloy reported by Singh et al. [12]. Fig. 8 shows the variation in residual stress across the thickness of the pressure tube at various reorientation temperatures. It was observed that the residual stresses are tensile near the inside diameter of the tube whereas these are compressive towards the outer diameter of the tube. Both the peak residual tensile and compressive stresses were observed to decrease with increase in reorientation temperature.

4. Discussion

4.1. Hydride morphology

For a given hydrogen content two features of the traces of hydride on radial–axial plane and that on the radial–circumferential plane of the pressure tube are to be noted (Fig. 4). Firstly, the trace on radial–axial plane is straighter and longer as compared to the trace on radial–circumferential plane. This is expected because the longer α phase grain dimension along axial direction of the pressure tube [18] provides uninterrupted growth along axial direction. The branching of the hydride on the radial–circumferential plane is due to shorter grain dimension along the circumferential direction [18] of the pressure tube (Figs. 1 and 3). Since hydrides always precipitate along the habit plane [13], which are nearly parallel to the basal plane, for the texture of the pressure tube [18,21] one out of every three α phase grains will have favorable texture for precipitation. Thus hydrides cannot grow straight along the circumferential direction and instead it will branch out every 3–5 μm to grow along the favorably oriented grains [12]. With increase in hydrogen content, the length of the hydride platelets increases though there is no significant change in interplatelet spacing. This can be understood in terms of the stress field generated around a hydride platelet [11]. The stresses generated at the edge of the platelet are tensile in nature and hence, it will be energetically more favorable for an existing platelet to grow rather than the nucleation of a new precipitate.

Interesting microscopic details of the radial and circumferential hydride plates are brought out in Fig. 6. The hydride plates, which appear as a single entity under optical microscope, show two submicroscopic levels of organization. At platelet level

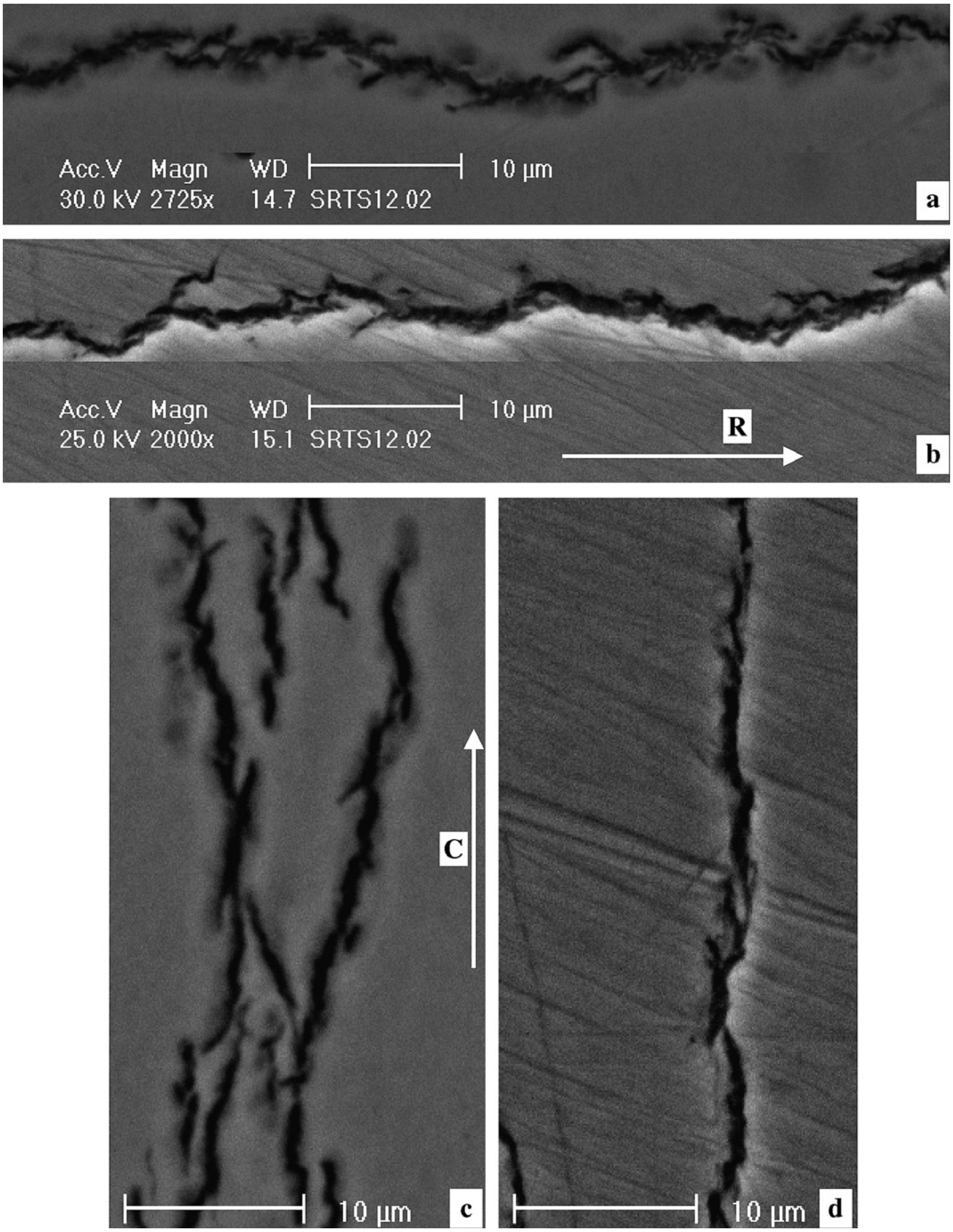

Fig. 6. Internal details of radial (a, b) and circumferential (c, d) hydride as observed in secondary electron (a, c) and in back scattered (b, d) mode for the specimen solution annealed at 673 K and subjected to reorientation treatment at 623 K.

of organization, the hydride plates comprise of several smaller hydride platelets stacked with a near parallel orientation with respect to each other. At sub-platelet level of organization each hydride platelet was observed to be comprising of several tiny sub-platelets stacked closely either laterally or end to end. The circumferential hydride plates exhibited both platelet and sub-platelet level of organization whereas the radial hydride plates exhibited only sub-platelet level of organization. Considering the fact that the α-Zr grains in CWSR pressure tube materials are only 0.2–0.4 µm thick [18], within even a few µm one can expect to find several α-Zr grains satisfying the habit plane for

Table 1
Threshold stress for reorientation of hydrides in Zr–2.5Nb pressure tube alloy along with reorientation parameters used in the present investigation

Sr. no.	Test ID	H-content (ppm)	Solution annealing temperature T_s (K)	Reorientation temperature T_r (K)	σ_{th} (MPa) (half thickness method)	σ_{th} (MPa) (area compensation method)
1	SRT-16	32(41)	573	423	Reorientation not obtained	Reorientation not obtained
2	SRT-17	32(41)	573	473	Reorientation not obtained	Reorientation not obtained
3	SRT-18	32(41)	573	523	235	238
4	SRT-19	73(60)	673	573	189	193
5	SRT-20	73(60)	673	623	163	177
6	SRT-21	73(60)	723	673	148	140

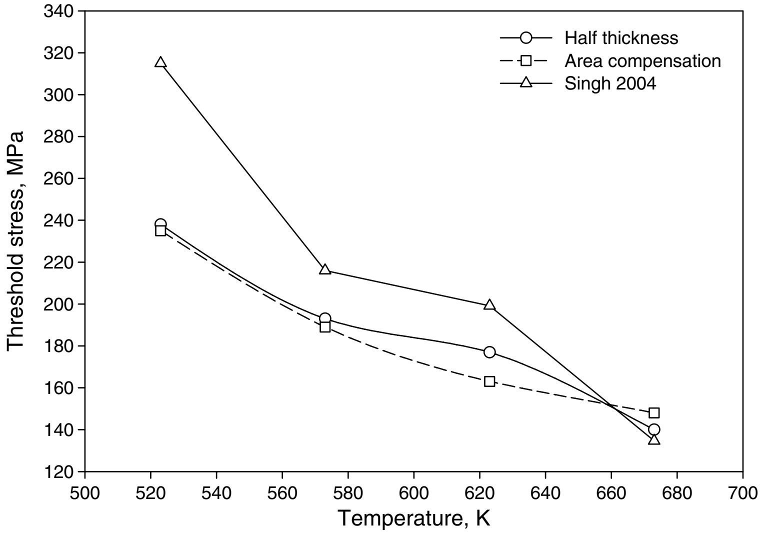

Fig. 7. Variation in mean threshold stress with reorientation temperature.

hydride precipitation. This possibly is the reason for circumferential hydrides exhibiting platelet level of organization (Fig. 6(c)). The α-Zr grain dimension normal to radial hydrides is about 2–4 μm and hence within few μm the probability of finding α-Zr grains with favorable habit plane for hydride precipitation will be very low, which could be the reason for the absence of platelet level of organization for radial hydrides. Another feature to be noted is the fact that the length of the hydride sub-platelet forming a hydride platelet is much smaller for radial hydride as compared to that for circumferential hydrides. This can also be understood in terms of the α-Zr grain dimensions. Since circumferential hydride subplatelets grow along circumferential direction of the pressure tube, with α-Zr grain dimension of 2–4 μm, its length is expected to be longer as compared to that of the radial hydride sub-platelets which grow along radial direction of the pressure tube, with α-Zr grain dimension of 0.2–0.4 μm.

Based on the orientation of hydride plates, the montage shown in Fig. 5 can be divided into two region regions, viz., region containing traces of circumferential hydrides (horizontal dark lines) and the region containing traces of radial hydrides (vertical dark lines). Such a selective formation of either circumferential or radial hydride shows that hydride precipitation is very sensitive to effective stress (applied stress + residual stress) prevailing in the material. This is in conformity to observation by Ells [15] and computation by Puls [22] that orientation of hydride plates formed under stress is decided during the nucleation stage of hydride precipitation. Once hydride nuclei of particular orientation form, its growth is energetically more favorable

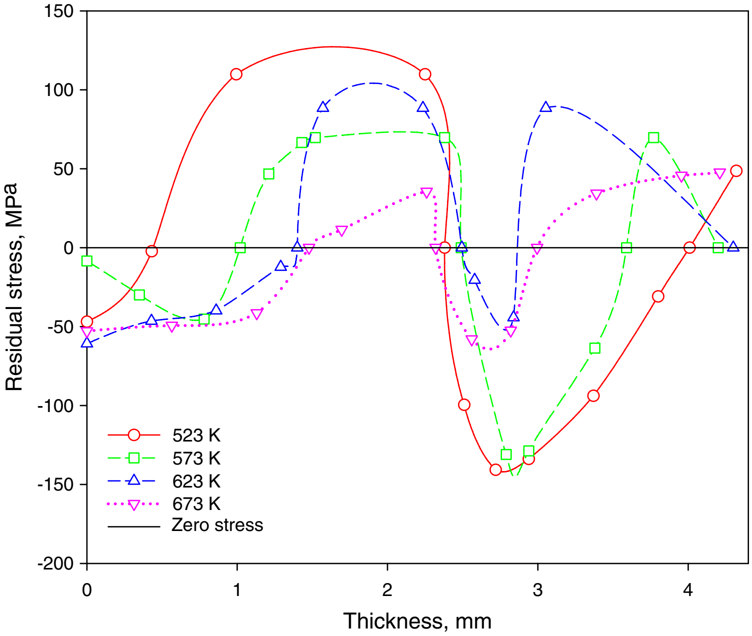

Fig. 8. Variation in residual stress across the thickness of the pressure tube at various reorientation temperatures.

than the fresh nucleation. However, the boundary region in Fig. 5 contains traces of both circumferential and radial hydrides. Also, the traces of hydrides in the boundary region are smaller than the selectively precipitated region. This probably could be due to simultaneous nucleation of both circumferential and radial hydrides in the boundary region – within a very narrow range of effective stress prevailing in the material for which the probability of formation of hydrides of both the orientation are comparable.

4.2. Threshold stress, σ_{th}

The threshold stress for reorientation of hydrides depends upon the yield strength of the material [7]. With increase in the yield strength of the material, σ_{th} is reported to increase. For a given alloy, as the reorientation temperature is increased, the yield strength decreases and hence σ_{th} is also expected to decrease with increase in reorientation temperature. In the present investigation also, σ_{th} is observed to decrease with increase in reorientation temperature. In Fig. 7 the σ_{th} values determined in the present investigation are compared with those reported by Singh et al. [12]. It can be seen in Fig. 7 that the mean threshold stress values reported by Singh et al. [12] are in good agreement with the values reported in the present investigation at reorientation temperatures of 623 and 673 K but are higher at reorientation temperatures of 523 and 573 K. It is felt that stress reorientation of hydrides is influenced by the solution annealing temperature. The role of solution annealing temperature is two fold; to dissolve hydrides and to anneal the dislocation network around pre-existing hydride sites [7]. For a solution annealing temperature higher than the critical value at which not only all the hydrides are in solution but the dislocation networks are also fully annealed, hydride precipitation under a stress comparable to the threshold stress, will exhibit equal probability for the precipitation of both radial and circumferential hydrides and hence one can expect to observe lowest value of mean threshold stress. If the solution annealing temperature is lower than the critical value, either the pre-existing circumferential hydrides or the dislocation network will facilitate the formation of circumferential hydrides as compared to the radial hydride and therefore, the threshold stress values determined in such a case will be higher than the values determined with solution annealing temperature above the critical value. Since in the samples used by Singh et al. [12] for determination of the mean σ_{th} the hydrogen content was higher than 100 wt ppm the presence of circumferential hydrides at the reorientation temperature of 523 and 573 K necessitated higher mean threshold σ_{th} values as compared to the present investigation.

4.3. Residual stress variation across tube thickness

Fig. 8 shows the variation in residual stresses across the thickness of the pressure tube. In the present investigation the tube sections were cold flattened for the fabrication of tapered gage tensile specimens. The cold flattening did not result in a flat sample. As a result, the tapered gage sample did have some curvature across the specimen axis. The observance of non-zero residual stress at the inside and outside surface could probably be due to the curvature of the tapered gage specimen [14]. Based on the residual stress variation across the tube thickness, entire thickness of the tube can be divided into four regions. The region of the tube near the inside diameter is under small compressive residual stress, which is followed by the region with large tensile residual stresses. The region of the tube near the outer diameter is under small tensile residual stresses, which is followed by a region with large compressive residual stresses. It may be noted that due to exponential dependence of terminal solid solubility of hydrogen in these alloys [8,9] on temperature, during the reorientation process, hydride nuclei form under stress at or near the reorientation temperature, and at lower temperatures growth of existing hydrides will be more probable rather than fresh hydride nucleation [22]. As a result the hydride orientation obtained during the reorientation process is expected to carry the signature of the residual stress present at or near the reorientation temperature. As the maximum residual stress will be limited by yield strength of the material, with increase in reorientation temperature the yield stress decreases and hence residual stress also decreases with increase in reorientation temperature. Thus hydride orientation can be used as an inexpensive tool to map the residual stresses in the pressure tube.

It is evident from Fig. 8 that in the midsection of the CWSR Zr–2.5Nb pressure tubes, at 523 K, the maximum residual tensile and compressive stresses could be of the order of 100 MPa and 150 MPa, respectively. Since the mean threshold at 523 K is ~235 MPa, residual stress cannot alone be responsible for reorientation phenomenon. The consequence of the residual stresses is that there can be two limiting values of threshold stress; lower and upper threshold stresses. The lower threshold stress corresponds to the region of the tube where residual stresses are tensile in nature, whereas the upper threshold stress corresponds to the region where the residual stresses are compressive [20]. As a result of this, for complete reorientation to occur across the entire thickness of the tube upper threshold stress needs to be exceeded during reorientation treatment. In other words for the reorientation stress in between lower and upper threshold stresses, the degree of reorientation, defined as the fraction of tube thickness containing radial hydrides, will increase with increase in reorientation stress.

5. Conclusions

The threshold stress for the reorientation of hydride was observed to vary across the thickness of the cold worked and stress-relieved Zr–2.5Nb pressure tube. The mean value of threshold stress for reorientation was determined by half thickness and area compensation method as a function of reorientation temperature. The threshold stresses determined by both the methods are in good agreement and were observed to decrease with increase in reorientation temperature. SEM examination of the hydrides revealed platelet and sub-platelet level of organization inside a hydride plate, which could be rationalized in terms of the α-Zr grain dimensions of the pressure tube material. The difference in the threshold stress and the mean threshold stress yielded the residual stress. For reorientation temperature of 523 K, maximum tensile residual stress was of the order of 100 MPa whereas the maximum compressive residual stress was of the order of 150 MPa. The values of the residual stress were observed to decrease with increase in reorientation temperature.

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