CHARACTERIZATION OF Zr-2.5%Nb-0.5%Cu GARTER SPRING WITH RECTANGULAR WIRE FOR 700 MWe PHWRS

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ABSTRACT- Garter spring assembly with modified corrugated girdle wire design is developed for the first time for the upcoming 700MWe Pressurized Heavy Water Reactors (PHWRs) in India. The garter spring assemblies are used to maintain gap between hot Pressure tube to cold Calandria tube in the coolant channel. Girdle wire positioned centrally through the spring and resistance welded to facilitate detection of the spring during in-service inspection using eddy current test. The new design of corrugated girdle wire is adopted in the 700 MWe PHWRs to accommodate the expansion of pressure tube during service due to diametric creep. Zr-2.5%Nb-0.5%Cu is used as material of construction for garter spring and girdle wire is made out of Zirconium alloy-4. The process of fabrication for garter spring assembly involves combination of hot extrusion and cold swaging followed by drawing with intermediate annealing operations. Finally the hook formed springs are solutionized, oil quenched followed by tempering to achieve the desired properties. The girdle wire is processed through a combination of hot extrusion and cold swaging followed by drawing with intermediate annealing operations. Finally the corrugations are formed on plain girdle wire and resistance welded to form finished assembly.

In this paper, qualification approach of garter spring assembly employing combination of destructive test such tensile test, hardness, metallography, corrosion test & chemical analysis and non-destructive tests such as ultrasonic examination, liquid penetrant examination & visual examination was brought out. Customized automated test was developed for measuring spring characteristics such as deflection measurement and measurement of residual extension.

Characterization of garter spring material w.r.t texture, strength, metallography at different stages of fabrication starting from raw material to finished hook formed spring was also brought out. At the same time it was aimed to understand the hydriding behavior and orientation of hydrides at different stages such as billet, rod, rectangular wire, hook formed spring and finished spring material. To understand the effect of hydrides on mechanical properties such as strength, elongation and hardness was also evaluated in the spring material as well as on girdle wire. A comparative study w.r.t metallurgical & mechanical property was made between as-fabricated & hydrided condition. Finally the performance of this new design with corrugated welded girdle wire as against the earlier design of plain girdle wire with one and half turn over lap was compared.

Introduction

700 MWe Pressurized Heavy Water Reactors (PHWRs) have 392nos. of coolant channels within calandria vessel, which holds heavy water moderator [1]. Each coolant channel assembly comprises of a pressure tube (PT), a calandria tube (CT) and four tight fit garter springs (GSs) to prevent PT-CT contact due to creep sag [3]. The pressure tubes, made of cold worked, stress

relieved Zr–2.5Nb alloy, serve as the primary in-core containment for the fuel and hot heavy water coolant [1-2]. Each pressure tube is surrounded by a concentric calandria tube, which separates the hot PT (approximately 297^0C) from the cold heavy water moderator. Garter springs in toroidal shape formed from Zr–2.5Nb–0.5Cu wires of rectangular cross-section and used in solutionized, quenched and tempered condition. The circular shape of the coil is retained by engagement of hooks at both the ends. The material selection of spring was based on its strength, good resilience property, excellent corrosion resistance and low neutron absorption cross section [3]. Girdle wire made of Zirconium alloy-4 is positioned concentrically through the spring and resistance welded to facilitate detection of the spring during in-service inspection using eddy current test [4]. In an earlier design of 220 MWe, two garter springs were fitted loose on the pressure tube and the spring coils were not under tension. Any displacement of GSs from their designated locations along the length of the pressure tubes may lead to contact of the PT and CT, and further lead to the associated problems of hydride blister formation and finally may cause catastrophic failure of pressure tube [2]. Further, the garter spring design was modified with tight fit to PT by having hooks at the end of the spring coil which are engaged after stretching the spring coil to a small predefined extension to avoid displacement of spring assembly from desired locations. The number of springs was increased to four. Design with four springs with overlapping plain girdle wire was adopted in 540 MWe reactors [4]. The GS being in-core component experiences high energy neutron irradiation. The performance of pressure tubes, which are a pressure boundary component, is thus affected by the integrity and correct position of GSs [1&3]. Therefore, it is essential that GS shall have adequate strength, ductility, corrosion resistance and shall retain sufficient deflection during its service life inside the reactor. So far there was no reported failure of garter spring assembly in Indian PHWRs. This is due to the development of established flow sheet for fabrication and strict adherence to the quality assurance plan.

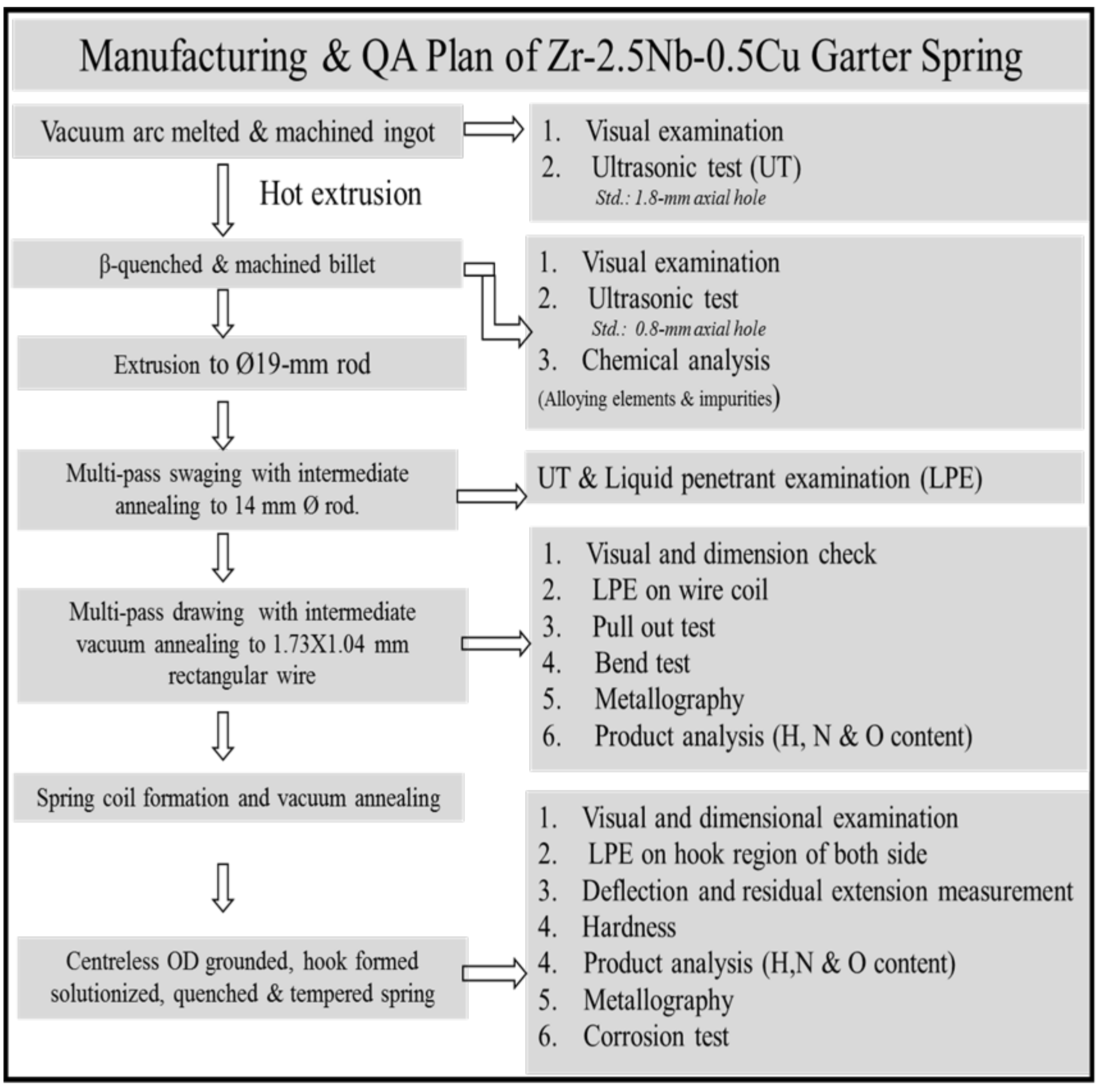
Generally, about 5% of diametric creep in PT is considered to be end of life of PT [5]. Keeping in view of diametric expansion of PT, Garter spring (Fig1a) made of Zr-2.5%Nb-0.5%Cu rectangular wire with innovative corrugated girdle wire (Fig1b) design were developed by NFC first time in world for the upcoming 700MWe Indian PHWRs to ensure easy accommodation of pressure tube expansion during service. This paper covers qualification approach of garter spring assembly.

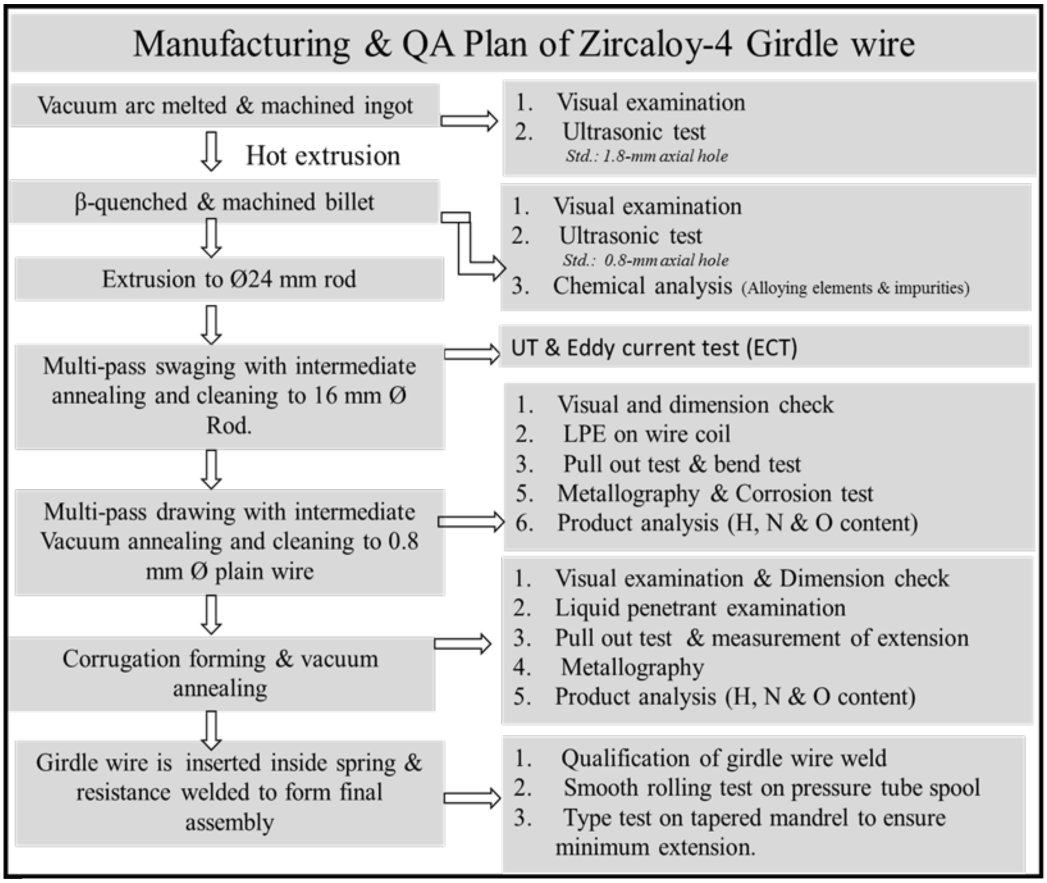
(a) (b)

Figure 1 (a) Garter spring assembly for 700 MWe PHWRs and (b) Corrugated girdle wire.

1. Manufacturing and Quality Assurance Plan of Garter Spring & Girdle Wire

The process of fabrication for garter spring assembly involves combination of hot extrusion and cold swaging followed by drawing with intermediate annealing operations. Finally the hook formed springs are solutionized, oil quenched followed by tempering to achieve the desired properties. The girdle wire fabrication is processed through a combination of hot extrusion and cold swaging followed by drawing with intermediate annealing operations. Finally the corrugations are formed out on plain girdle wire and resistance welded to form finished assembly. Detail manufacturing and QA Plans are given below.





2. Experimental Work

2.1 Zr-2.5%Nb-0.5%Cu garter spring material

In the present study samples from different stages are evaluated for microstructure, texture, hydriding and strength. Orientation of hydride and its effect on mechanical property was also investigated.

2.2 Girdle wire material

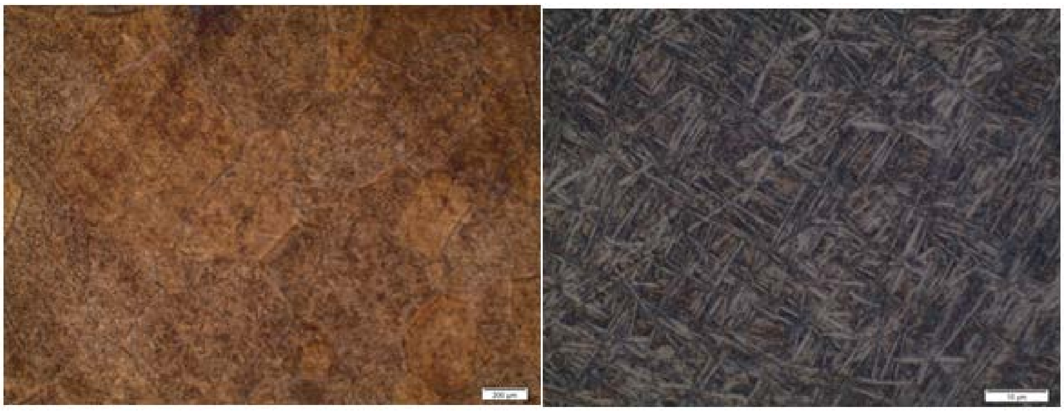
Strength and microstructural examination was carried out on Zirconium alloy-4 girdle wire. Orientation of hydride and its effect on mechanical property on both plain and corrugated girdle wire was also investigated.

2.3 Hydrogen charging Process

Specimens were charged with about 125 ppm of hydrogen by gas charging method and were heated in a vertical wall muffle furnace to a temperature of 430-450°C. Hydrogen is supplied into the metal under vacuum at 100 mbar. Sufficient incubation time was given for hydriding and specimens were gradually cooled under Argon environment.

3. Results and Discussions

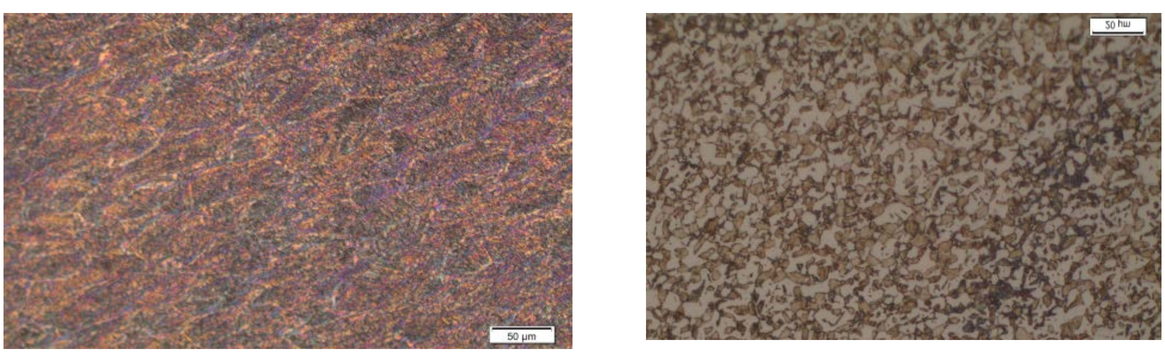
3.1 Microstructural examination of Zr-2.5%Nb-0.5%Cu garter spring material



(a) (b)

Figure 2[a-b] Optical micrographs of Zr-2.5%Nb-0.5%Cu extruded and β-quenched billet at 50x and 1000x respectively.

Both the longitudinal and transverse section of β-quenched billet revealed prior β-grain formation and the grains are found uniformly distributed as shown in the Fig.2a. Formation of Widmanstatten structure is revealed at higher magnification (1000x) as shown in the Fig.2b. Range of grain size 100 μm to 1000 μm at 50x. The width of the martensite plates are less than 1 μm.



(a) (b)

Figure 3[a-b] Optical micrographs of Zr-2.5%Nb-0.5%Cu annealed rod (14 mm Ø) and wire stage (1.73 mm X 1.04 mm rectangular wire) respectively (at 500X).

Microstructural examination of 14 mm dia. rod and wire revealed recrystallized, equiaxed and uniformly distributed grains in both longitudinal and transverse sections with two phase structure (α+β) [Fig. 3a]. The average grain size was about 20 μm in rod and very fine in wire. In wire, nearly equiaxed β phase uniformly distributed in the α-matrix was evidenced [Fig.3b].

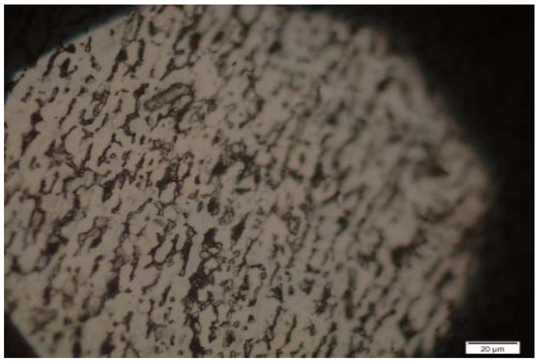


Figure 4[a] Optical micrographs showing finished Zr-2.5%Nb-0.5%Cu spring in solutionzed, quenched and tempered condition (magnification 500X).

Microstructural examination of finished Zr-2.5%Nb-0.5%Cu spring [Fig.4a] clearly revealed two phase (α+β) microstructure. Elongated lamellar β-phases were observed in the α-matrix. β-phase being softer in nature elongated over hard α-matrix resulting in elongated morphology.

3.2 Micro-structural examination of girdle wire

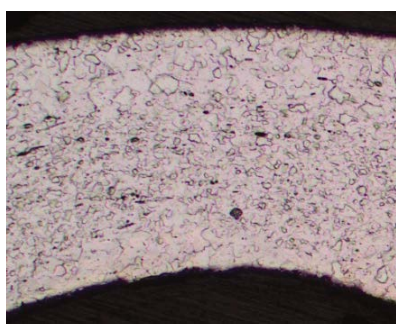


Figure 4[b] Optical micrographs showing Annealed corrugated Zirconium alloy-4 girdle wire (magnification 500X).

Microstructural examination of finished corrugated Zirconium alloy-4girdle wire in annealed condition revealed recrystallized structure [Fig.4b].

3.3 Texture measurement

Two specimens of Zr-2.5%Nb-0.5%Cu were examined for texture analysis using X-ray diffraction technique (XRD). Specimens were prepared along three perpendicular direction and subjected to XRD analysis with Cu Kα X-ray. Kearns f-parameters were calculated and the values of r_{adial} (f_r), $t_{angential}$ (f_t), longitudinal (f_a) are presented in [Table-1].

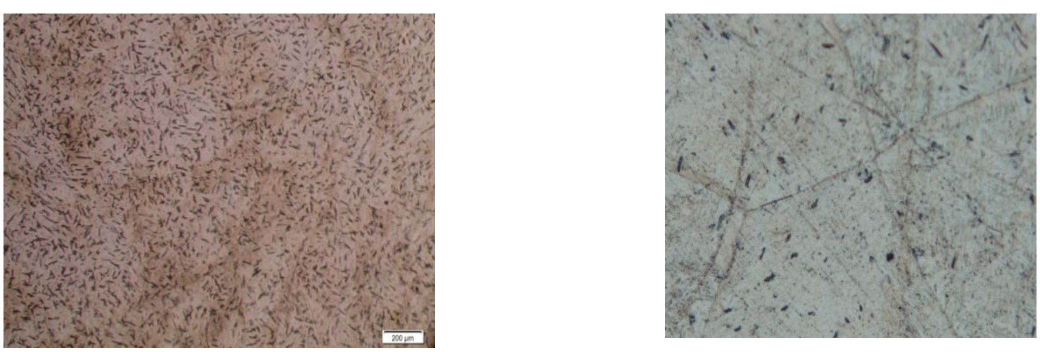
XRD results revealed completely random distribution of basal poles along the radial, tangential and longitudinal directions [Table-1]. Hence it can be stated that randomization of texture was ensured during the beta quenching operation of billet prior to second hot extrusion.

For annealed rod, distribution of basal poles was mostly oriented in radial and transverse direction and a minor fraction of basal poles were along the axial direction [Table-1]. Hot working and cold working operation on beta quenched billet to manufacture rod introduced radial-circumferential texture.

Table 1 Texture test results

Sample	Kearns f parameters		
	fr	ft	fa
Beta quenched billet	0.34	0.31	0.29
Annealed rod (Zr-2.5%Nb-0.5%Cu)	0.44	0.43	0.14
Annealed Rod (Zr-4)	0.4	0.42	0.16

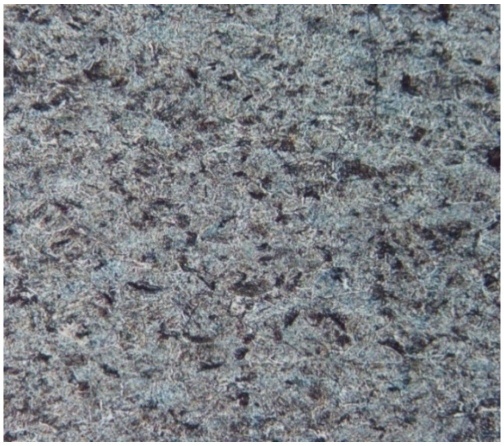
3.4 Microstructural characterization of hydrided specimens



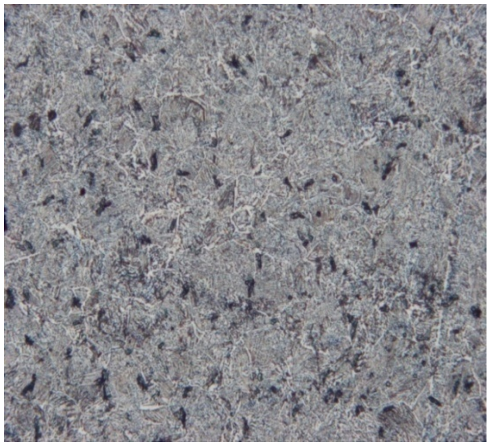
(a) (b)

Figure 5[a-b] Optical micrographs showing random hydride platelets in extruded & beta quenched billets of Zr-2.5%Nb-0.5%Cu material on artificially hydrogen charged specimen.

Optical micrographic examination of artificially hydrided specimens of hot extruded and beta quenched billets revealed completely random hydride in all the direction [Fig. 5(a-b)]. This was corroborated with the texture measurement data and re-confirmed texture randomization.



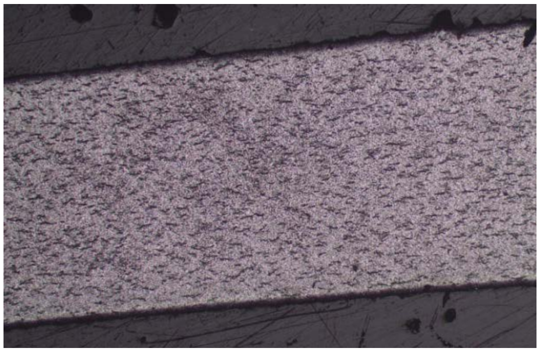
(a)



(b)

Figure 6 [a-b]: Optical micrographs showing hydride platelets oriented in radial and tangential plane in annealed Zr-2.5%Nb-0.5%Cu rod on artificially hydrogen charged specimen.

Optical microstructural examination of artificially hydrided annealed rod specimen revealed precipitation of hydride platelets in radial-tangential plane [Fig. 6(a-b)]. This observation again confirmed the texture analysis result as shown in table-1.



(a)

(b)

Figure 7 [a-b] Optical micrographs showing hydride platelets oriented in axial direction of along the axis of Zr-2.5%Nb-0.5%Cu wire on artificially hydrogen charged specimen.

Optical microstructural examination of artificially hydrided Zr-2.5%Nb-0.5%Cu wire specimen revealed precipitation of hydride platelets in axial direction only [Fig.7 (a-b)]. Hence thermo-mechanical processing of wire fabrication ensured avoiding precipitation of detrimental radial hydrides, which may otherwise affect the in-reactor performance of garter spring. In case of in-reactor hydrogen pick-up during service, precipitation of hydride platelets in the axial direction and absence of radial hydride platelets ensures desirable texture.

Optical microstructural examination of artificially hydrided hook region of finished garter spring [Fig.8] revealed precipitation of hydride platelets. Two distinguished region were seen with respect to the hydride orientation across the wire depth. Most of the wire depth has revealed hydride precipitation along the hook circumferential direction. However radial hydrides were observed at the inner side of bend radius up to small depth. This may be due to non-uniform distribution of tensile residual stress in the hook region of solutionized, quenched and tempered garter spring.

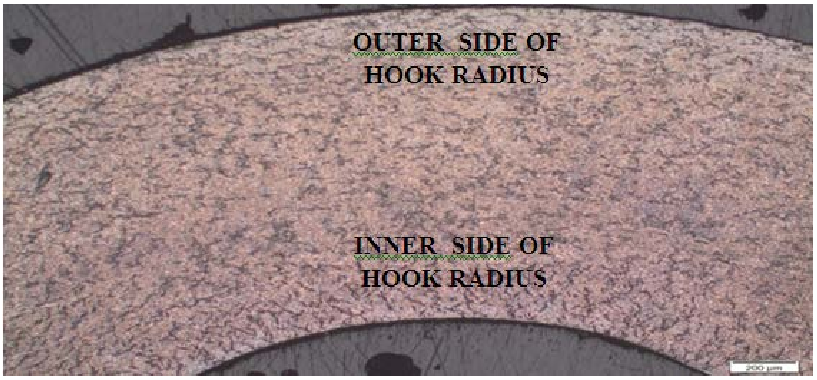


Figure 8 Optical micrograph showing hydride platelets in the hook region of Zr-2.5%Nb-0.5%Cu spring in the artificially hydrogen charged condition.

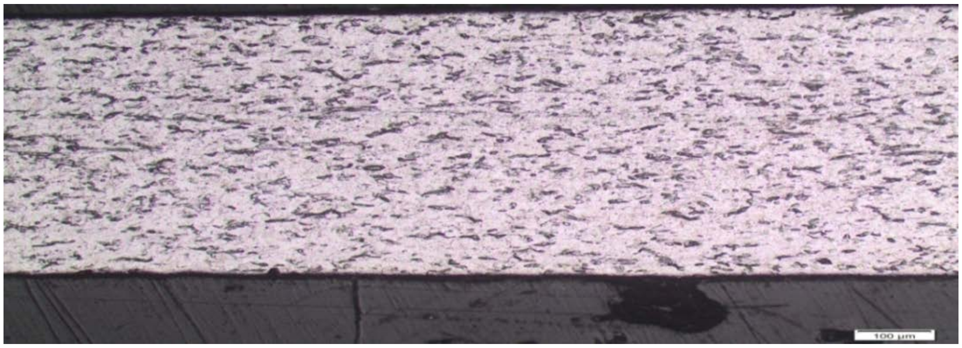


Figure 9 Optical micrographs showing hydride platelets oriented in axial direction of along the axis of annealed Zirconium alloy-4 plain girdle wire artificially hydrogen charged.

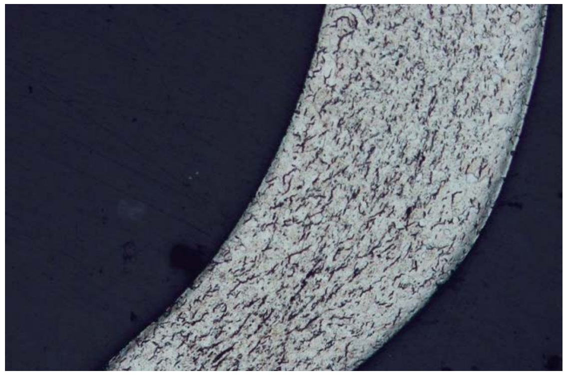


Figure 10 Optical micrographs showing hydride platelets oriented in axial direction of along the axis of annealed Zirconium alloy-4 corrugated girdle wire artificially hydrogen charged.

Optical microstructural examination of artificially hydrided finished Zirconium alloy-4 plain girdle wire [Fig.9] and corrugated wire [Fig.10] specimens revealed precipitation of hydride platelets in axial direction only. Hence thermo-mechanical processing of wire fabrication ensured avoiding precipitation of detrimental radial hydrides ensuring desirable texture for in-reactor performance.

3.5 Pull-out test result

Pull out tests are carried out on hydrided and as-fabricated garter spring and girdle wire.

Table 2 Pull out test result on hydrided and as-fabricated garter spring and girdle wire

Specimens	**Condition**	**UTS (MPa)**	**%Increase in length**
Plain girdle wire	Cold drawn	530.9	16.39
Plain girdle wire	Annealed	508.5	19.67
Plain girdle wire	Annealed & hydrided	580.1	12.79
Corrugated girdle wire	Annealed	428.0	25.92
Corrugated girdle wire	Annealed & hydrided	440.8	22.22
1.81x1.11mm rectangular wire	Annealed	519.7	29.62
1.81x1.11mm rectangular wire	Annealed & hydrided	528.9	22.22
1.73x1.04mm rectangular wire	hydrided	568.0	22.22

The increase in ultimate tensile strength (UTS) and reduction in % elongation was observed in the hydrided samples when compared to the as-fabricated one of same size in all the specimens.

The reduction in ductility and increased strength confirmed that hydride precipitation introduced brittleness in the material [Table-2].

3.6 Diametric Expansion of corrugated girdle wire

The garter spring assembly with corrugated girdle wire joined by resistance welding was smoothly rolled on a tapered mandrel with starting diameter of 110 mm up to 135 mm over a length of 400 mm, in order to simulate the in reactor diametric expansion behavior. 14% diametric expansion till failure of girdle wire was observed as against the design requirement of 5%. In order to ascertain the irradiated girdle wire with loss of ductility, a cold drawn wire was corrugated and rolling expansion test was performed. This has resulted in 9% diametric expansion. Hence it was assured that present design can easily accommodate 5% diametric expansion pressure tube due creep.

The performance of the new design with corrugated girdle wire was compared with the old design of plain girdle wire. The plain girdle wire assembled in the garter spring by resistance welding was smoothly rolled on the same tapered mandrel and found failure of girdle wire away from weld at the diametric expansion of 6%.

3.7 Testing of detection sensitivity of garter spring assembly simulating in-service inspection (ISI)

In the earlier design of 540 MWe PHWRs, garter spring assembly using plain girdle wire with overlap was adopted. Later on for 700 MWe PHWRs, corrugated girdle wire design with resistance welding was adopted. Since the primary function of the girdle wire is to facilitate detection of garter spring during ISI by eddy current examination, the detection sensitivity was compared between garter spring assemblies made through these two design concepts. It was found that detection sensitivity in corrugated & welded girdle wire design was significantly higher than the earlier design of plain girdle wire with overlap.

4. Conclusion

- The garter spring assembly with corrugated wire meets all the design and functional requirements including diametric expansion and satisfactory in service inspection detection sensitivity.
- The new design with corrugated & welded girdle wire demonstrated accommodation of significantly higher diametric expansion of pressure tube.
- Favorable hydride orientation was ensured in the garter spring and girdle wire.
- The hydride orientation in hook region is predominantly along the circumferential direction.

5. References

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