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Ultrasonic measurements for in-service assessment of wrought Inconel 625 cracker tubes of heavy water plants

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Abstract

The degradation in mechanical properties of Inconel 625 ammonia cracker tubes occurs during the service for long duration in heavy water plants. The present study brings out the possibility of using Poisson's ratio (derived from measurement of time of flight of ultrasonic waves) in combination with hardness measurements, as an effective non-destructive tool for assessment of in-service degradation of Inconel 625 cracker tubes and qualification of re-solution annealing heat treatment for their rejuvenation. Further, the study also indicates the feasibility of extending the life of some of the tubes beyond the presently followed 120 000 h, before they are taken up for re-solution annealing, without affecting their serviceability. However, further studies are required to identify quantitative criterion for Poisson's ratio and hardness values, for deciding on the basis for removal of the tubes for rejuvenation.

1. Introduction

Nickel base superalloy, Inconel 625 is used in aeronautical, aerospace, chemical petrochemical, marine and nuclear applications. In nuclear applications, Inconel 625 is used in reactor core and control rod components in pressurized water reactors and as ammonia cracker tubes in heavy water plants. The choice for this material is based upon a good combination of its yield strength, tensile strength, creep strength, excellent fabricability, weldability and good resistance to high temperature corrosion on prolonged exposure in aggressive environments. Although the alloy was initially designed and used in solid solution strengthened condition, it is observed that precipitation of intermetallic phases and carbides occurs on subjecting the alloy to ageing treatment in the range of 823–1023 K [1]. Inconel 625 tubes are used extensively in ammonia cracker units of heavy water plants. During service, the alloy is exposed to temperatures close to 873 K for a prolonged period (∼120 000 h) leading to a substantial decrease in ductility and toughness. The degradation in the mechanical properties is attributed to heavy precipitation of intermetallic γ'' ($Ni_3(Nb,Al,Ti)$) and $Ni_2(Cr,Mo)$ phases [2–4]. The grain boundary

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has also been found to be decorated with continuous network of carbides after the service exposure [2–4]. The degraded mechanical properties of such a component can be regained to a significant extent by giving it a re-solution heat treatment [2,4], provided the creep damage (such as formation of voids/micro-cracks) has not set in. After the service exposure for 120 000 h, these tubes are re-solution annealed at 1433 K for 2 h to dissolve all the precipitates and rejuvenate the mechanical properties. A practical and accurate non-destructive technique is needed for in-situ monitoring of the properties of Inconel 625 components, both during service and after post service rejuvenation heat treatment. In this direction, correlation among microstructure, mechanical properties and ultrasonic velocity in Inconel 625 were established in our earlier work [4].

The laboratory study on the influence of precipitation on ultrasonic velocity in Inconel 625, revealed that ultrasonic velocity increased with the precipitation of various intermetallics [4]. This study also exhibited that the correlation between ultrasonic velocity and mechanical property (yield stress) is dependent upon the types of the precipitates such as γ'', δ and $Ni_2(Cr,Mo)$. It has also been observed that the dissolution of $Ni_2(Cr,Mo)$ phase and precipitation of δ-phase have more effect on ultrasonic velocity as compared to that on yield stress, whereas dissolution and precipitation of γ'' has more influence on yield stress than on ultrasonic velocity. Determination of ultrasonic velocity requires the measurement of time of flight of ultrasonic wave and also the thickness of the tube at the point of measurement with an accuracy of a few microns. However, as the thickness of the tube is different at different locations and it is not possible to determine the thickness of the tube at the measurement locations, ultrasonic velocity cannot be measured as such on the tubes. One of our earlier studies on the variation in Poisson's ratio with ultrasonic velocity revealed that Poisson's ratio decreases linearly with increase in ultrasonic velocity [5]. It has been demonstrated that the decrease in Poisson's ratio with increase in ultrasonic velocity is due to the larger influence of microstructural changes on ultrasonic shear wave velocity as compared to longitudinal wave velocity. Larger increase in ultrasonic shear wave velocity would lead to decrease in Poisson's ratio, as per Eq. (1). Larger influence of microstructural changes on ultrasonic shear wave velocity is attributed to the association of two perpendicular planes (propagation and vibration) in the case of shear wave propagation as compared to one in the case of longitudinal wave [5]. It can be inferred based on these two studies that Poisson's ratio decreases with the precipitation in Inconel 625. Further, determination of Poisson's ratio requires only the ratio of the ultrasonic longitudinal wave velocity and shear wave velocity as per Eq. (2), and hence is independent of the thickness (function of only the time of flight of the two waves at the same location):

$$\nu = \frac{\frac{V_L^2}{V_S^2} - 2}{2\left(\frac{V_L^2}{V_S^2} - 1\right)} \tag{1}$$

or

$$\nu = \frac{\frac{\mathrm{TOF}_S^2}{\mathrm{TOF}_L^2} - 2}{2\left(\frac{\mathrm{TOF}_S^2}{\mathrm{TOF}_L^2} - 1\right)} \tag{2}$$

as

$$V = \frac{2x\,\mathrm{Thickness}}{\mathrm{TOF}}, \tag{3}$$

where ν, V_L and V_S are Poisson's ratio, longitudinal wave velocity and shear wave velocity, respectively, and TOF_L and TOF_S are the time of flight for longitudinal and shear waves, respectively, for the same thickness of the tube, i.e., at the same location. As the measurement of Poisson's ratio does not require thickness, it has been used as a non-destructive parameter for the assessment of in-service degradation of Inconel 625 cracker tubes.

The present study explores the feasibility of using Poisson's ratio (through ultrasonic measurements), ultrasonic attenuation and hardness measurements for the assessment of in-service degradation of Inconel 625 cracker tubes and for the assessment of the adequacy of rejuvenation heat treatment. Poisson's ratio and ultrasonic attenuation have been measured on various tubes subjected to different service exposures at heavy water plants at Thal and Tuticorin, India and these parameters have been correlated with the hardness measurements carried out at the respective locations. Ultrasonic and hardness measurements were also carried out on the rejuvenated (re-solution annealed) tubes with and without service exposure.

2. Experimental

2.1. Ultrasonic measurements

Ultrasonic measurements were carried out on the cracker tubes of 6.95 mm wall thickness, 88 mm

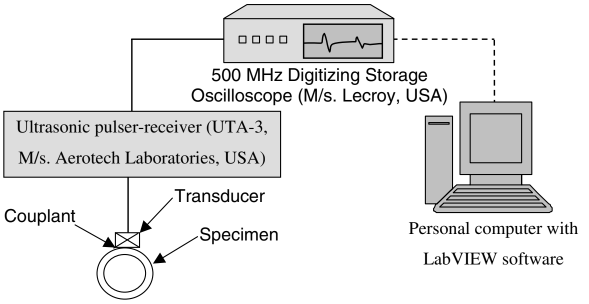

Fig. 1. Schematic of the experimental setup for measurement of time of flight of ultrasonic waves.

outer diameter and 12.55 m length. Fig. 1 shows the schematic of the experimental setup for measurement of time of flight and attenuation of ultrasonic waves. A 35 MHz broad band pulser–receiver (M/s Aerotech, USA) and 500 MHz dual channel digitizing storage oscilloscope (M/s Lecroy, USA) were used for carrying out the ultrasonic measurements. For these measurements, the rf signals were digitized at 1 GHz for longitudinal waves and at 500 MHz for shear waves. The first and second backwall echoes (5000 data points) were gated together and recorded. Time of flight of ultrasonic waves was measured using 2.5 MHz shear and 5 MHz longitudinal wave transducers. A cross correlation technique was used for precise velocity measurements [6]. The accuracy in time of flight measurement was better than ±1 ns, which led to the maximum scatter in Poisson's ratio of ±0.0007. Attenuation of ultrasonic longitudinal waves was also calculated from the first and second backwall echoes assuming a constant thickness of 8.89 mm. The maximum error due to the thickness variation of ±0.5 mm would be less than ±0.05 dB/mm in attenuation measurements.

2.2. Hardness measurements

Hardness measurements were also carried out at all the locations of ultrasonic measurements. Hardness measurements were carried out using hand held portable hardness tester EQUITIP 2 (Proceq Testing Equipments, Switzerland). An average of three measurements at each location is reported. The maximum scatter in the hardness measurement at any location was found to be less than ±5 VHN.

2.3. Cracker tubes investigated

Five virgin tubes (unused/fresh tubes in solution annealed condition), six re-solution annealed tubes (re-solution annealed after 120 000 h of service exposure), two re-solution annealed tubes followed by 23 000 h of service exposure and 65 virgin tubes after service exposure of 120 000 h (taken out of Cracker unit for re-solution annealing) were investigated at Heavy Water Plant, Thal. At Heavy Water Plant, Tuticorin, ultrasonic and hardness measurements were carried out on six virgin tubes after service exposure of 747 h and 15 virgin tubes after service exposure of 57 194 h. Measurements were also carried out on one virgin tube in the Mini Cracker (MC) unit at Tuticorin, which had seen service of about 20 000 h and a small cut portion of a virgin tube that failed after service of about 24 000 h. All the measurements were carried out at 1 m elevation from the bottom weld.

2.4. Metallography

The optical microstructure of the virgin tube failed after service of about 24 000 h was obtained and compared with the microstructure of another tube service exposed under normal conditions. These tubes were polished using an in-situ grinding machine and etched electrolytically for nearly 20 s using saturated oxalic acid solution at ~3–5 V with a stainless steel cathode.

3. Results and discussion

The results obtained from Poisson's ratio and hardness measurements on all the tubes are presented in Fig. 2 and Tables 1a and b. The variation in Poisson's ratio with hardness (Fig. 2) revealed that the tubes in different conditions can be represented by specific clusters in the plot. Table 2 shows the ranges of Poisson's ratio, hardness and attenuation for the tubes in different conditions. It can be seen from Fig. 2 and Table 2 that the variation in Poisson's ratio and hardness lie in the ranges of 0.314–0.318 and 140–174 VHN, respectively, for the virgin tubes. Upon service exposure of the virgin tubes for 747 h, the Poisson's ratio decreases to 0.309–0.313, whereas, hardness does not change much (140–200 VHN) as compared to the virgin tubes, except for a slight increase in the upper bound. This is attributed to the fact that during the initial stage of precipitation, the alloying elements come out of the solution to form the precipitates. The depletion of these elements from the matrix increases the modulus and in-turn decreases the Poisson's ratio of the alloy. However, as the

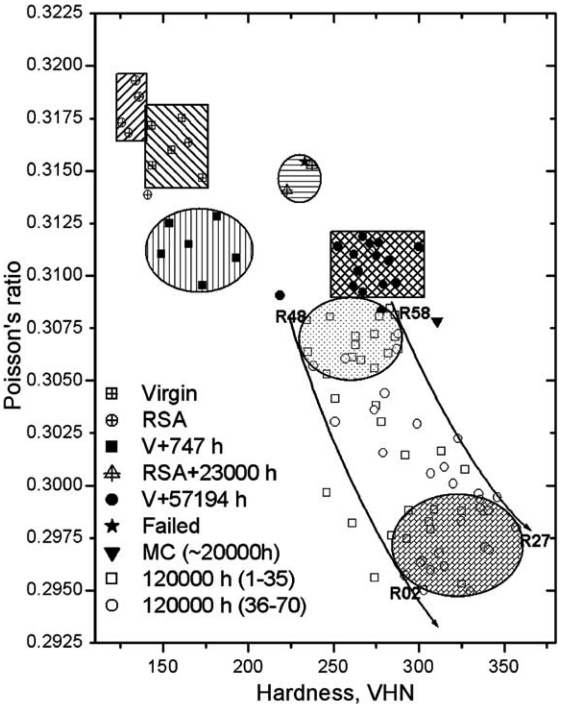

Fig. 2. Variation in Poisson's ratio with hardness for cracker tubes in different service exposed conditions at heavy water plants (V: virgin, MC: mini cracker, RSA: re-solution annealed).

precipitates could be of very fine in size after this short duration, there is not much change in the hardness value. Similar results of different response of ultrasonic velocity and hardness due to precipitation has also been reported in aluminum alloys [7,8] and nickel base superalloy PE16 [9]. With the service exposure of the tubes for 50 000 h, hardness increases to 250–300 VHN, due to the precipitation of different intermetallics. However, Poisson's ratio does not change much as compared to that after 747 h of exposure, as the maximum change in the Poisson's ratio is observed only during the initial exposure, when the alloying elements came out of the solution. This difference in the effect of different precipitation stages on Poisson's ratio and hardness suggests that Poisson's ratio may be a better parameter for monitoring the degradation during the initial period, whereas, hardness may be a better parameter for the intermediate stage. Further, this would also help in deciding the inspection interval for monitoring the degradation in the tubes.

The tubes, service exposed for 120 000 h, exhibited a large scatter in the Poisson's ratio (0.295–0.308) and hardness (230–360 VHN) values, and their correlation. Whereas, maximum scatter in the

Table 1a
Poisson's ratio and hardness for different tubes (RSA: re-solution annealed, SE: service exposed) at Heavy Water Plant, Thal

Tube no.	Poisson's ratio	Hardness, VHN
Tubes service exposed for 120 000 h		
R01	0.29639	302
R02	0.2957	292
R03	0.29496	330
R04	0.30089	315
R05	0.30651	287
R06	0.2988	338
R07	0.30295	299
R08	0.29596	307
R09	0.29499	303
R10	0.30057	307
R11	0.2996	335
R12 (Cast)	–	–
R13	0.2988	341
R14	0.29613	315
R15	0.29631	301
R16	0.29829	325
R17	0.31106	271
R18	0.3001	320
R19	0.30724	288
R20	0.30305	251
R21	0.30224	323
R22	0.29944	346
R23	0.30156	279
R24	0.30604	257
R25 (Cast)	–	–
R26	0.29894	336
R27	0.29799	357
R28	0.29705	339
R29	0.29932	336
R30	0.29693	341
R31	0.3036	274
R32	0.30569	238
R33	0.29679	312
R34	0.3044	280
R36	0.30597	266
R37	0.30077	327
R38	0.29885	309
R39	0.30532	246
R40	0.30164	313
R41	0.30612	261
R42	0.29746	293
R43	0.30813	286
R44	0.2982	261
R45	0.29562	274
R46	0.29966	246
R47 (Cast)	–	–
R48	0.30787	234
R49	0.30712	263
R50	0.30651	288
R51	0.30637	235
R52	0.30304	278
R53	0.30414	251
R54	0.3067	263
R55	0.29883	294
R56	0.30144	292

(*continued on next page*)

Table 1a (*continued*)

Tube no.	Poisson's ratio	Hardness, VHN
R57	0.30709	286
R58	0.30805	277
R59	0.30844	283
R60 (Cast)	–	–
R61	0.30721	274
R62	0.29879	325
R63	0.29828	306
R64	0.30631	282
R65	0.30805	248
R66	0.29791	307
R67	0.30561	274
R68	0.30381	275
R69	0.29531	325
R70	0.29763	284
T41J2	0.31634	165
Virgin	0.31599	155
Tubes in cracker units		
A/Tube70 (Virgin)	0.3175	161
A/Tube65 (Virgin)	0.3152	144
A/Tube54 (Virgin)	0.3134	175
B/Tube35 (Virgin)	0.3172	140
A/Tube18 (RSA)	0.3168	130
A/Tube01 (RSA)	0.3139	141
B/Tube30 (RSA)	0.3187	134
A/Tube5 (RSA)	0.3193	134
A/Tube36 (RSA)	0.317	135
B/Tube1 (RSA)	0.3167	138
A/Tube35 (RSA + 23000 h SE)	0.3153	237
B/Tube18 (RSA + 23000 h SE)	0.314	235

Table 1b

Poisson's ratio and hardness for different tubes service exposed at Heavy Water Plant, Tuticorin

Tube no.	Poisson's ratio	Hardness, VHN
Tubes service exposed for 747 h		
D	0.30956	173
69	0.3125	153.5
E	0.31104	149
68	0.31151	165
64	0.31281	181.5
C	0.31084	193
Tubes service exposed for 57194 h		
1	0.31071	282.5
14	0.31094	275
6	0.31022	264.5
16	0.31154	271
28	0.3092	267
23	0.31103	262
33	0.3096	279
50	0.30952	261.5
38	0.30907	218.5
43	0.31186	267
55	0.31158	276.5
67	0.31139	300
65	0.30834	278
70	0.31139	252.5
60	0.30965	287
Tube service exposed for 20000 h in mini cracker unit		
MC	0.30784	310.7
Tube failed after service exposure of 24000 h		
Failed	0.31544	233

Poisson's ratio and hardness values for the tubes in the solution annealed conditions (virgin tubes and re-solution annealed tubes) is only 0.314–0.319 and 126–174 VHN. Even with a large difference in the grain size in virgin and re-solution annealed tubes, maximum scatter in the values are about 2.5 times more for the service exposed tubes as compared to the solution annealed tubes. Further, the measurement scatter for Poisson's ratio and hardness is ±0.0007 and ±5 VHN, respectively. This clearly indicates that the scatter in the values of Poisson's ratio and hardness in service exposed tubes is due to the service generated factor only. Our earlier study [4] has clearly shown that such a scatter can arise due to different amount of different types of precipitates. Hence, it can be deduced that even though all these tubes are service exposed for the same duration of 120000 h, these tubes would

Table 2

Range of Poisson's ratio, hardness and attenuation for tubes in different microstructural conditions

Condition	No. of tubes investigated	Range of Poisson's ratio	Range of hardness (VHN)	Range of attenuation (dB/mm)
Virgin	5	0.314–0.318	140–174	0.18–0.34
Re-solution annealed (RSA)	6	0.317–0.319	126–135	0.35–0.50
V + 747 h	6	0.309–0.313	140–200	0.25–0.34
V + 50000 h	15	0.309–0.312	250–300	0.27–0.36
RSA + 23000 h	2	0.314–0.315	220–240	0.43–0.60
V + 120000 h	65	0.295–0.308	230–360	0.15–0.28
Tube failed in 1982	1	0.315	233	0.51

have had different temperature–time histories, thus exhibiting different amounts of different types of precipitates. The temperature records seen in the operation logbook of the plant, also exhibited large scatter (823–973 K) at different locations in the cracker unit. Different values of hardness for the same Poisson's ratio and vice-versa are attributed to difference in the relative amounts of the two precipitates, i.e., γ'' and $Ni_2(Cr,Mo)$, reported to form depending upon the actual operating temperatures [1]. As discussed in the Introduction, higher amount of γ'' would lead to larger change in hardness as compared to Poisson's ratio, whereas, higher amount of $Ni_2(Cr,Mo)$ would lead to larger change in the Poisson's ratio as compared to the hardness.

The large variations in Poisson's ratio and hardness values for the tubes service exposed for the same duration (120 000 h) clearly indicate that the degradation of the tubes is not the function of service life only, but is also dependent upon the operating conditions (in particular temperature). As the operating conditions for different tubes are different, the extent of degradation is also expected to be different for different tubes exposed for the same duration. This can be clearly visualized by comparing the dotted and bricked areas in Fig. 2. It can be seen that the tubes in the bricked area exhibit higher hardness and lower Poisson's ratio as compared to the tubes in the dotted areas. This clearly indicates that the tubes in the dotted areas exhibit lesser degradation as compared to the tubes in the bricked area. Hence, the service life of these tubes before they are taken up for re-solution annealing should not merely be based on the service

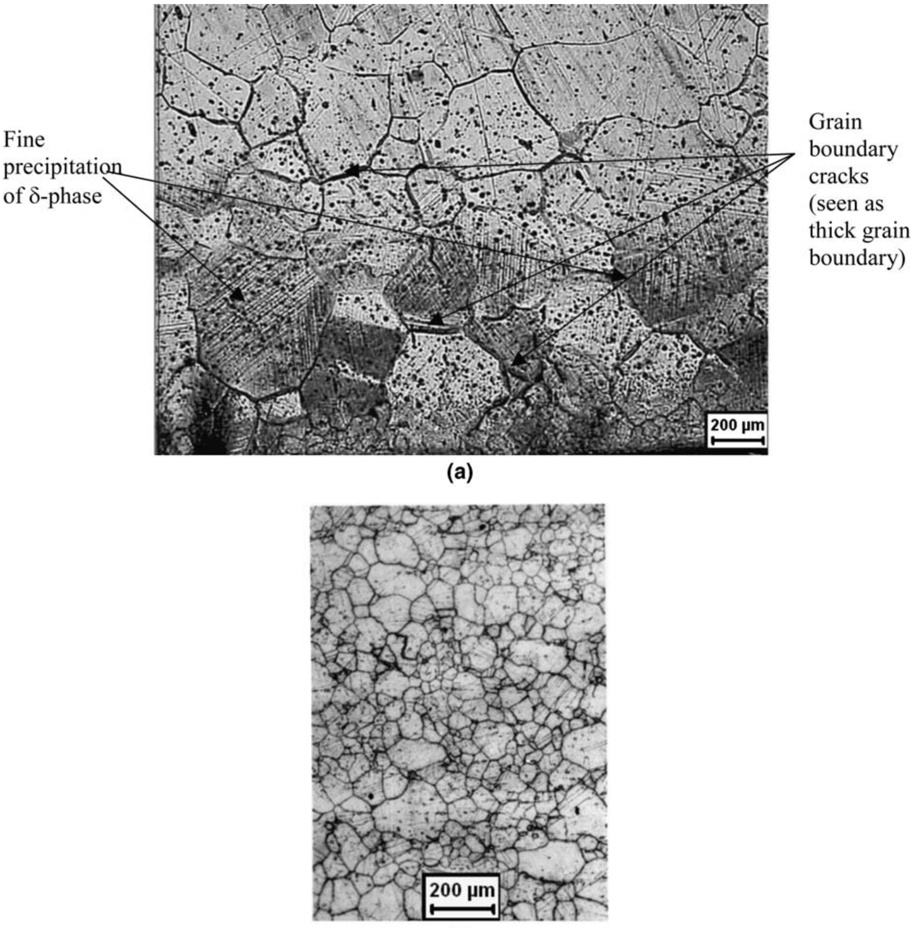

Fig. 3. Optical photomicrographs obtained on the (a) tube failed after service exposure of 24 000 h (ultrasonic attenuation = 0.51 dB/mm, hardness = 233 VHN and Poisson's ratio = 0.3154) and (b) a service exposed tube in operation (with ultrasonic attenuation = 0.28 dB/mm, hardness = 165 VHN and Poisson's ratio = 0.3115).

duration. Further, since the tubes in the bricked area have not failed during the service, it can be said that the life of the tubes in the dotted area can be extended without affecting their serviceability. However, further studies are required to identify quantitative criterion for Poisson's ratio and hardness values, for deciding on the basis for removal of the tubes for rejuvenation.

The re-solution annealing of the service exposed tubes led to the decrease in hardness (126–135 VHN) even below that for the virgin tubes. Similarly, the Poisson's ratio increased to slightly above that of the virgin tubes. This is attributed to the fact that the re-solution annealing treatment leads to grain growth also, in addition to the dissolution of the precipitates in the matrix. The increase in the grain size is reported to increase the Poisson's ratio in austenitic stainless steels [5]. These measurements on the re-solution annealed tubes reveal that both hardness and Poisson's ratio can be used for the assessment of adequacy of the re-solution annealing treatment for rejuvenation of the mechanical properties of these tubes. While hardness can provide only the surface information, Poisson's ratio can provide the information about the average property in complete thickness of the tube. The service exposure of the re-solution annealed alloy for 23 000 h leads to decrease in the Poisson's ratio (0.314–0.315) and increase in the hardness (220–240 VHN). Further, it can be seen clearly from Fig. 2 that the range of Poisson's ratio is higher for the re-solution annealed tubes as compared to the virgin tubes. This is attributed to the larger grain size in re-solution annealed tubes.

Fig. 2 also shows the Poisson's ratio and hardness values for the tube, that failed after service exposure to about 24 000 h. Even though this tube had the starting condition as virgin, the values of Poisson's ratio and hardness of this tube lie close to that for the RSA tubes service exposed to 23 000 h. This indicates that this tube consists of a different microstructure as compared to the virgin tubes exposed to normal service conditions. Fig. 3(a) shows the optical microstructure from the cross section of this tube near the outer surface. Fig. 3(b) shows the optical microstructure of a virgin tube exposed to normal service conditions, for ready comparison. The microstructure in the failed tube exhibited larger grain size (∼200 μm) as compared to that of the tube exposed to normal service condition (∼50 μm). Further, the failed tube also consisted of grain boundary cracks near the outer surface. This tube also exhibited the precipitation of δ-phase leading to increased hardness. These observations on this failed tube indicate that the measurement of the Poisson's ratio and hardness in combination can clearly bring out any anomalous change in the microstructure of the tube, such as increase in the grain size or formation of creep cracks because of abnormal service conditions such as accidental increase in temperature/load.

Fig. 4 shows the variation in attenuation of ultrasonic longitudinal waves for the tubes in different microstructural conditions. It can be seen clearly that all the virgin tubes as well as virgin tubes followed by normal service exposure, exhibit lower attenuation (<0.36 dB/mm), whereas, the RSA tubes and the RSA tubes followed by service exposure can be characterized by higher attenuation (>0.36 dB/mm). This increase in the attenuation in the RSA tubes clearly indicates the grain growth in the tubes upon re-solution annealing, as the attenuation of ultrasonic waves of any frequency is primarily a function of grain size in polycrystalline material [10]. The attenuation in the failed tube exhibited anomalous behavior, like the hardness

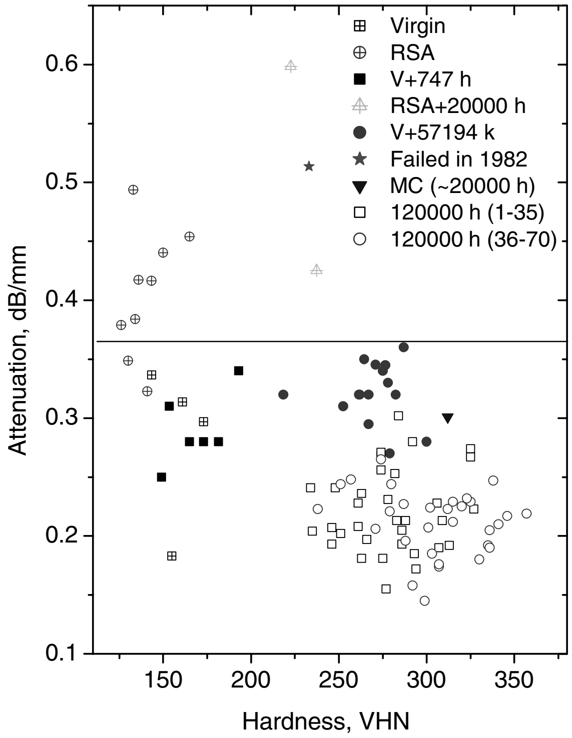

Fig. 4. Variation in attenuation with hardness for cracker tubes in different service exposed conditions at heavy water plants (V: virgin, MC: mini cracker, RSA: re-solution annealed).

and Poisson's ratio. Even though the starting condition for this tube was as virgin condition with finer grain size, it exhibited very high attenuation similar to that for the RSA tubes. This is attributed to the grain growth and presence of microcracks/voids, as observed in the metallographic studies (Fig. 3(a)). The attenuation measurements of the tubes suggested that like the Poisson's ratio and hardness, periodic attenuation measurements can also clearly reveal any anomalous change in the microstructure of the tube, such as increase in grain size or formation of creep cracks due to abnormal service condition or any accidental increase in temperature/load.

4. Future studies planned

The measurements carried out so far clearly bring out the possibility of using the Poisson's ratio and hardness for assessing the progress of degradation of the cracker tubes consequent to precipitation of different intermetallic phases. It is also demonstrated that the life span of these tubes for re-solution annealing should not be based on merely the service duration. The tubes service exposed for 120 000 h exhibited a large scatter in the Poisson's ratio and the hardness. Even for the same Poisson's ratio, different values of hardness were obtained in different tubes and vice-versa. However, based on the results obtained from the present study, the limits of the values of hardness and Poisson's ratio that should be used as the basis for determining the life of these tubes before they should be taken up for re-solution annealing, cannot be explicitly stated. To unfold this, mechanical properties need to be evaluated for the service-exposed tubes having the extreme values of hardness and Poisson's ratio. The mechanical properties for the tubes R48 (exhibiting lowest hardness and highest Poisson's ratio indicating minimum damage based on both the parameters), R58 (exhibiting intermediate hardness and highest Poisson's ratio), R02 (exhibiting intermediate hardness and lowest Poisson's ratio) and R27 (exhibiting highest hardness and almost lowest Poisson's ratio indicating maximum damage based on both the parameters) need to be evaluated. This study would provide the correlation between the degradation in mechanical properties with the two parameters, Poisson's ratio and hardness, for different microstructural conditions. This would in-turn enable to identify definite quantitative criterion for Poisson's ratio and hardness values, for deciding on the methodology for assessment of extent of degradation and time for removal of the tubes for rejuvenation.

The Poisson's ratio and hardness measurements should be carried out at different elevations of the tubes in order to determine the regions of maximum damage that would become the basis for their continued use/rejuvenation.

5. Conclusions

Degradation in mechanical properties of Inconel 625 ammonia cracker tubes occurs during service in heavy water plants. The measurement of ultrasonic parameters and hardness on Inconel 625 tubes in different microstructural conditions revealed that:

1. Poisson's ratio and hardness can be used in combination to assess the progress of degradation of the cracker tubes that take place consequent to the precipitation of different intermetallic phases during service and also to assess the adequacy of the re-solution annealing treatment used for rejuvenation of degraded mechanical properties.
2. Poisson's ratio is a better parameter to study the progress of precipitation in the initial stage, whereas, hardness is a better parameter for intermediate stage of degradation.
3. Any accidental change in the microstructure, such as grain growth, can be readily detected by the measurement of Poisson's ratio and hardness, in addition to ultrasonic attenuation.
4. A large variation in the hardness and Poisson's ratio values for the tubes service exposed for 120 000 h, clearly indicates that different tubes exhibit different extent of damage/degradation upon service exposure for the same duration. This indicates that the operating conditions (in particular temperature) for different tubes are different during their service. Hence, the life of these tubes, before they are taken out for rejuvenation treatment, should not be based merely on the service duration, but should be based on suitable measurable parameters, such as Poisson's ratio, hardness and ultrasonic attenuation. Further, the study also exhibited that the life span of some of the tubes can be easily extended without affecting their serviceability.
5. The parameters and their values (criteria) for determining the life of the tubes before they are taken up for re-solution annealing need to be established based on the evaluation of mechanical properties of the service exposed

tubes exhibiting the extreme values of hardness and Poisson's ratio.

6. The attenuation measurements could also reveal anomalous changes in the microstructure of the tubes, such as increase in the grain size or formation of creep cracks due to abnormal service conditions such as any accidental increase in temperature/load.

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