NONDESTRUCTIVE CHARACTERIZATION OF ZIRCALOY TUBES WITH HYDRIDE RIMS

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Abstract

In this research, a laser ultrasound technique (LUT) is reported for nondestructive characterization of hydride rims (HR) in Zircaloy cladding tubes. With the LUT, guided waves propagating in the Zircaloy tubes with different HR thickness are generated and detected remotely by optical means. By measuring the dispersive ultrasonic wavespeeds with the LUT, combining with the inversion technique, relations between the dispersion relations and thickness of HR are established. Good accuracy in measuring the HR thickness is demonstrated with this combined LUT with inversion algorism technique.

1. Introduction

Zircaloy cladding can undergo considerable changes in mechanical properties while in reactor service. It has been established that precipitated hydrides are responsible for hydrogen embrittlement of Zirconium and alloys, and the degree of embrittlement was reported to be affected mainly by hydrogen concentration (HC). Very often, the HC of Zircaloy fuel cladding is determined by off-line destructive techniques, which are time-consuming and costly. Poolside NDE technique is desired for the characterization of HC in Zircaloy cladding materials.

In our previous study, a laser ultrasound technique (LUT) is introduced for the characterization of HC in Zircaloy tubes with homogeneous hydride distribution. Dispersion curves of guided acoustic modes propagating along the tubes measured with the LUT are able to discriminate the HC with a resolution of 200 ppm. However, the hydride precipitation is generally non-uniform across the thickness of the Zircaloy tubes. Due to the thermal gradient, the hydride precipitation can have the form of rims in the outer and/or inner parts of the Zircaloy tubes. In this study, a NDE technique employing the LUT and a simplex inversion process is reported for the characterization of hydride rims. It is shown that hydride rims with thicknesses ranging from 20 microns to 80 microns are successfully characterized with an accuracy of better than 10%.

2. Experiments and inversion calculations

The LUT system includes a pulsed Nd:YAG laser, an interferometer, a scanning stage, an oscilloscope, and a computer with fast A/D converter. The interferometer used for the non-contact detection of ultrasound is a heterodyne interferometer. The scanning stage controlled by the computer drives a mirror to scan the Nd:YAG laser beam along the axial direction of the Zircaloy tubes, such as Fig. 1.

Inverse technology is using numerical method (Simplex), cooperate with the theory guided wave models of one and two-layered tube.

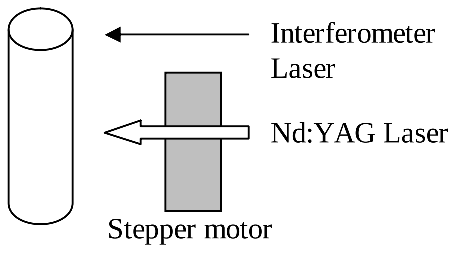

Figure 1: Experimental configuration

2.1. Laser ultrasound measurement technique

In this study, a laser-generation/laser-detection LUT is introduced for the characterization for HC in the Zircaloy tubes. Fig. 4 shows a schematic for the experimental configuration of the LUT system. The LUT system includes a pulsed Nd:YAG laser, an interferometer, a scanning stage, an oscilloscope, and a computer with fast A/D converter. The pulsed Nd:YAG laser (Quantel YG780) with a wavelength of 532 nm, a duration time of 6.6 ns, and an energy of about 100 mJ is used for the generation of ultrasonic waves. The interferometer (Polytec OFV 511) used for the non-contact detection of ultrasound is a heterodyne interferometer with a detection bandwidth of 30 MHz. The scanning stage controlled by the computer drives a mirror to scan the Nd:YAG laser beam along the axial direction of the Zircaloy tubes. The oscilloscope is used to monitor the ultrasound waveform. The computer with a fast A/D converter is used for controlling the scanning stage, waveform acquisition, and signal processing.

Ultrasonic waves propagating in Zircaloy tubes are dispersive, and are measured with the LUT in a way of B-scan followed by a two-dimensional fast Fourier transform (2D-FFT) signal processing. B-scan is a two dimensional graphical presentation, in rectangular coordinates, in which the travel time of an ultrasonic pulse is represented as a displacement along one axis, transducer movement is represented as a displacement along the other axis, and the acoustic amplitude for the reflected pulses are shown as the gray-scale. Fig. 5 shows a waveform generated and detected with the LUT for the archive sample. For the B-scan, the impinging spot of generation laser is initially placed near the illuminated spot of the interferometer by a distance of about 5 mm, and then scanned away. A total scanning distance of 10 mm with 100 steps is used to obtain a set of dispersion spectra. After the waveforms at each step are collected, a set of B-scan data for the archived sample is shown in a gray scale format in Fig. 6. In this figure, the horizontal axis denotes the elapsed time, the vertical axis denotes the scanning position, and the gray scale represents the relative amplitude of acoustic waves. Multi-mode dispersion spectra are further extracted from the B-scan data by the 2D-FFT signal processing. In the 2D-FFT, the first FFT is taken with respect to time, and the second FFT with respect to the scanning position. The 2D-FFT transforms the B-scan data into ultrasound amplitude as a function of frequency (f) and wavenumber (k). A peak-detection routine is used to find the trajectories of peak amplitude in the f-k space. Finally, the dispersion curves in the form of ultrasound phase velocity (V) versus frequency are obtained with the aid of the relation $V=2pf/k$.

2.2. Simplex inversion calculation

Inverse technology is using numerical method (Simplex), cooperate with the theory guided wave models of one and two-layered tube. Cooperate with simplex procedure can precede the inverse of the unknown parameter, show in Fig. 2. The most important is the establishment of the objective function in Simplex, the precision of the inverse will have very great differences with the difference of function.

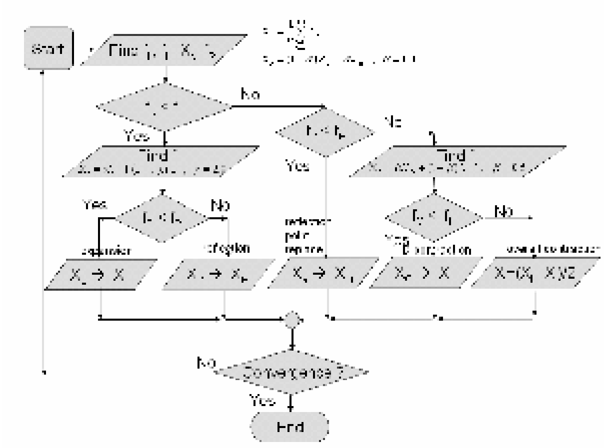

Figure 2: Simplex procedure.

3. Material specimen

A single-layered Zircaloy tube and Zircaloy tubes with hydride rims (HR) are investigated. Two-layered tubes are the Zircaloy matrix coatred with the ZrH_2 layer either in the inner or outer side of the tubes, as shown in Fig. 3. And the geometry properties of specimen are show in Table 1.

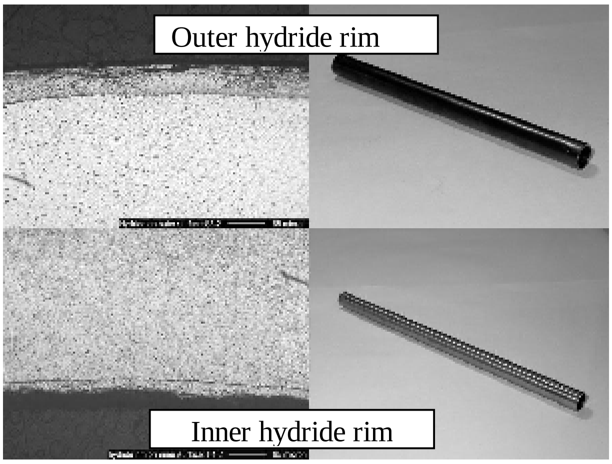

Figure 3: Zircaloy samples with inner or outer HRs.

Table 1: Material specimen and geometry properties

Specimen number	Inner radius (mm)	Outer radius (mm)	HR thickness (μ m)
ZrNONE	4.165	4.74	N/A
ZrIN01	4.19	4.74	10~15
ZrIN02	4.16	4.72	10~15
ZrIN04	4.165	4.745	30~40
ZrOUT01	4.175	4.725	33
ZrOUT02	4.18	4.73	38
ZrOUT03	4.17	4.76	80

ZrOUT04	4.17	4.73	20

4. Results and discussions

The result is divided into two parts, LUT experiment measures the results and inverse results. And then introduce one and two-layered tubes results.

4.1. One-layered tube

Fig. 4 is the experiment result of LUT. LUT can be succeeded in applying to the measurement of dispersion curve of one-layered tube, and there is quite good signal/noise ratio.

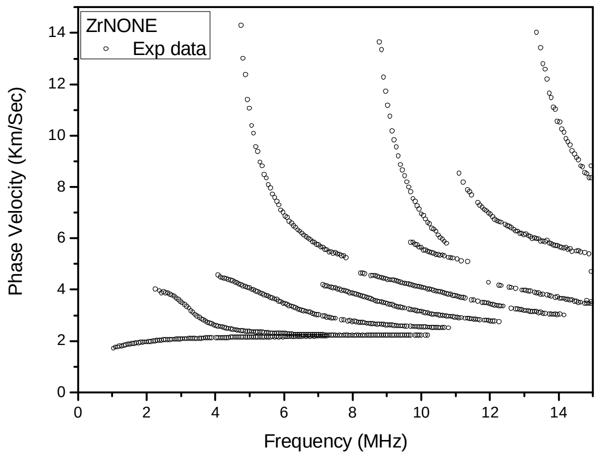

Figure 4: Experimental dispersions for the single-layered tube.

4.1.2. Benchmark test

Before starting inversion calculation, it's must confirm the exactness of the inverse mechanism first and use benchmark test to test. At first, set up a stainless steel that material properties are Yang's modulus(E) 207GPa, Poisson's ratio(ν) 0.3, density 7.85g/cm^3 and geometry properties are inner radius 4mm, outer radius 4.5mm be a basic test stuff. Utilize this material to draw a dispersion curve. Inverse this dispersion curve, and confirm the exactness of the inversion calculation by compared the error of result received with original material and geometry properties.

Fig. 5 is the results of Dispersions for the single-layered benchmark test. It can confirm the inverse result isn't the local minimum because the result is coincident each other. And by check the Fig. 6, it also can confirm that the inversion calculation for single-layered has steady results.

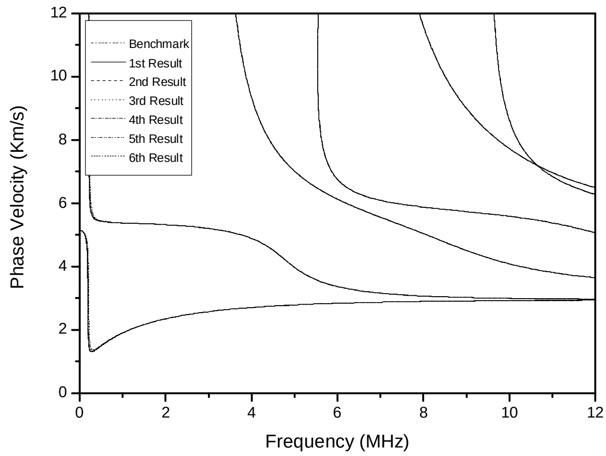

Figure 5: The results of Dispersions for the single-layered benchmark test.

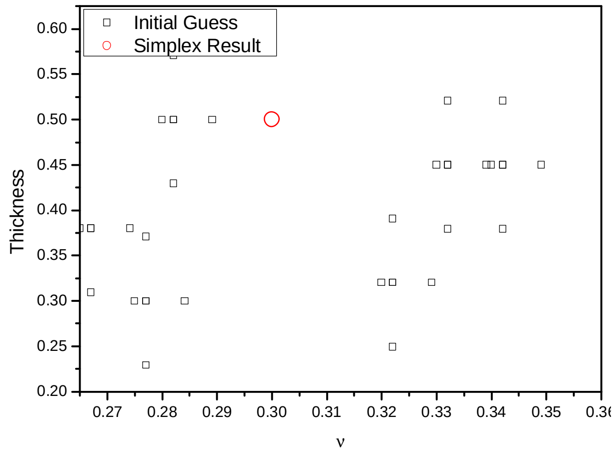

Figure 6: Results for the single-layered benchmark test.

4.1.3. Inversion outcomes

The inverse results show in Table. 1. Error ranges of any inverse result are all smaller than 2 pieces of percentage, therefore can know there can be very accurate inverse results inthis technology.

Table 2: Inverse results for the single-layered tube

	E(MPa)	ν	IR(mm)	OR(mm)
1st	98706.65	0.3053	4.263	4.823
2nd	98730.41	0.3062	4.196	4.756
3rd	98715.24	0.3058	4.244	4.804
4th	98715.56	0.3059	4.229	4.789
5th	98706.65	0.3053	4.263	4.823
6th	98730.41	0.3062	4.196	4.756
Ave	98717.49	0.306	4.231	4.792
Error(%)	0.024	0.294	1.572	1.389

4.2. Two-layered tube

In two-layered tubes, Fig. 7 and Fig. 8 are the experiment result of LUT on the two-layered tubes with inner and outer hydride rims. LUT can be succeeded in applying to the measurement of dispersion curve of one-layered tube, and there is quite good signal/noise ratio.

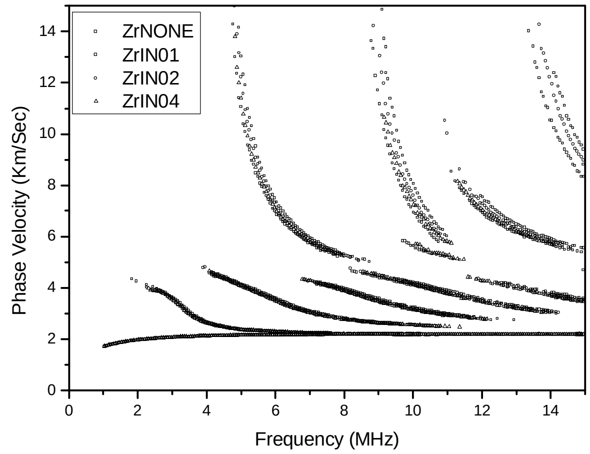

Figure 7: Experimental result of LUT on two-layered tube.

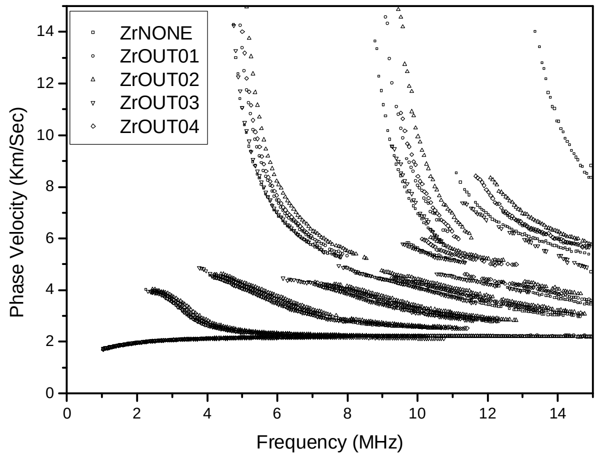

Figure 8: Dispersion for Zircaloy tubes with outer HR.

4.2.2. Benchmark test

The same as single-layered, inversion calculation for two-layered needs to carry on benchmark test first too. On this inversion calculation , the basic layered will be fixed and inverse the material and geometry properties of rims. Table. 3 show the material and geometry properties of both basic layered and rim.

Table 3:The material and geometry properties of two-layered test stuff.

	E(GPa)	ν	ρ (g/cm^3)
Steel	207	0.3	7.85
Red brass	115	0.375	8.75
OR(mm)	OH(mm)	IH(mm)	
4.5	0.05	0.45	

The results of Dispersions for the two-layered benchmark test show in Fig. 9. And Fig. 10 is the Results for the two-layered benchmark test.

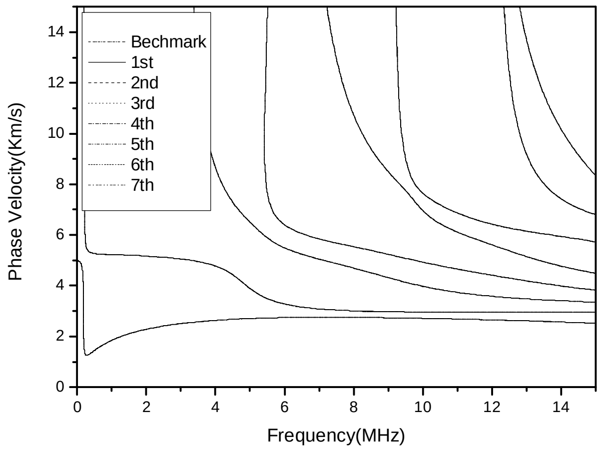

Figure 9: The results of Dispersions for the two-layered benchmark test

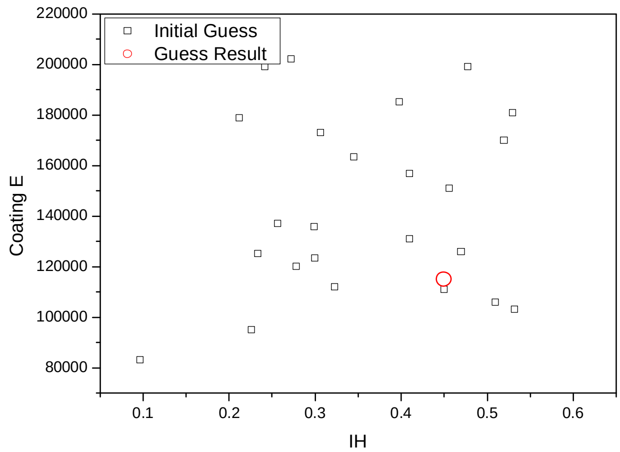

Figure 10: Results for the two-layered benchmark test

4.2.3. Inversion outcomes

The inverse results show in Table. 4. Though the error range is bigger than that of one-layered tube, only differ by several μ m in fact. So this technology still has a very accurate inverse result.

Table 4: Inverse results for the two-layered tubes.

	Inversion IH(mm)	Inversion OH(mm)	Error (IH)(%)	Error (OH)(%)
IN01	0.010	0.531	19.679	1.922
IN02	0.013	0.530	37.712	1.958
IN04	0.030	0.526	2.775	4.296
OUT01	0.510	0.027	1.002	16.443
OUT02	0.478	0.034	11.709	10.224
OUT03	0.470	0.080	5.324	4.743
OUT04	0.509	0.021	2.418	1.324

5. Conclusion

Dispersion behaviors of guided waves propagating in Zircaloy tubes with/without hydride rim are successfully measured with a laser ultrasound technique (LUT). Together with a simplex inversion algorism, mechanical and geometrical properties for the Zircaloys are successfully obtained with the combined LUT/Simplex method. Results of the current research will serve as useful tool for nondestructive characterization of hydride rims in Zr tubes.

6. References

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