Case Studies in Nondestructive Testing and Evaluation 6 (2016) 26–31

Contents lists available at ScienceDirect

Case Studies in Nondestructive Testing and Evaluation

www.elsevier.com/locate/csndt

Robotic ultrasonic testing of AGR fuel cladding

Maxim Morozov [a,*], S. Gareth Pierce [a], Gordon Dobie [a], Gary T. Bolton [b], Thomas Bennett [b]

[a] University of Strathclyde, Technology & Innovation Centre, 99 George Street, Glasgow, Scotland, G1 1RD, UK
[b] National Nuclear Laboratory, UK

ARTICLE INFO

Article history:
Available online 13 August 2016

ABSTRACT

The purpose of the presented work was to undertake experimental trials to demonstrate the potential capabilities of a novel in-situ robotic ultrasonic scanning technique for measuring and monitoring loss of the cladding wall thickness in fuel pins of Advanced Gas-cooled Reactors using non-radioactive samples. AGR fuel pins are stainless steel cylindrical ribbed pipes of inner diameter of the rod being about 15 mm and wall thickness of about 300 µm. Spent AGR fuel pins are stored in a water pond and thus may be prone to corrosion and stress-corrosion cracking under adverse conditions. An ultrasonic immersion transducer with central frequency of 25 MHz was used to measure wall thickness of the AGR fuel cladding. The novelty of the approach consists in the usage of a frequency domain technique to measure the wall thickness combined with cylindrical ultrasonic scanning of the samples performed using an industrial robotic manipulator. The frequency domain approach could detect wall thicknesses in the range 96 µm to 700 µm with a resolution of about 10 µm. In addition to the frequency domain measurements, using conventional time domain techniques, it was possible to detect very short (2.5 mm long) and shallow (100 µm in depth) crack-like defects in the fuel cladding.

1. Introduction

The Advanced Gas-cooled Reactor (AGR) is a type of nuclear reactor which uses graphite as the neutron moderator and carbon dioxide as coolant. AGR requires stainless steel fuel cladding to withstand the high temperature. Spent AGR fuel pins are stored in water ponds and thus may be prone to corrosion and stress-corrosion cracking under certain abnormal conditions. Following the planned cessation of spent fuel reprocessing in the UK, storage periods prior to geological disposal are expected to span many decades. Therefore, there is interest in developing a robust and diverse regime of fuel condition monitoring and inspection techniques in order to confirm that fuel remains in good condition.

Fig. 1 shows an illustration of the geometry of the AGR fuel cladding. AGR fuel pins are stainless steel cylindrical ribbed pipes of about 1000 mm length, average diameter of the pin is about 15 mm, wall thickness is about 300 µm, rib height is about 400 µm and rib pitch is 2.75 mm. The material of AGR fuel cladding is austenitic stainless steel (SS) of the following chemical composition: 20Cr–25Ni–Nb [1,2]. Previous investigations demonstrated feasibility of immersion ultrasound testing (UT) for thickness measurement of AGR fuel cladding [3].

* Corresponding author.
E-mail address: maxim.morozov@strath.ac.uk (M. Morozov).

http://dx.doi.org/10.1016/j.csndt.2016.08.001
2214-6571/

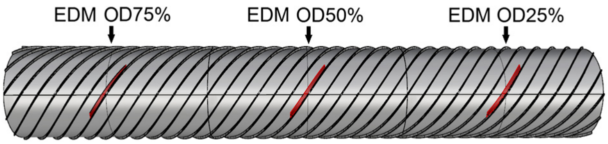

Fig. 1. AGR fuel cladding with helical EDM OD notches (red).

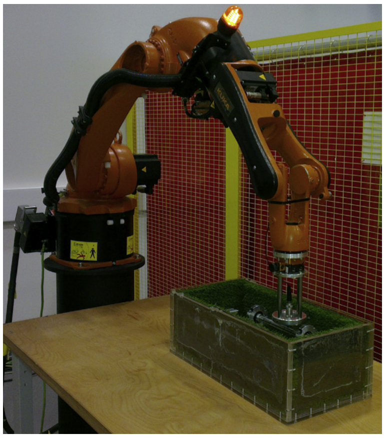

Fig. 2. Robotic 3D scanning of AGR fuel cladding.

This paper represents the first use of 6 axis robotic arm for ultrasonic inspection of AGR fuel cladding. It overcomes challenges with accurate positioning of the ultrasonic immersion transducer and its alignment in contrast to traditional 3D scanners. The sample's inherent thin wall prevents the use of standard time domain depth measurement, so a novel frequency domain technique is presented.

2. Methodology

2.1. Samples

The following samples were examined in this study:

1) Thin (381 μm) flat SS sheet with rectangular slots of 8 mm width and depths between 100 μm and 200 μm – used to investigate the sensitivity and resolution of immersion UT NDT when measuring thin layers;
2) AGR cladding with three Electric Discharge Machined (EDM) notches – to demonstrate feasibility of robotic delivery of UT thickness scan. Fig. 1 shows the location of helical Outer Diameter (OD) EDM notches on the fuel cladding (red). The notches had depths of 75%, 50% and 25% of the wall thickness, widths of approximately 200 μm and lengths of 2.5 mm. The three notches were positioned at 33 mm after each other along the pin axis.

2.2. Experimental setup

A measurement platform was developed which consisted of the following units:

1. Pulser/Receiver: JSR PR35, bandwidth 30 MHz.
2. Data acquisition: Digital Oscilloscope Tektronix DPO4054B (analog bandwidth 500 MHz, maximum sampling rate 2.5 GS/s).
3. Transducer: Olympus Immersion Transducer VIDEOSCAN series, central frequency 25 MHz ($f_L = 18.51$ MHz, $f_H = 30.20$ MHz, 0.25″ Element Diameter, Standard Case Style, Straight UHF Connector, Spherical Focus of 0.5 inch.
4. 3D CNC scanner Colinbus PB3D for the flat sample and an industrial robotic arm KUKA KR 5 arc HW for the AGR fuel cladding. Robot positional data were acquired via Robot Sensor Interface.
5. Desktop PC.
6. Immersion tank.

The experimental setup for 3D ultrasonic scanning of AGR fuel cladding is shown in Fig. 2. Partial (due the fact that the robot flange does not have sufficient Ingress Protection rating to enable it to submerge) cylindrical scans of the pin were performed with the immersion transducer always being oriented along the axial direction:

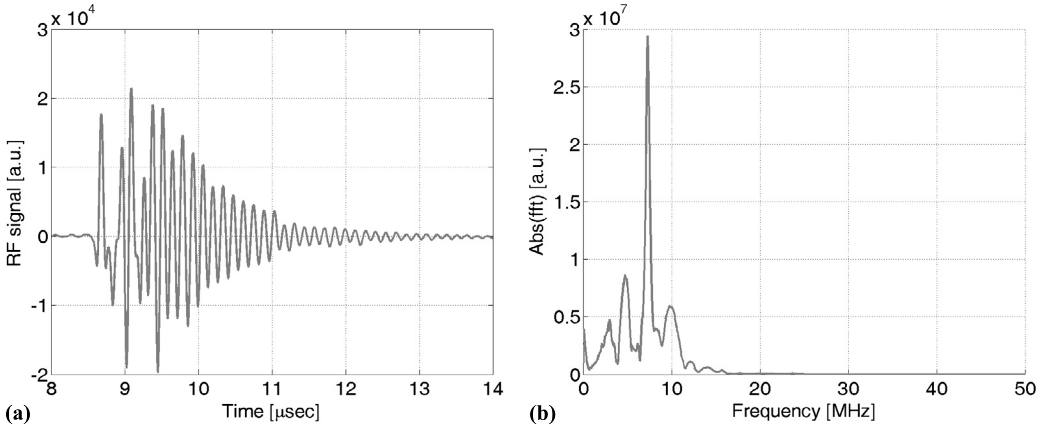

Fig. 3. (a) Ultrasonic RF signal and (b) signal FFT.

1. In the circumferential measurement direction the range was 80 degrees with a resolution of 1.79 degrees.
2. In the axial scanning direction the resolution was found to be 0.25 mm.

2.3. Thickness measurement technique

The main objective of the presented study was to automatically evaluate wall thinning of AGR fuel cladding. However the measurement of machined slots, representing cracks was also performed. Given the small thickness of the SS cladding (few hundreds of micro-metres), thickness measurement in the time domain based on pulse position difference between ultrasound reflections from the upper and back surfaces using a 25 MHz UT probe is challenging due to the low resolution of the reflections from the upper surface and the back wall. A frequency domain (spectral) approach was adopted whereby a high energy, non-damped ultrasonic pulse was transmitted into the sample which generated an RF response representing an attenuating oscillation with period proportional to the wall thickness as shown in Fig. 3a. A Fourier Transform was performed to estimate the frequency of this oscillation which corresponded to the maximum peak in the spectrum, see Fig. 3b. The thickness was then calculated from equation (1):

$$\text{Thickness} = \frac{1}{2}\frac{v_{sound}}{f_{peak}} \tag{1}$$

where velocity of sound in SS (v_{sound}) is 5.79 mm/μs.

The thickness sensitivity of the method is limited by the half wavelength of the ultrasonic wave corresponding to the highest frequency of the transducer bandwidth. Since the transducer used had $f_H = 30.20$ MHz, the minimum measurable thickness of stainless steel was approximately 96 μm. Thickness resolution is determined by the spectral resolution which is given as the ratio of sampling rate of the data acquisition to the number of acquired waveform points. In this case the practically achievable spectral resolution was 50 kHz corresponding to thickness resolution up to 10 μm. The Peak Frequency must not exceed the Nyquist limit (0.5 of the Sampling Rate). Since thickness is an inverse function of the peak frequency, thickness resolution is better for thinner samples.

A similar method was developed for accurate thickness measurement of the plate sample using air-coupled ultrasound. Lamb wave resonance allows efficient transmission of airborne sound waves through plates. This resonance occurs at a point of zero group velocity, located at the frequency minimum of the first order symmetric mode. At the zero group velocity frequency there is particularly efficient acoustic coupling between the air and the plate [4,5].

3. Results and discussion

3.1. Thickness measurements on the flat sample

Fig. 4 shows a 2D thickness map of the SS sheet with rectangular slots. Table 1 presents the statistical results of the measurement. The mean measured thickness was 17 μm higher than the nominal thickness of the sheet (381 μm). Uncertainty of the measurement was 1.7 μm. The deepest (the left-most) slot had higher roughness than the other slots resulting in strong scattering of incident ultrasonic waves and therefore inaccurate thickness measurement.

3.2. Robotic thickness measurements on the AGR pin

Fig. 5 shows a 3D thickness map of the AGR pin cladding obtained as result of a cylindrical robotic scan and Fig. 6 shows the corresponding single line thickness measurement. Table 2 presents statistical results of the ultrasonic thickness

Table 1
Thickness measurement result on flat SS sheet.

Minimum thickness, μm	391.2
Mean thickness, μm	398.0
Maximum thickness, μm	402.1
Standard deviation, μm	1.7

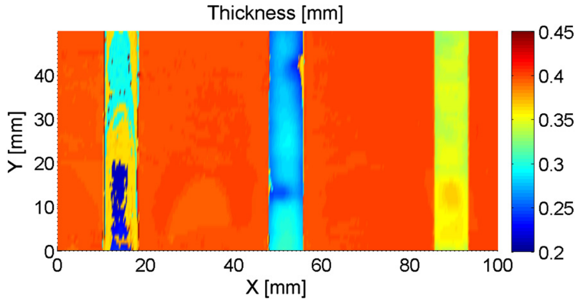

Fig. 4. Thickness map of the SS sheet with rectangular slots of depths between 100 μm and 200 μm.

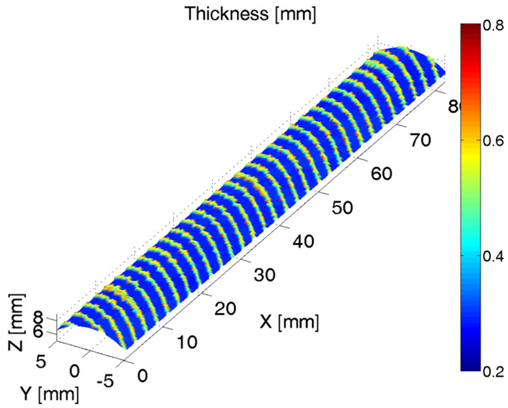

Fig. 5. 3D thickness map of the AGR pin cladding.

Table 2
Thickness measurement result on AGR pin.

Minimum thickness, μm	281.1
Mean thickness, μm	289.1
Maximum thickness, μm	298.5
Standard deviation, μm	3.7

measurement where the mean cladding wall thickness was determined to be 289.1 μm. The cladding thickness was independently measured with a Vernier calliper to be 300 μm. Since the ribs were very narrow, significant ultrasonic scatter was to be expected, thus leading to considerable noise of the thickness measurement above the ribs. Regarding the effect of error in the azimuthal direction, that is the deviation of the incident angle of the ultrasonic from normal to the pin surface, the maximum deviation angle at which thickness measurement became erroneous was found to be at an angle of 10.8 degrees. This was due to the ability of focused immersion transducers of the same frequency and size as opposed to unfocused, to tolerate more beam angulation or misalignment [6]. The total scan time was 6 hours and the scanning speed was limited by the fact that the signal acquisition system was distributed (external) with respect to the controller (PC). Bespoke signal acquisition system with an embedded microcontroller would enable much faster data processing. Positional data of the robot end effector was encoded every 12 ms. Therefore, in order to scan the sample surface with spatial resolution of 0.25 mm, linear scan speed should be below 20.83 mm/s:

$$\text{Scan Speed} \le \frac{\text{Spatial Resolution}}{\text{Encoding Cycle}} \le V_{\max} \tag{2}$$

where $V_{\max}$ is the maximum linear speed of the robot (2 m s^{-1}).

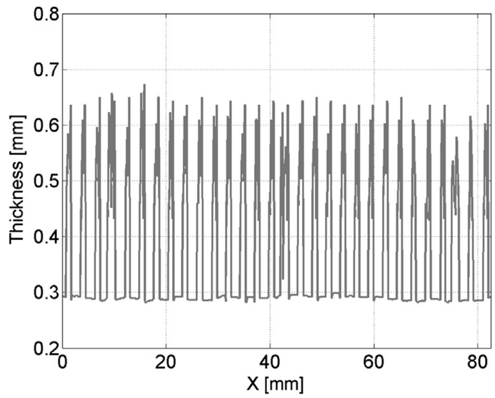

Fig. 6. Single line thickness measurement of the AGR pin cladding.

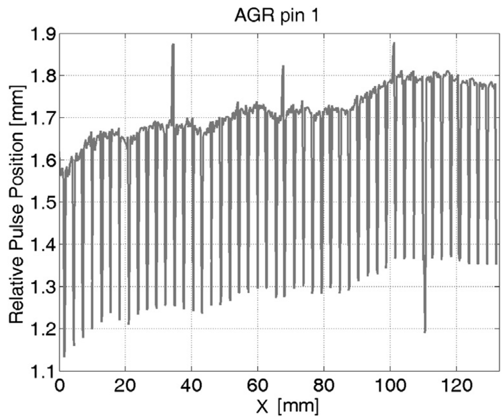

Fig. 7. Single line measurement of the relative position of the reflected pulse above the line containing the EDM notches.

3.3. EDM defect evaluation in the AGR pin by means of a linear scan with the ultrasonic transducer being carried by the robot

UT measurements in the time domain aimed at outer defect (EDM notches) detection were also carried out. Again the EDM orientation on the samples is shown in Fig. 1 in red. Fig. 7 shows the relative position of the reflected pulse obtained by a linear scan along the pin axis. Since the ribs represented an addition to the cladding wall outer diameter, they were closer to the transducer and their position was smaller. As expected, rib height was indicated at approximately 400 µm. UT responses to the EDM notches (oriented along ribs as shown in Fig. 1, 2.5 mm long) can be clearly distinguished from the ribs reflections at about 35 mm, 68 mm and 101 mm. The notches had depths approximately 75%, 50% and 25% of the wall thickness. (Note, the baseline drift in Fig. 7 was due to inaccuracy of the robot positioning.)

4. Conclusions

This paper has presented the results of an experimental feasibility study of robotic ultrasonic measurement of the cladding wall thickness of fuel pins of Advanced Gas-cooled Reactor (AGR) for various typologies of defects. It has been demonstrated that it was possible to measure the thickness of AGR fuel cladding, specifically between 96 µm and 700 µm, using a 25 MHz focused ultrasonic immersion transducer by means of the frequency domain approach. It has been experimentally shown that robotic 3D scanning of AGR fuel pins can be implemented with a spatial resolution of 0.25 mm with a linear scan speed not exceeding 20 mm/s. Small (2.5 mm long) and shallow (100 µm in depth) crack-like defects (EDM notches) were detected using time-domain techniques. Robot positional inaccuracy (±1 mm) in the radial direction did not significantly affect the thickness measurement. The angle of deviation of the incident angle of the ultrasonic from normal to the pin surface, at which thickness measurement became erroneous, was found to be 10.8 degrees. This paper represents the first use of 6 axes robotic arm delivery of ultrasonic inspection of AGR fuel cladding. It overcomes traditional challenges with accurate geometric positioning of the ultrasonic immersion transducer and its alignment in comparison to traditional Cartesian axis 3D scanners. The sample's small wall thickness prevented the use of standard time domain depth measurement; therefore a novel frequency domain technique was developed.

Following the conclusions of this report the following recommendations are made:

- If ultrasonic inspection is considered to be suitable as part of a future fuel condition monitoring and inspection regime then further research will be required into the development of bespoke signal acquisition electronics.
- Development of a method for an in situ robot base calibration will be required for the deployment of any robotic based deployment solution.
- A full system should be tested on active samples in order to assess its performance in a radiation environment.
- For practical application a fully submersible manipulator flange would be desirable.

Acknowledgements

This work was funded by the Nuclear Decommissioning Authority.

References

[1] Bolton G. Corrosion sensing for advanced gas-cooled reactor fuel cladding. NNL 12302 ed 2012.
[2] Bolton G. AGR fuel cladding corrosion monitoring using electrical potential drop. NNL 12788 ed 2014.
[3] Bolton G. AGR fuel cladding thickness measurement using ultrasonic immersion testing. NNL 12789 ed 2013.
[4] Holland SD, Chimenti DE. Air-coupled acoustic imaging with zero-group-velocity Lamb modes. Appl Phys Lett 2003;83:2704–6.
[5] Holland SD, Chimenti DE. High contrast air-coupled acoustic imaging with zero group velocity lamb modes. Ultrasonics 2004;42:957–60.
[6] Fowler K, Elfbaum G, Nelligan T. Theory and application of precision ultrasonic thickness gaging. NDTnet 1997;2.