Robotic Ultrasonic Inspection of AGR Fuel Cladding

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Abstract

The purpose of the presented work was to undertake experimental trials to demonstrate the potential capabilities of an in-situ robotic ultrasonic scanning technique for measuring and monitoring loss of the cladding wall thickness in fuel pins of Advanced Gas-cooled Reactors (AGR) using inactive (i.e. non-radioactive) samples. AGR fuel pins are stainless steel cylindrical ribbed pipes of length circa of 1000 mm, inner diameter of the rod being circa 15 mm and wall thickness of circa 300µm. 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 25MHz was used to measure wall thickness of the AGR fuel cladding using a frequency domain technique. Cylindrical ultrasonic scan of the samples

was performed using industrial robotic arm KUKA KR 5 arc HW. Also, very short (2.5mm long) and shallow (100μm in depth) crack-like defects were detected using time-domain technique.

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. Figure 1 shows an illustration of the geometry of the AGR fuel cladding. AGR fuel pins are stainless steel cylindrical ribbed pipes of circa 1000mm length, average diameter of the pin is circa 15mm, wall thickness is circa 300μm, rib height is circa 400μm and rib pitch is 2.75mm. Material of AGR fuel cladding is austenitic stainless steel (SS) of the following chemical composition: 20Cr-25Ni-Nb [1, 2]. Its electrical conductivity σ is reported to be 0.993 MS/m [1, 2]. Normally, austenitic SS is non-ferromagnetic, that is its relative magnetic permeability (μ_r) is very close to 1. These electromagnetic properties make AGR fuel cladding suitable for inspection by means of electromagnetic Non-Destructive Testing (NDT) methods such as Eddy Current Testing (ECT) [3]. Previous investigations showed feasibility of immersion ultrasound testing (UT) for thickness measurement of AGR fuel cladding [4].
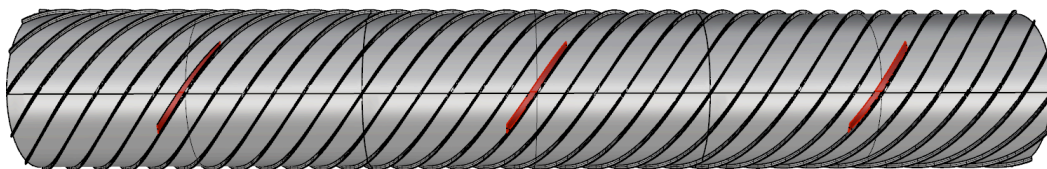

Figure 1. AGR fuel cladding with helical EDM notches (red).

2. Methodology

2.1 Samples

The following samples were examined in this study:

1) Thin (381μm) flat SS sheet with rectangular slots of 8mm width and depths between 100μm and 200μm – to investigate sensitivity and resolution of immersion UT NDT when measuring thin layers;

2) AGR cladding with Electric Discharge Machined (EDM) notches – to demonstrate robotic delivery of UT thickness scan.
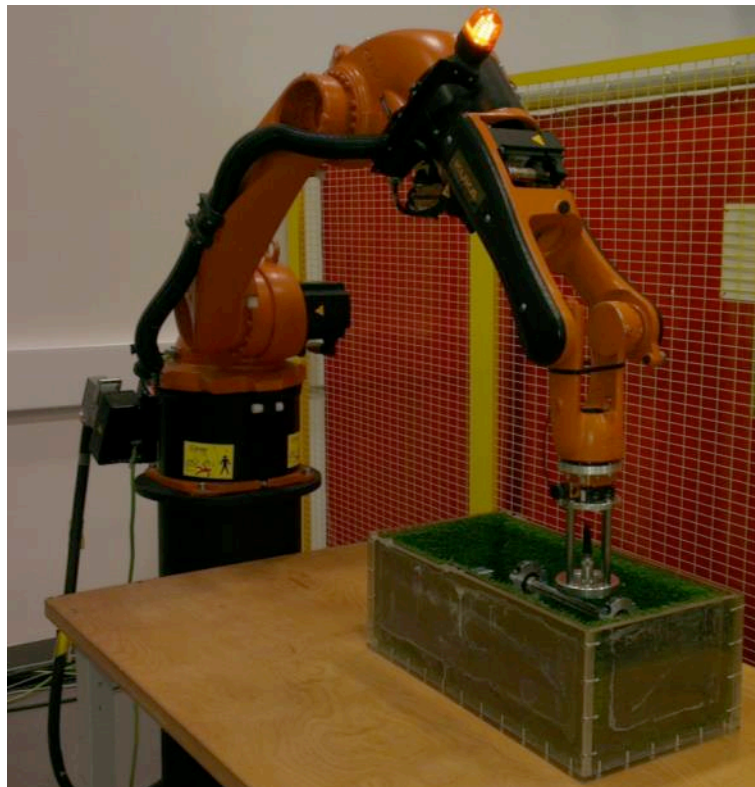

Figure 2: Robotic 3D scanning of AGR fuel cladding

2.2 Experimental setup

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

1. Pulser/Receiver: JSR PR35 [5], bandwidth 30MHz

2. Data acquisition: Digital Oscilloscope Tektronix DPO4054B (analog bandwidth 500MHz, maximum sampling rate 2.5GS/s) [6]

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 [7]

4. 3D CNC scanner Colinbus PB3D [8] for the flat sample and an industrial robotic arm KUKA KR 5 arc HW [9] for the AGR fuel cladding. Robot positional data were acquired via Robot Sensor Interface [10]

5. Desktop PC

6. Immersion tank

The experimental setup for 3D ultrasonic scanning of AGR fuel cladding is shown in Figure 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:

1. In circumferential measurement the range was 80 degrees with resolution of 1.79 degrees

2. In axial direction the resolution was found to be 0.25mm

2.3 Thickness Measurement Technique

The main objective of the presented study was to automatically evaluate wall thinning of AGR fuel cladding, 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 25MHz UT probe is challenging due to the low resolution. Therefore a frequency domain (spectral) approach was used. A high energy, non-damped ultrasonic pulse is transmitted into the sample which generates an RF response representing attenuating oscillation with the period proportional to the wall thickness as shown in Figure 3a. Fourier transform is carried out to find the frequency of this oscillation which corresponds to the maximum peak in the spectrum, see Figure 3b. Then thickness is found as follows:

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

(1)

Speed of Sound in SS (v_{sound}) is 5.79 mm/μs.

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 would be approximately 96 μm. Thickness resolution is determined by the spectral resolution which is given as ratio of sampling rate of the data acquisition to the number of acquired waveform points. In this case the practically achievable spectral resolution was 50kHz. 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.
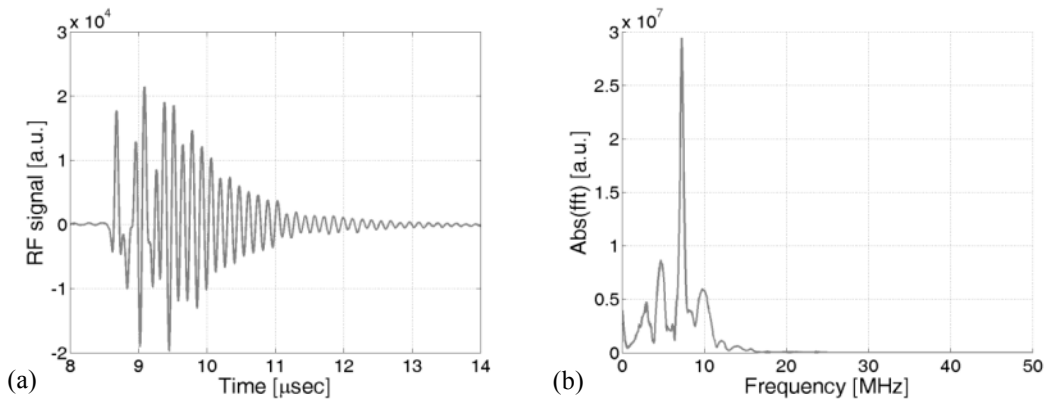

Figure 3. (a) Ultrasonic RF signal and (b) signal FFT

3. Results and discussion

3.1 Thickness measurements on the flat sample

Figure 4 shows a 2D thickness map of the SS sheet with rectangular slots. Table 1 presents statistical results of the measurement. The mean measured thickness is 17μm higher than the nominal thickness of the sheet (381μm). However, it should be kept in mind that a generic sound speed in SS was used in calculation (speed of sound for this specific material is not known). Uncertainty of the measurement is 1.7μm. The deepest

(the left-most) slot had higher roughness than the other slots resulting in strong scattering of ultrasonic wave and therefore inaccurate thickness measurement.

Table 1. Thickness measurement result on flat SS sheet

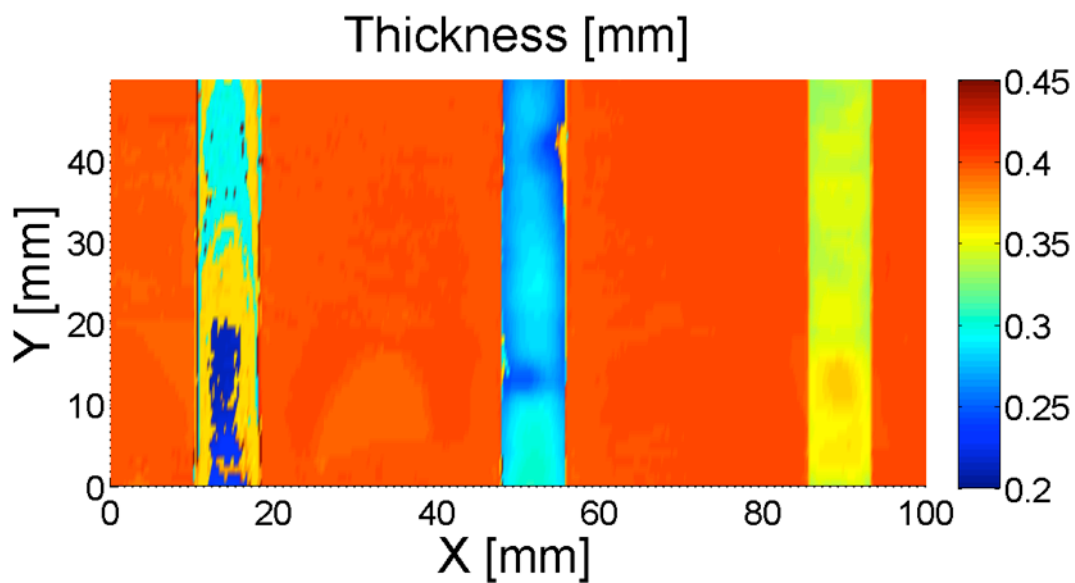|	
Minimum Thickness, μm	391.2
Mean Thickness, μm	398.0
Maximum Thickness, μm	402.1
Standard deviation, μm	1.7

Figure 4. Thickness map of the SS sheet with rectangular slots

3.2 Robotic thickness measurements on the AGR pin

Figure 5 shows 3D thickness map of the AGR pin cladding obtained as result of a cylindrical robotic scan. Three "thick ribs" (forth from the left, centre-most and forth from the right) correspond to the ribs which have EDM notches near their root. Figure 6 shows single line thickness measurement of the AGR pin cladding. Table 2 presents statistical results of the measurement. It transpires that the mean cladding wall thickness was determined to be 289.1μm. The cladding thickness was measured with a calliper to be 300μm. The ribs are very narrow and strongly scatter the ultrasound wave, therefore thickness measurements above ribs exhibits considerable noise.

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 becomes erroneous was found to be at an angle of 10.8 degrees. This is 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 [11]. Total scan time was 6 hours. The main limitation of scanning speed consists of 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. Also, positional data of the robot end effector was encoded every 12ms. That is spatial resolution of 0.25mm requires linear scan speed not higher than 20.83 mm/s:

$$\text{Scan Speed} \leq \frac{\text{Spatial Resolution}}{\text{Encoding Cycle}} \leq V_{max}$$

(2)

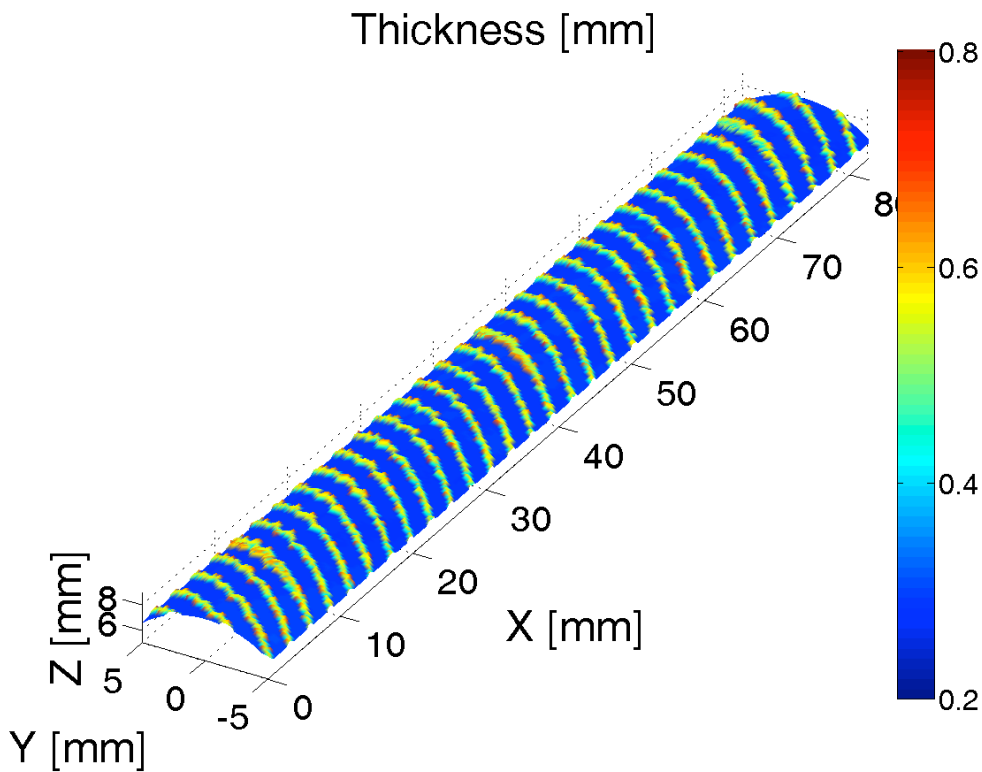Where V_{max} is the maximum linear speed of the robot (2 ms^{-1}).

Figure 5. 3D thickness map of the AGR pin cladding
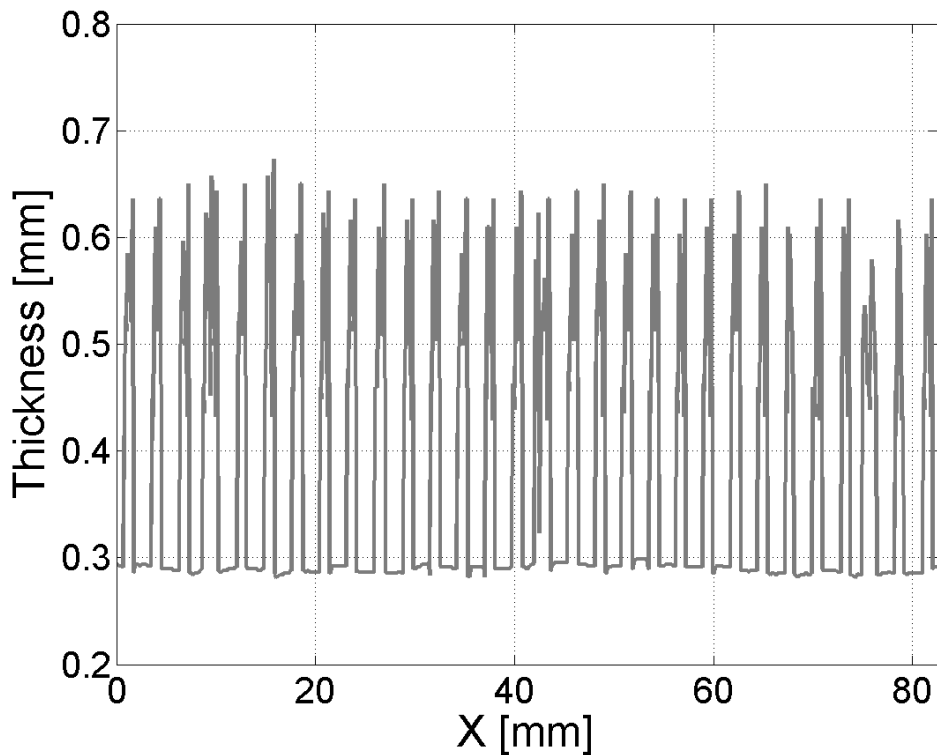
Figure 6. Single line thickness measurement of the AGR pin cladding

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

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 carried out. Figure 7 shows a single line scan of the relative position of the reflected pulse. Since the ribs represent an addition to the cladding wall outer diameter, they are closer to the transducer and their position is smaller. As expected, rib height is approximately 400μm. UT responses to the EDM notches (oriented along ribs, 2.5mm long) can be clearly distinguished from the ribs reflections at circa 35mm, 68mm and 101mm. The notches were approximately 75%, 50% and 25% of the wall thickness.

There is a visible drift in the stand-off of the transducer from the pin surface due to robot's inaccuracy, this drift manifests itself in the increasing trend visible across the graph.
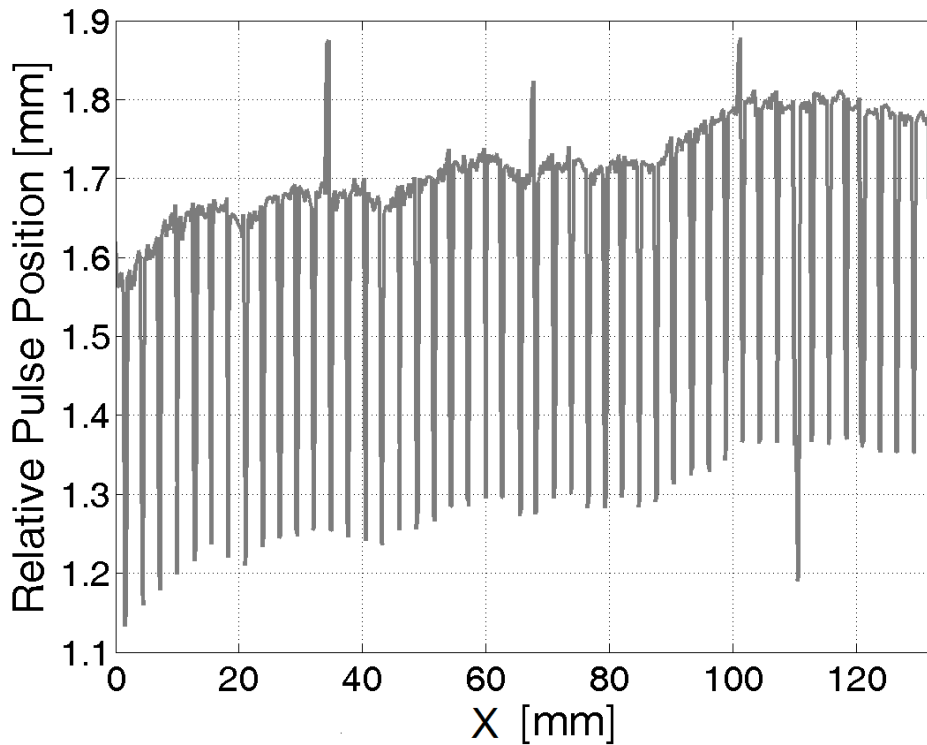

Figure 7. Single line measurement of the relative position of the reflected pulse

3. Conclusions

This paper presented 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 is possible to measure the thickness of AGR fuel cladding, specifically between 96μm and 700μm, using a 25MHz 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 spatial resolution of 0.25mm with a linear scan speed not exceeding 20 mm/s. Small (2.5mm long) and shallow (100μm in depth) crack-like defects (EDM notches) can be detected using time-domain techniques. Robot positional inaccuracy (±1mm) in the radial direction does not significantly affect the thickness measurement. Angle of deviation of the incident angle of the ultrasonic from

normal to the pin surface, at which thickness measurement becomes erroneous, was found to be 10.8 degrees.

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 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.
- The full system should be tested on active samples in order to assess its performance in a radiation environment.

Acknowledgements

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