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Study of asymmetric gradiometer sensor configurations for eddy current based non-destructive testing in an industrial environment

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ABSTRACT

This paper presents the design and validation of a novel eddy current (EC) probe that can be used to detect deep sub-surface cracks and characterise the properties of graphite bricks, such as those used to make up the core of an Advanced Gas-cooled Reactor (AGR). In this study, a curved asymmetrical gradiometer probe has been devised and optimised to enhance the depth sensitivity to defects and conductivity variations in the graphite. Experimental and numerical studies are carried out. The results show an average of 43.00% improvement in sensitivity compared to a traditional axial gradiometer routinely used during AGR core inspections. Further experimental tests on a graphite brick containing multiple closed key-way root sub-surface cracks show the superiority of the proposed probe over the traditional probe at locating deep sub-surface cracks that were not detected previously.

1. Introduction

The Advanced Gas-cooled Reactor (AGR) is a type of reactor that is only operated in the United Kingdom (UK). Currently there are fourteen operational AGRs in the UK, located at seven different power stations. The majority of the AGR core is made up of stacked bored cylindrical graphite bricks, which serve to moderate the fast-moving neutrons, maintain the lattice spacing between the fuel elements and control rods, and provide a pathway for the flow of the coolant gas [1].

The graphite bricks, which constitute the AGR core, are prone to degradation caused by the high radiation levels and the coolant chemistry. Those bricks which are in direct proximity to the fuel elements tend to suffer the highest radiation flux. As a result, they suffer from irradiation and radiolytic oxidation during the course of their lifetime [2,3]. Irradiation causes the AGR graphite bricks to undergo dimensional change, the rate of which is dependent upon their radiation dose [2,3]. The parts of the brick at the bore, which are nearest to the fuel elements, are exposed to the highest levels of radiation. This gives rise to a gradient in the radiation level over the radial cross-section of the brick. This irradiation gradient introduces differential stresses between the graphite bore and periphery, and may eventually lead to cracking. The tensile stress at the bore is higher than the periphery during the early life of the reactor, and hence crack growth tends to occur from the bore outwards to the periphery. As the reactors age the tensile stress becomes larger at the periphery and cracks are then expected to initiate from the graphite key-way corners and grow towards the bore.

The graphite bricks in the reactor core are irreplaceable; therefore the general operational and safety functions of the AGRs depend significantly upon the condition of these bricks. For this reason, the ability to monitor the effects of graphite ageing mechanisms is essential in assessing the condition of the bricks in the core, which in turn is essential for supporting the safety case for continued operation of the reactors.

Eddy current (EC) based Non-Destructive Testing (NDT) is now being routinely used to inspect the AGR graphite for crack formation and for near-surface density mapping. The authors in Ref. [4] have developed a complete EC inspection system, which is now being used during statutory inspections. On metals, EC could not be used at the thicknesses (≈ 95 mm) of interest in the graphite bricks. The reason that the EC method is suitable for nuclear graphite inspection is because graphite has a much lower electrical conductivity than typical metals (≈ 100 kS/m for virgin graphite), so the EC at any given frequency penetrates further. With the application of Multi-Frequency (MF) EC techniques, it is possible to probe the graphite brick to different depths and collect enough data to assess the presence of a defect or characterise graphite properties [6,8].

A study concerning the detectability of graphite sub-surface slots

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was carried out by *Fletcher* et al. [5]. They investigated the effects of different key-way originating slots on the MF response of two different symmetrical gradiometer sensors and proposed a technique by which the positions and the sizes of the slots could be estimated. However, this study was limited to slots, and in the case of a realistic sub-surface crack, especially closed crack identification becomes more complicated as contact between the crack faces could allow the passage of induced eddy currents. In order to detect a closed crack the probe sensitivity needs to be sufficient. A recent study by *Tesfalem* et al. [6] demonstrated the ability of the EC system to achieve greater sensitivity through the entire radial thickness of a cylindrical graphite brick compared to the existing gradiometer sensor. Increased probe sensitivity throughout the entire radial extent of the graphite brick also increases the likelihood of identifying closed sub-surface cracks. This is particularly useful when inspecting for key-way root cracks, which are expected to initiate from brick key-way corners and to grow inwards towards the bore.

This paper presents detailed experimental and numerical studies of a new asymmetric probe empirically optimised for inspection of the graphite bricks in an AGR core. This is then followed by an experimental study of closed graphite key-way root cracks (the types of crack expected in AGR core), which were produced in an unirradiated fuel channel brick test specimen. The sensor configuration is based on an asymmetric axial gradiometer arrangement, which has been devised to maximise the depth sensitivity. This paper demonstrates that greater depth sensitivity can be obtained by optimising the geometry of the sensor coils. This approach may be of interest to the wider EC NDT community as it suggests that depth sensitivity could be increased for other EC applications in metals, albeit with smaller diameter and higher-frequency probes.

2. Background

2.1. Overview of the NDT problem

The problem considered in this paper aims to deal with NDT application in an industrial environment such as those the cores of AGRs. In general case, the industrial environment refers to the environments that could potentially affect the output signal of the NDT due to external industrial activities, operational conditions and deployment or inspection access and procedures. For instance, the AGR core has a very complex structure allowing inspection only through the fuel channel bricks, and hence the inspection tool can only be deployed from the top of the pile cap using chain and umbilical cables. This in turn results in additional stray capacitance reducing the range of frequencies that the core could be inspected. Secondly, the inspection tool is designed such that it can be decontaminated when necessary, and maintain certain weight for other safety related factors. In this particular case, the inspection tool is covered with stainless steel casing, which could affect the EC measurements if the probe is not configured in such a way that it maintains maximum detection capability. Although this paper considers only the AGR core environment to enhance the detection of deep sub-surface cracks, the arrangement of the proposed sensor could also be used within other industrial applications such as high and low temperature tube inspection systems.

As briefly mentioned above the existing NDT of the graphite core in the AGRs is carried out from the brick bores using a specialised in-core inspection tool known as the Prototype Eddy Current Inspection Tool (PECIT). This tool is deployed from the top of the pile cap, and is fitted with three EC sensors separated circumferentially round the tool by 120^o. The EC sensors in the tool are arranged to inspect the graphite brick over its radial cross section as well as to measure the density variation around the brick bore axially and circumferentially [4]. The tool has a rotating head enclosed by a cylindrical stainless steel casing, and uses non-conducting mechanical scissor-type arms to deploy the EC sensors towards the fuel channel bore (see Fig. 1). The inspections are made during the outages of the reactors while the fuel elements are removed, and during the inspection the tool is lowered into the bores of the fuel channel bricks using chains and an umbilical cable. The measurement speed, location and other inspection functions of the tool are set from the control console on the pile cap.

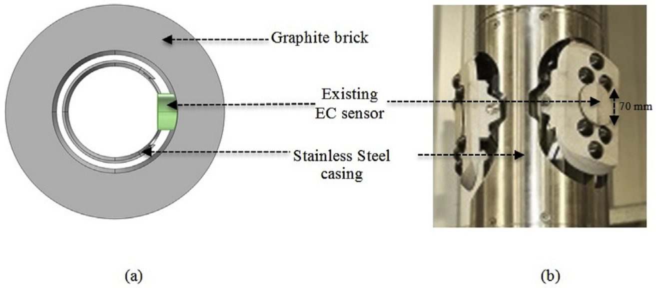

Fig. 1. (a) Simplified cross-sectional view of the tool stainless steel casing and the fuel channel brick and (b) section of the PECIT.

The EC sensors currently used to inspect the fuel channel bricks are based on a symmetrical gradiometer, which has a maximum diameter of 70 mm, and provides valuable information about the condition of the fuel channel bricks. However, as this sensor was initially designed for near-surface defect detection and graphite bulk density mapping, it may lack the desired sub-surface sensitivity at greater depths from the graphite bore. It may be possible to increase the gradiometer probe sensitivity at greater depths through optimisation of the sensor parameters. However, due to the mechanical constraints imposed by the complex geometry of the graphite brick and the inspection tool, the optimisation process is restricted, and hence the maximum sensitivity that can be achieved may be limited. For instance, increasing the existing gradiometer sensor diameter would increase its sensitivity with depth, but at the same time the graphite brick curvature and the interaction of the tool stainless steel casing with the EC fields constrains the amount by which the sensor diameter can be increased.

The primary issue this paper addresses is how to devise a sensor that increases the sensitivity to deep sub-surface defects whilst minimising the electromagnetic field interaction with the conducting components of the PECIT. Fig. 1a illustrates a simplified cross-sectional arrangement of the PECIT and the fuel channel brick, whereas Fig. 1b shows an image of the PECIT, which consists of a stainless steel casing and the existing EC sensor.

2.2. Asymmetric gradiometer approach

A gradiometer sensor is a type of magnetic field sensor that measures the magnetic field gradient generated from an external source in the form of differential output voltages V_{grad} between the induced voltages in the pickup (PC) and backing-off (BC) coils (1).

$$V_{grad} = V_{pc}(t) - V_{bc}(t) \tag{1}$$

In the case of a conventional axial gradiometer, which is often used for material characterisation and defect identification, the PC and BC coils are made using the same parameters and are placed on opposite sides of the exciter (Tx1) coil with identical separation distances. This allows the gradiometer to maintain symmetry, and hence cancellation of the background field during the inspection of a material. In contrast, the axial asymmetric gradiometer sensor is configured with different parameters for the PC and BC coils, including coil radius, number of turns and separation distance from the Tx1. This in turn changes the symmetry of the gradiometer, but compensated through the selection of an appropriate turns ratio between the PC and BC coils. The main advantage of the asymmetric gradiometer configuration is that the sensor geometry is not constrained by the symmetry requirement of the system. Therefore, each coil could be independently optimised to

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