POTENTIAL ROLE OF NEUTRON DIFFRACTION AND RADIOGRAPHY IN THE NDE OF HIGH VALUED ENGINEERING SYSTEMS

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ABSTRACT

Neutron diffraction and radiography methods are well suited to provide essential information on the assessment of residual stresses in bulk components as well as problems associated with the ingress of water/moisture/oil into encapsulated structures such as aircraft wings and helicopter blades. Residual stresses are analysed through the direct investigation of the material microstructure properties where the material crystalline lattice parameters serves as a built-in strain gauges that are read by diffraction. For the ingress of water/moisture/oil, the detection of aluminium corrosion, etc., the elementally selective neutron absorption characteristics of hydrogeneous materials, aluminium and its corrosion products are employed. The nuclear methods are also useful in specialized fault analysis and quality assurance applications. Facilities for these analyses exist at the SAFARI-1 Research Reactor of NESCA near Pretoria.

1 Introduction

The nuclear based methods, neutron diffraction and neutron radiography, employ thermal neutrons for the non-destructive evaluation of materials and components. Amongst others thermal neutrons are produced during the fission process of ^{235}U in a steady state nuclear reactor such as the SAFARI-1 Research Reactor of NECSA located close to Pretoria. These neutrons with energies in the range 24 meV to 660 eV, have enhanced penetrating capabilities into most material, especially the conventional engineering materials aluminium, all types of steel, super alloys and metal-matrix composite materials. To illustrate this, Table 1 compares the 50% transmission thicknesses for different types of radiation through a number of elements that constitute the technologically important materials.

X-rays in general are stopped by “dense” (high atomic number) materials and pass through “light” ones, while in many instances, neutrons have the reverse quality. Neutrons can for example reveal details of plastic, oil, rubber and water encapsulated inside steel, aluminium, or lead owing to the high neutron attenuation coefficient of hydrogen (Mass attenuation coefficient (MAC) = 22,38cm^2/g; and Macroscopic cross-section $\mu =$ 0.002cm^{-1}). Table 2 gives an indication of the density and linear attenuation coefficient (LAC) of hydrogen, aluminium, its corrosion products and water. As the latter two substances have distinctly different neutron attenuation coefficients than pure aluminium, such phases can be visualized in components encapsulated in aluminium.

The superior penetrating capabilities of neutrons, their large MAC contrast for many elements, as well as their wave properties, provide ideal probes for the NDE of materials.

Table 1: Penetrating capabilities of different types of radiation

Material	Density	310 keV X-rays		1.33 MeV Gamma rays		25 meV Neutrons	
		MAC [cm^2/g]	$T_{50\%}$ [mm]	MAC [cm^2/g]	$T_{50\%}$ [mm]	MAC [cm^2/g]	$T_{50\%}$ [mm]
Pb	11.1	0.354	1.8	0.056	11.2	0.032	19.5
Pt	21.4	0.324	1.0	0.059	5.5	0.058	5.6
W	18.9	0.3	1.2	0.056	6.5	0.079	4.6
Sn	7.29	0.156	6.1	0.049	19.4	0.023	41.3
Fe	7.86	0.11	8.0	0.053	16.6	0.15	5.9
Al	2.7	0.103	24.9	0.053	48.4	0.031	82.8

MAC=Mass attenuation coefficient

$T_{50\%}$ = Thickness of material that reduces the incident intensity by 50%

Table 2: Thermal neutron attenuation coefficient of hydrogen, water, aluminium and its corrosion products.

Material	Density	LAC [cm-1]	MAC [cm^2/g]
H	9 x10^{-5}	2 x 10^{-3}	22.4
H_2O	1	3.45	3.45
Al	2.7	0.09	0.03
$Al(OH)_3$	2.53	2.4	0.95
AlO(OH)	3.014	1.5	0.5

2 SAFARI-1 facilities

SAFARI-1, the research reactor of NECSA, is a light-water cooled and moderated steady state reactor that produces neutrons for commercial applications, as well as in support of industrial technology development and research [1]. A number of beam-line facilities exist along the southern perimeter of the reactor pool where the properties of thermal neutrons are employed to analyse various properties and characteristics of condensed matter and engineering components. Two facilities of importance to this forum are neutron diffraction and neutron radiography.

2.1 Neutron diffraction

Neutron diffraction is an analysis method in which the microstructures of crystalline materials are investigated to provide information on various material properties and phenomena [2]. One specific application of value to the mechanical engineering fraternity is the NDE of the three-dimensional residual strains/stresses fields existing within materials and components. Residual strains/stresses are defined as those elastic strains/stresses that exist in a material in the absence of external forces. They result primarily from the inhomogeneous thermal/metallurgical/mechanical processes which include differential plastic flow of material regions such as during manufacture, differential cooling of large parts for example in the vicinity of welds, or from differential volume changes or volumetric mismatch of constituent phases. The total stress that any volume of material experiences is the vector sum of the applied external loading and residual stresses. As a rule of thumb, tensile residual stresses are detrimental as they favour crack propagation. Conversely compressive stresses are purposefully induced in a material as they mitigate against crack growth.

With the neutron diffraction method the penetrating capabilities of thermal neutrons together with their intrinsic wave properties are exploited to enable direct investigation of the material crystalline lattice at dimensions of 10^{-10}m. When a bulk specimen is strained/stressed, the lattice-plane spacing invariably senses this. The magnitude of their deformation depends on the lattice-plane orientation with respect to the stress direction. Diffraction can measure lattice-plane (d_{hkl}) spacing with very high accuracy. Subsequent variations in d_{hkl} are converted to lattice strains (ε_{hkl}) with

$$\varepsilon_{hkl} = \frac{d_{hkl} - d^0{}_{hkl}}{d^0{}_{hkl}}$$

where $d^0{}_{hkl}$ is the strain-free reference lattice-plane spacing.

Residual strain analysis is performed in the interior of samples by selective exposure of material regions to the neutron beam. This probe volume is devised with apertures inserted in the incident and scattered beam paths as shown in Fig.1. The measured strains (ε_j) are related to the tri-axial stress state (σ_i) through the generalized Hooke's law [3]

$$\sigma_i = \frac{E}{1+\nu}\left[\varepsilon_i + \frac{\nu}{1-2\nu}\sum \varepsilon_j\right]$$

E and ν are the material Young modules and Poisson ratio.

The strain measurement protocol comprises accurate Bragg peak shift measurements at different positions inside the material by diffraction, conversion of the Bragg peak shifts to strains, and then to stresses using elasticity theory to introduce the three-dimensional strain fields.

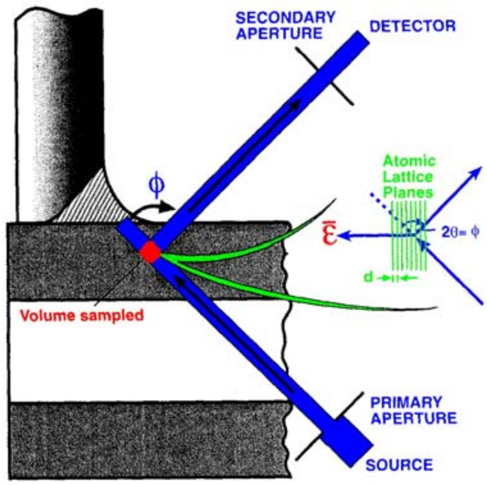

Figure 1. Schematic representation of the neutron strain scanner.

2.2 Neutron radiography

Radiography is based on the principle that radiation (x-rays, gamma rays or neutrons) is attenuated by matter through absorption and scattering. In general the methods provide complementary information as shown in Table 1 with the degree of attenuation being different for different materials. Neutron radiography[1] employs the elementally selective attenuation of thermal neutrons in matter to image the interior of non-transparent materials and components. The process is described by the equation

$$\varphi = \varphi_0 e^{-\Sigma \rho x}$$

Where φ is the intensity after attenuation by the sample, φ_0 the radiation incident on the sample, Σ the attenuation coefficient, ρ the density of the sample and x the thickness of the sample traversed by the beam.

Therefore high attenuating materials in the presence low attenuating materials can be visualized. In the case of neutron radiography the shadow image of the transmitted intensity is imaged by capturing on a CCD chip or with conventional film methods. Each method has it inherent advantages and disadvantages. With CCD imaging, radiographs are acquired within a few seconds. This is ideal for the investigation of dynamic events such as the flow of water/moisture/oil through encapsulated structures such as concrete and porous rock. Film methods are more tedious, but give better spatial resolution, 50µm compared to the 100µm of CCD systems.

A schematic of the SAFARI-1 neutron radiography facility is given in Fig. 2.

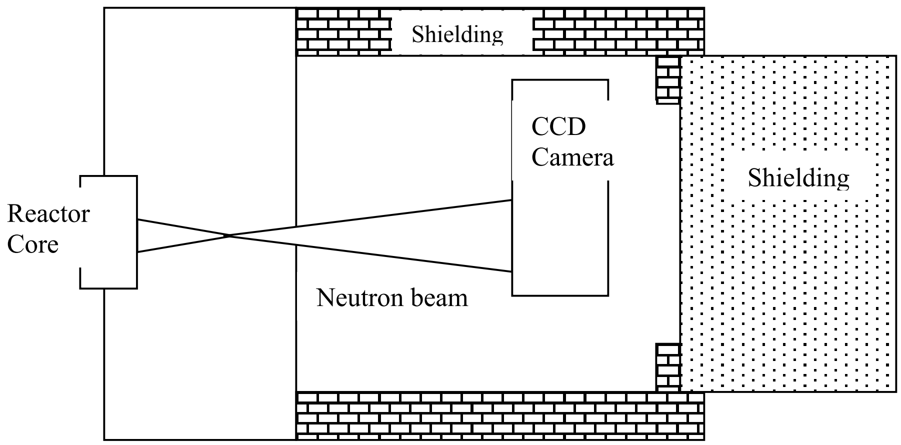

Figure 2. Schematic representation of the SAFARI-1 neutron radiography facility.

The applications of the method are in the detection of water/moisture/oil ingress in bulk and enveloped structures, the presence of aluminium corrosion products, delaminations in bonded structures, as well as in quality assurance problems of enveloped structures and components. Selective examples are given in section 3.

3 Fields of application

3.1 Residual strain/stress

The three-dimensional residual strain/stress fields have significant influences on the effective strength of materials and components as they may enhance or degrade material properties through processes such as fatigue, fracture, corrosion, wear, friction, etc., depending on their sign and magnitude. A number of typical systems to illustrate the neutron diffraction strain measurement method are discussed.

- T-butt welded mild steel plate

  During welding, stresses close to the yield stress of the material may be induced by the longitudinal contraction effects associated with the differential cooling of the material regions. Shown in Fig. 3 are the residual strains that exist in the base-plate section of a T-butt welded plate. Comparison of variations in the magnitudes of the strains on the respective welds, A and B, reveal that the heat input during weld B relieved some of the strain generated by the first weld. Diffraction therefore can also be employed as an effective heat treatment processes verification procedure.

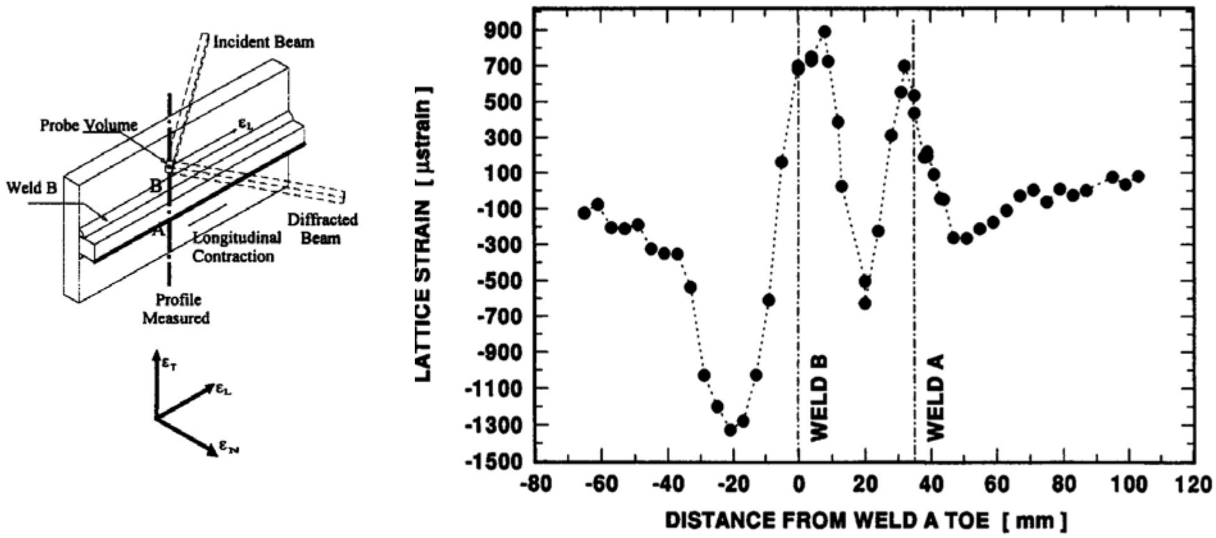

Figure 3.: Left: Geometry of the T-butt weld. The welds are located at positions A and B. Right: Residual strains associated with the longitudinal contraction from the different material regions during the inhomogeneous heating and cooling processes.

- Autofrettaged tubes/cold expansion of fastener holes.

  In many applications, compressive strains are deliberately induced in components to improve their strength and fatigue properties. Examples are autofretaged tubes[4.5] and fastener holes (widely used in the aerospace industry). The technique essentially consist of over pressurising the internal bore in a controlled manner (using a fluid or pulling an oversized mandrel through the hole). This creates substantial compressive stresses at the bore due to plastic flow during deformation. Shown in Fig. 4 is the identification of the regions over which of the plastic deformation extends from the bores of two autofrettaged steel tubes of different wall thickness ratios referenced to a stress-relieved sample [4].

3.2 Aluminium corrosion in enclosed structures

Erosion of aluminium structures due to corrosion can lead to failures as a result of material loss, as well as delamination or debonding of parts in integrated airframe structures. A primary cause is the ingress of water and/or moisture beneath the aluminium skin.

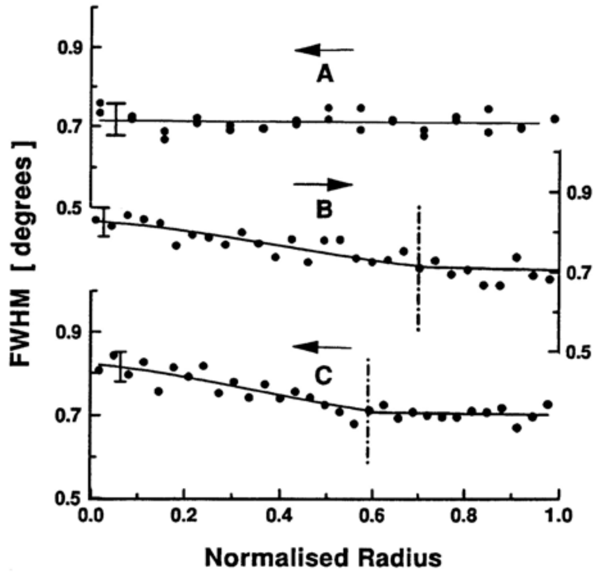

Figure 4. Full with at half maximum intensity of Bragg peaks used to identify the plastic boundaries across the wall of three different samples. A, represents the stress-relieved reference, with B and C the respective autofrettaged sections of different wall thickness ratios.

Qualitative investigations on helicopter blade sections, in service for many years (20), revealed the following problem areas on the tip and cuff regions [6]:

- Ingress of water/moisture/oil within the internal regions shown by the black areas of Fig. 5.

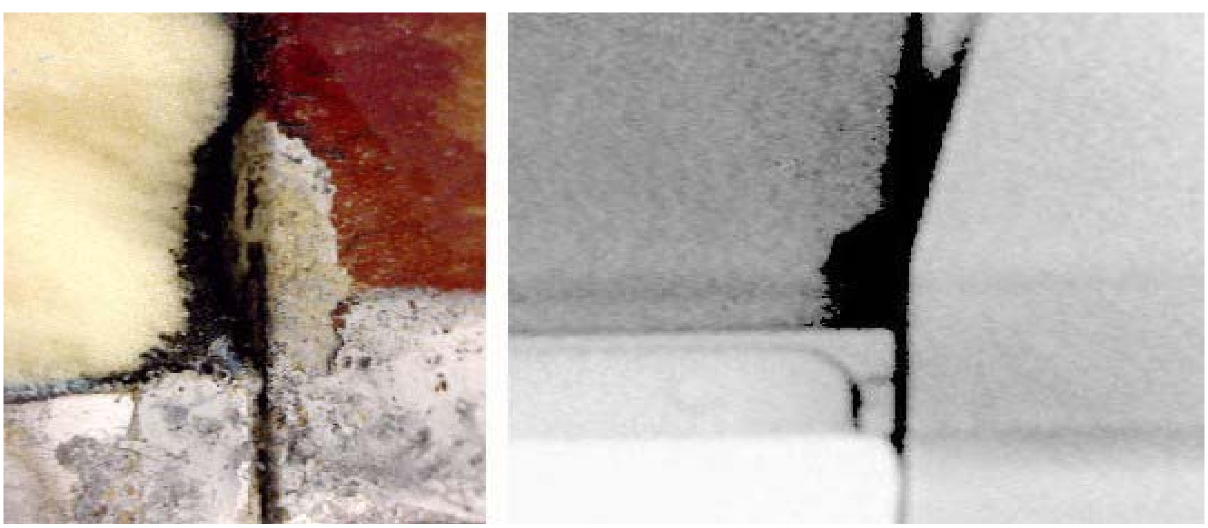

Figure 5. Photograph (left) and neutron radiograph (right) showing the ingress of oil.

- Aluminium corrosion beneath the aluminium skin in the cuff-region. The detectablity is ultimately dependent on the presence of the corrosion product, its thickness and composition. Bayerite ($Al(OH)_3$) generally constitutes 60-90% of the corrosion products found in aeronautical systems with organic compounds of aluminium salts, oxides and monohydrates also present [7]
- Delamination of the outer skin at the thick base foam-area on the blade.
- Non-uniformity and absence of resin in bonded regions shown by the white section on Fig 6.

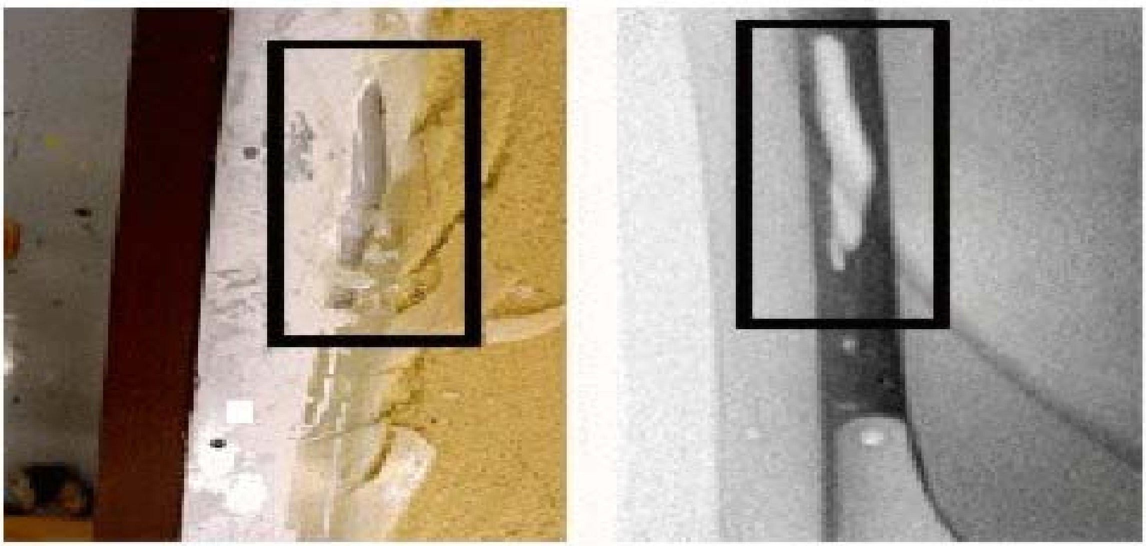

Figure 6. Photograph (left) and neutron radiograph showing regions of the bonding where there is an absence of resin.

Neutron radiography can furthermore provide valuable information in fault analysis, such as leaking O-rings in hydraulic systems as depicted in Figure-7, as well as blockages in fuel and hydraulic lines.

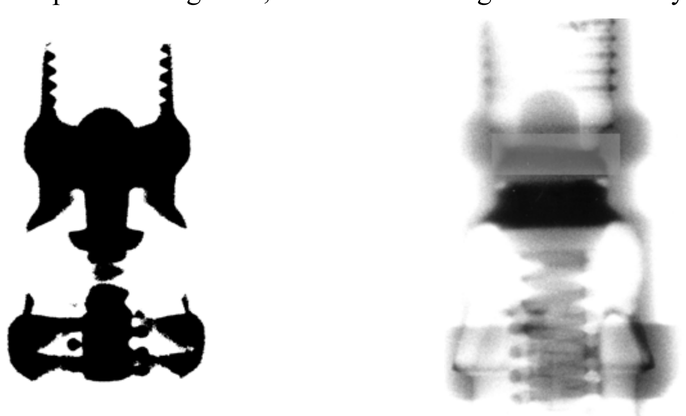

Figure 7. X-ray radiograph (left) showing no O-ring in structure while neutron radiograph (right) clearly show the condition of the O-ring (deformed black area) in the Stainless steel coupler.

4 [1]Conclusion

This paper demonstrates the capabilities of the two nuclear based methods, neutron diffraction and neutron radiography in the NDE of high valued engineering. In many cases they can provide unique information such as in the evaluation of the residual strain fields in critical components; evaluation of the efficiency of beneficial processes such as autofrettage; evaluation of welded structures and repaired components; detection of water/moisture/oil ingress; aluminium corrosion in enclosed structures; delamination problems; lack or over use of resin; as well as in fault analysis and quality assurance aspects of assembled components and heat-treatment processes.

Refereces

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