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Detection of Aluminum Corrosion Products by Neutron Radiography

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The neutron radiography technique has been employed to study aluminum corrosion. The compound material experimentally analyzed was bayerite and the experimental data were obtained in a radiographic facility installed at the IEA-R1 Nuclear Research Reactor. The calculated and experimentally determined values for the minimal discernible thickness of bayerite were $X_b^{min} = 0.024$ mm and $X_b^{min} \cong 0.11$ mm, respectively. Calculations show that for real corrosion products, $X_{cp}^{min} = 0.031$ mm, which is significantly smaller than 0.05 mm reported by other authors. The values for X_b^{min} and X_{cp}^{min} calculated in this paper show that, due to the filtering of the Maxwellian thermal neutron spectrum by polycrystalline bismuth, an improvement in the technique sensitivity can be achieved.

Introduction

The detection of aluminum corrosion products has a large practical application mainly in the aeronautic industry for the maintenance of aircraft structures, specially those exposed to marine environments. Basically the corrosion products are constituted by bayerite [$Al(OH)_3$] in 60–90%. Hydrates, oxides, salts and organic compounds can also be present (Rant *et al.*, 1986).

Several nondestructive testing (NDT) techniques, such as x-ray radiography, ultrasonics, eddy current and acoustic emission have been employed for aluminum corrosion inspection.

In addition, neutron radiography (NR) is a powerful NDT technique, which alows one to detect small quantities of hydrogen-rich substances even when wrapped by thick metal layers (Berger, 1965, Hawkesworth, 1977), and thus it is an important tool to inspect aluminum for corrosion products. Corrosion layers smaller than 0.05 mm can be detected. Because of the irregular shape of a corrosion area, the spatial resolution of the technique allows its discrimination in the presence of other hydrogen-rich substances, such as adhesives and sealants (Orphan *et al.*, 1986).

In this paper the NR facility used to obtain the experimental data is described, and some quantitative results concerning the sensitivity of the technique for detection of aluminum corrosion products using a neutron spectrum filtered by polycrystalline bismuth are presented.

Experimental

The NR facility sketched in Fig. 1 was designed and constructed in the Nuclear Physics Division of the IPEN-CNEN/SP and is installed at the beam-hole No. 08 of the IEA-R1 2MW Pool Type Nuclear Research Reactor.

The facility is constituted by two collimators. The first is a conical convergent graphite collimator while the second is a conical divergent cadmium collimator. After collimation the neutron beam is filtered by a polycrystalline bismuth 20 cm thick. Both collimators, as well as the filter, are installed inside an aluminum tube 2.40 m length, in which and in its outlet aperture the sample is irradiated. The sample holder is an aluminum chamber which is positioned by remote control in the neutron beam.

In addition to the principal shielding of the facility, and in order to assure a low neutron background, two paraffin-borax blocks are moved sequentially upward and downward at the same time that the holder is being positioned in the neutron beam.

The main characteristics of this facility are shown in Table 1.

The irradiations were performed by using a test object basically constituted by an aluminum plate 12.5 × 11.5 cm and 1.0 cm thick in which four hole sets with 8.0, 4.0, 2.0 and 1.0 mm in diameter were drilled. Each set is composed by 11 double holes with depths ranging from 0.1 to 8.0 mm. One of the holes was filled with bayerite while the other of the same diameter was left empty. This base is covered by an

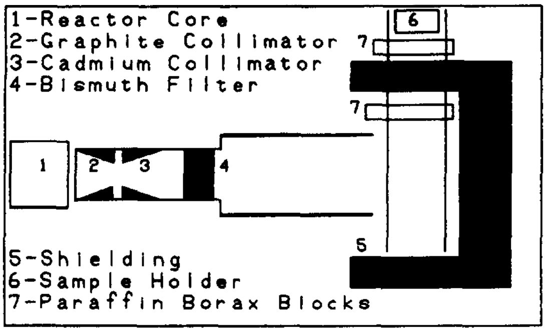

Fig 1 Sketch of the experimental facility

aluminum sheet 1.0 mm thick The bayerite was prepared by a chemical reaction between an $AlCl_3$ aqueous solution and NH_4OH The density of bayerite powder desposited in the holes was determined by weighing and the results obtained ranged from 0 9 to 1 2 g/cm^3

The direct conversion method with Gd (0 127 mm thick) screen has been employed and the best neutron radiographs in terms of sensitivity were obtained for 3 min exposure. The film used was the Kodak AA x-ray double coated.

Data Analysis

The minimal discernible thickness X^{min} of bayerite(b) or real corrosion products(cp) was the parameter selected to evaluate the technique sensitivity, which is calculated by

$$X^{min} = -\frac{R_c}{\Sigma} \qquad (1)$$

with

$$R_c = \frac{D_{Al} - D}{D_{Al}},$$

where R_c, relative contrast, D_{Al}, optical density for the aluminum base, D, optical density for the product; Σ, macroscopic cross section for the product

In the present facility, the Maxwellian thermal neutron spectrum coming from the reactor core, is distorted by the bismuth filter This filter is addition to reducing the gamma radiation contribution at the sample, thus enabling employment of the direct-conversion method, displaces the neutron spectrum to a low-energy region, resulting in an increase in the effective scattering cross section for hydrogen from 38 (Maxwellian) to 64 barn (Murray, 1954) The values of Σ_b and consequently of X_b^{min}, considering the minimal visually detectable relative contrast $R_c = 0\ 01$ reported by Rant *et al* (1986), for both spectra were calculated, and the results are shown in Table 2 A comparison between both results demonstrates that due to the spectrum displacing, an improvement in the technique sensitivity can be achieved

Table 1 Experimental facility characteristics

Beam flux at the sample = 2 × 10^6 n/s cm^2
Collimation ratio-L/D(length/inlet aperature diameter) ≅ 50
n/γ ratio ≥ 10^5 n/cm^2 mR
Beam diameter = 20 cm
Au–Cadmium ratio = 150

Table 2 Comparison between calculated and experimental data for bayerite

	Material	Density (g/cm^3)	Macroscopic cross section-Σ_b cm^{-1}		Minimal disc thick X_b^{min} mm
Calc	$Al(OH)_3$	2 53	Maxw spec	2 48	0 04
			Filt spec	4 18	0 024
Exper	$Al(OH)_3$	*1 01		1 3	0 11

*Mean density value

For real corrosion products, such as those scraped from corroded aluminum exposed to marine environments, the calculated value of X_{cp}^{min}, shown in Table 3, for the present facility can reach the value 0 031 mm, estimated from the value of $\Sigma_b = 4\ 18$ cm^{-1} calculated in this paper (Table 2), and from the values of Σ_{cp} and of Σ_b reported by Rant *et al* (1986). This value of X_{cp}^{min} is smaller than the limit value of 0 05 mm reported by these authors and by Dance (1970) to detect aluminum corrosion products by means of the thermal neutron radiography technique

In order to experimentally obtain the technique sensitivity, optical densitometric readings in the filled and empty holes as well as in the aluminum base have been performed The film background due to the gamma radiation was subtracted Figure 2 shows the behavior of the net optical density for the bayerite as a function of its thickness for the hole with 8 0 mm in diameter The experimental value for Σ_b is the slope of the straight line fitted in the linear portion of this graph with corresponds to bayerite thickness ranging from 0 to 4.0 mm Above this thickness value, saturations in the optical readings occurs leading to a decrease in the technique sensitivity The minimal discernible thickness X_b^{min} was determined using the equation (1) and the value of R_c for the present optical densitometric readings The results are shown in Table 2

The discrepancy between the calculated (for the filtered spectrum) and the experimentally obtained values for Σ_b and X_b^{min} may be explained by considering the poor accuracy of the present optical densitometric readings for which $R_c \cong 0\ 015$, and that the

Table 3 Comparison between data for real corrosion products

		Minimal disc thick X_{cp}^{min} (mm)
Real corrosion products	(1)	0 031
	(2)	0 15
	(3)	0 05

(1) Calculated for the filtered specrum, (2) calculated for the filtered spectrum and for the present experimental conditions, (3) reported by Dance and Rant

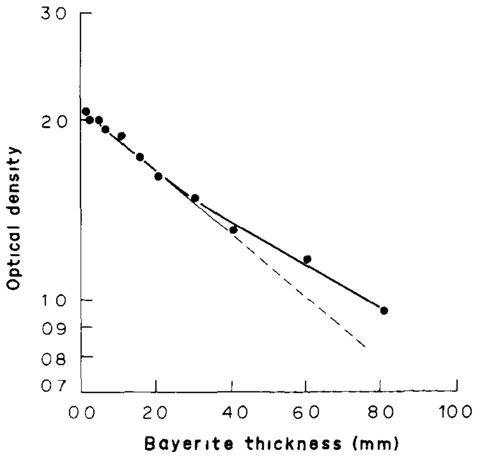

Fig 2 Optical density behavior for bayerite as a function of its thickness

density of the bayerite deposited in the holes (0.9–1.2 g/cm^3) is significantly lower than its normal value of 2.53 g/cm^3.

For these experimental conditions the calculated value for X_{cp}^{min} for real corrosion products, shown in Table 3, is 0.15 mm, which is also somewhat greater than the calculated value of 0.031 mm.

Taking into account the approximate relation $X_{cp} = 3X$ (Rant *et al*, 1986) between the thickness of corrosion products and the depth of corrosion, corroded aluminum thickness on the order of 0.05 mm can be detected using the present experimental conditions.

It was observed that the smaller the hole diameter the smaller the technique sensitivity. This was attributed to an increase of the beam geometrical unsharpness contribution.

It is important to note that all the filled holes in the aluminum plate were visible in the film.

Conclusions

The results obtained in this experiment corroborate once again that NR is a powerful technique to inspect aluminum corrosion products. The calculated values for the minimal discernible thickness for pure bayerite and for real corrosion products were $X_b^{min} = 0.024$ mm and $X_{cp}^{min} = 0.031$ mm, respectively. These results show that the employment of a bismuth filter can improve the technique sensitivity, since the limit value reported by Dance and Rant to detect real corrosion products by means of the neutron radiography technique was 0.05 mm.

Because the high neutron transparency for aluminum, several centimeters can be inspected by the NR technique. In the present work bayerite 0.1 mm thick was visible in aluminum 11 mm thick. This result confirms one of the main characteristics of the technique, that is, the visualization of hydrogen-rich substances even wrapped by thick metal layers.

It is important to note that the present experimental conditions, for which corrosion products thickness of about 0.15 mm can be detected, are independent of the radiographic facility, and the technique can be improved if a precise optical densitometer is available.

The employment of transportable neutron radiographic facilities (Schatz, 1989) has increased the application of the NR technique in this field. Although these radiographs have a slightly inferior quality when compared with that obtained in static reactor systems, they overcome the difficulty of inspecting structures *in loco*.

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