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Analysis of Ultrasonic Propagation Characteristics in ATF Cladding Tube for Failed Fuel Rod Detection

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1. Introduction

Accident-Tolerant Fuel (ATF) enhances safety by applying a thin chromium coating with excellent high-temperature oxidation resistance to zirconium-based cladding tubes [1]. When fuel failure is suspected, ultrasonic inspection is used during fuel retrieval to detect water inside the cladding, identifying failed fuel rods. The through-transmission ultrasonic testing (TTUT) method is widely used, where an ultrasonic probe transmits waves from one side, and a receiving probe on the opposite side detects the transmitted energy [2]. Since ultrasonic waves lose energy when passing through different media, the chromium-coated ATF cladding is expected to cause greater energy loss than conventional zirconium cladding, potentially leading to misinterpretation as fuel damage. This study quantitatively analyzes the ultrasonic energy reflected and transmitted in ATF cladding tubes and proposes performance requirements for ultrasonic transducers suitable for ATF cladding inspection.

2. Methods and Results

Due to differences in elastic modulus between chromium (~272GPa) and zirconium alloy (~95GPa), their acoustic impedances vary, affecting ultrasonic wave reflection and transmission. The reflectance and transmittance at each medium interface were analyzed, and the ultrasonic energy received by the transducer was calculated. Additionally, CIVA software simulations were conducted to evaluate ultrasonic propagation in actual cylindrical cladding tubes.

2.1 Ultrasonic Propagation Model

Ultrasonic propagation is closely related to the physical properties of the medium, and acoustic impedance in particular plays an important role. Acoustic impedance(Z) is a physical quantity that represents the degree of resistance when ultrasonic waves propagate in a medium, and is defined as the product of density(ρ) and velocity(c), as follows [3]:

(1) $$Z = \rho \cdot c$$

When ultrasonic waves encounter the boundary between two media, some are reflected, and some are transmitted. If the impedance of the first medium is Z_1 and the impedance of the second medium is Z_2, the sound pressure reflectance(R) is expressed by Equation (2), and the sound pressure transmittance(T) is expressed by Equation (3).

(2) $$R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$$

(3) $$T = 1 - R = \frac{4Z_1 Z_2}{(Z_1 + Z_2)^2}$$

As shown in Fig. 1(a), in conventional zirconium cladding tubes, the first medium is water, and the second medium is the cladding tube. In ATF cladding tubes, a chromium layer is added to the outer surface of the cladding tube, as shown in Fig. 1(b). The physical properties and impedances of each medium are shown in Table 1.

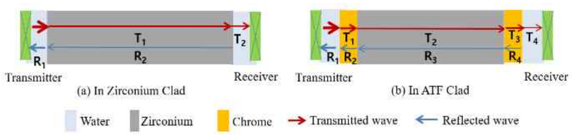


Fig. 1. Reflection and transmission of ultrasonic signals at material interfaces

The final transmitted ultrasonic energy in conventional zirconium cladding tubes and ATF cladding tubes is expressed by Equations (4) and (5), and by substituting the impedance value in Table I, it is as follows.

(4) $$\begin{aligned} T_{total\text{-}Zr} &= T_1 \times T_2 \\ &= (0.177) \times (0.177) \\ &\approx 0.0313 \end{aligned}$$

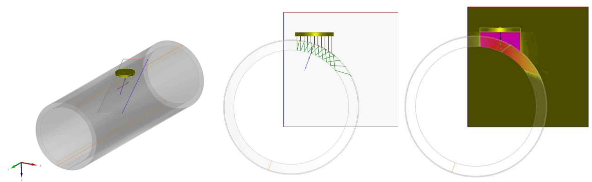
(5) $T_{\text{total-ATF}} = T_1 \times T_2 \times T_3 \times T_4$
$= (0.124) \times (0.962) \times (0.962) \times (0.124)$
≈ 0.0142

Table I: Impedance of each material

Medium	Density (ρ, kg/m³)	Velocity (c, m/s)	Acoustic Impedance (z, MRayl)
Water	1000	1480	1.48
Cr	7190	6300	45.3
Zr	6550	4650	30.5

2.2 Simulation

The ultrasonic wave propagation simulation using the CIVA program was conducted under the same conditions as the cladding tube [4]. The longitudinal wave from the transmitting transducer propagated through repeated reflections within the tube. Only the transmitting transducer was installed (Fig. 2. a), and Fig. 2 (b) illustrates the reflection process along the cladding tube. The analysis of ultrasonic energy transmission to the receiving transducer was not possible due to the complexity of mode conversion. A future study will attempt this using a simplified model.



(a) Simulation setup (b) Mode conversion in cladding
Fig.2. Simulation of ultrasonic propagation in a cladding tube

2.3 Results

In conventional zirconium cladding, approximately 3.13% of the ultrasonic signal reaches the receiving transducer, whereas in chromium-coated ATF cladding, only 1.42% is transmitted, resulting in a 55% signal reduction. This significant attenuation suggests that applying TTUT to ATF cladding may hinder accurate fuel failure detection

3. Conclusions

ATF cladding exhibits approximately 55% greater ultrasonic energy attenuation than conventional zirconium cladding due to the chromium coating, making ultrasonic inspection for fuel failure detection more challenging. To mitigate signal reduction caused by impedance differences, improvements in TTUT signal processing are necessary. The following solutions are proposed:

1) Probe design improvement: Enhance signal transmission efficiency by adopting reflection and surface wave inspection methods instead of the conventional transmission method.

2) Optimal frequency selection: Identify the optimal frequency within the 10 MHz range using signal-to-noise ratio (SNR) analysis.

3) Diversified signal processing techniques: Improve accuracy by expanding analysis methods beyond A-Scan to include B-Scan and C-Scan techniques.

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