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Original Article

Nondestructive inspection of spent nuclear fuel storage canisters using shear horizontal guided waves

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ABSTRACT

Nondestructive inspection (NDI) is an integral part of structural integrity analyses of dry storage casks that house spent nuclear fuel. One significant concern for the structural integrity is stress corrosion cracking in the heat-affected zone of welds in the stainless steel canister that confines the spent fuel. *In situ* NDI methodology for detection of stress corrosion cracking is investigated, where the inspection uses a delivery robot because of the presence of the harsh environment and geometric constrains inside the cask protecting the canister. Shear horizontal (SH) guided waves that are sensitive to cracks oriented either perpendicular or parallel to the wave vector are used to locate welds and to detect cracks. SH waves are excited and received by electromagnetic acoustic transducers (EMATs) using noncontact ultrasonic transduction and pulse-echo mode. A laboratory-scale canister mock-up is fabricated and inspected using the proposed methodology to evaluate the ability of EMATs to excite and receive SH waves and to locate welds. The EMAT's capability to detect notches from various distances is evaluated on a plate containing 25%-through-thickness surface-breaking notches. Based on the results of the distances at which notch reflections are detectable, NDI coverage for spent nuclear fuel storage canisters is determined.

1. Introduction

Dry storage casks are increasingly deployed throughout the United States and internationally to store spent nuclear fuel rods, before they are transported to a repository for disposal [1,2]. Recently, Korea is also highly interested in the construction and use of dry storage systems as the current on-site wet storage pools are expected to be full by 2024 [3,4]. Originally, dry storage casks were designed for intermediate-term storage relative to the nuclear fuel cycle. In the absence of a final repository, the extended use of dry storage is inevitable, which makes it necessary to assess the structural integrity of storage casks through inspections [5–9].

Most of the storage casks in the United States use stainless steel canisters that confine the spent fuel assemblies. After being sealed, the canister is transported to the Independent Spent Fuel Storage Installation and placed inside a ventilated concrete overpack for protection and shielding as well as to allow convective cooling. The stainless steel canister acts as an important shield barrier for the fission products. Therefore, its structural integrity has considerable safety implications and should definitely be guaranteed.

One potential degradation mode of the stainless steel canister is chloride-induced stress corrosion cracking (SCC), which is most likely to occur in dry storage systems located in marine environments [10–12]. Once atmospheric chlorides that enter the ventilated concrete overpack are deposited on the canister surface, they could deliquesce after the canister has cooled sufficiently. This provides a conducive environment for SCC [13]. The other two necessities for SCC to occur are already known to be present in the vicinity of the welds; material susceptibility and tensile driving force. Austenitic stainless steel can be susceptible to SCC when it is heated such that grain boundaries become chromium depleted, as can happen during welding [14]. In addition, the welding can result in high thermal residual tensile stresses that act as a driving force for cracks [15].

SCC typically initiates at the surface of welds or in the heat-affected zone (HAZ). Fabrication defects such as gas bubbles can serve as origins of cracking [16]. The cracks can be mixed between intergranular and transgranular and can exhibit dendritic branching. Based on observed service-induced crack characteristics [17], the crack location and orientation are highly dependent on the cracking

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mechanism and material. Nevertheless, it is common that SCC occurs near the welds due to the presence of high residual stresses and susceptible material there. Recent research using finite element analyses of the residual stress field [15,18] and preliminary residual stress measurements [19] have indicated that tensile residual stresses occur through the thickness both along the weld and across it. This suggests that SCC could grow normal to the weld or along it, which is consistent with general mechanics of materials expectations [20].

There is a strong preference to perform the canister inspection while it remains safely inside the cask. However, the *in situ* inspection has significant challenges due to the harsh environment and geometric constraints inside the cask. The environment includes both elevated temperature and gamma radiation. Based on the numerical modeling of dry storage casks, the temperature and gamma radiation dose inside the overpack that the robotic inspection system should be designed for are conservatively 177°C (350°F) and 27 krad/h, respectively [5,7]. Moreover, vertical-axis dry storage casks provide severe geometric constraints, for instance, the HI-STORM 100 model cask (Holtec International, Turtle Creek, PA, USA) is shown in Fig. 1 [7]. The cylindrical canister that stores spent nuclear fuel is fabricated by welding together two rolled and axially welded cylindrical sections, so that there are four full-penetration welds of primary concern: the mid-circumferential weld, the bottom weld, and two axial welds (upper half and lower half), which are indicated in Fig. 1. For protection and shielding of the canister, it is inserted into a concrete overpack having vertical guide channels attached to the steel cladding and is sealed with a lid. Moreover, from the viewpoint of inspection, the shielding structure of the overpack makes access to the canister surface possible only through the narrow ventilation system. Thus, it is necessary that the inspection be performed with a robotic delivery system. In addition to a constricted tortuous access path, the vertical guide channels (nominally 50-mm deep, 150-mm wide, and at 214-mm intervals) block access to portions of the circumferential and bottom welds under the channels. Moreover, if the axial weld is located at a channel, it is completely inaccessible. Consequently, this limited accessibility to welds prevents the use of nondestructive inspection (NDI) techniques that rely on point-wise scanning, such as visual testing, eddy current testing, and ultrasonic testing using bulk waves, as much of the welds can be hidden by guide channels. The most appropriate technique would be guided wave ultrasonic testing because it can be considered as a line scan method and can potentially inspect all the welds.

This research investigates an *in situ* inspection methodology for detection of stress corrosion cracks in the HAZ of spent nuclear fuel storage canisters. Shear horizontal (SH) guided waves using noncontact electromagnetic acoustic transducers (EMATs) are used in an attempt to provide 100% coverage of the canister and to make measurements with a robotic system. The next Section 2.1 introduces SH guided waves and compact EMATs developed for this application. The robotic inspection methodology for spent nuclear fuel storage canisters under limited accessibility is described in Section 2.2. To verify the proposed inspection methodology, a laboratory-scale canister mock-up and a 15.9-mm thick 304 stainless steel notch plate were fabricated and inspected. Sections 2.3 and 3 describe the laboratory experimental procedures and results, respectively, and are followed by the conclusions in Section 4.

2. Materials and methods

2.1. SH guided wave EMATs

SH waves are one type of guided waves that propagate in a homogeneous plate with traction-free boundaries. They have in-plane transverse displacements resonating between the confined boundaries, whereas Lamb waves have vertical displacements. The in-plane displacement characteristics enable them to interact well with cracks oriented not only perpendicular to the wave vector direction but also parallel to it [21]. This sensitivity to cracks in both directions is valuable in canister NDI because stress corrosion cracks are most likely to be located in the HAZ of welds and to be oriented transverse to the weld or parallel to it.

Guided waves are inherently multimodal and dispersive. These characteristics can be represented by dispersion curves that are simply trigonometric functions that result from the eigenproblem obtained from the governing differential equations and the traction-free boundary conditions [22]. The phase velocity and group velocity dispersion curves for SH modes of a 15.9-mm thick stainless steel plate are shown in Fig. 2. The black lines represent possible propagating SH modes in the plate and indicate the relationship between wave speed and frequency. The fundamental shear horizontal mode (SH_0) is nondispersive, whereas the other modes are dispersive and have specific cutoff frequencies.

When a comb-type transducer, such as an EMAT, is used to generate SH waves, the combination of the transducer's periodicity and the excitation frequency sent to the transducer determines which modes are activated. The transducer periodicity corresponds with the wavelength, and the fundamental relation, $c = \lambda f$, must be satisfied, where c, λ, and f are phase velocity, wavelength, and frequency, respectively. In this research, a wavelength of 12.7 mm and an excitation frequency of 250 kHz were selected as a compromise between crack sensitivity and the presence of multiple modes [6]. The SH modes excited under these conditions are illustrated in Fig. 2. It is worth pointing out that the dispersion curves in Fig. 2 are for a flat plate and that SH waves propagating around an annulus are different in general, see for example [23,24]. However, the

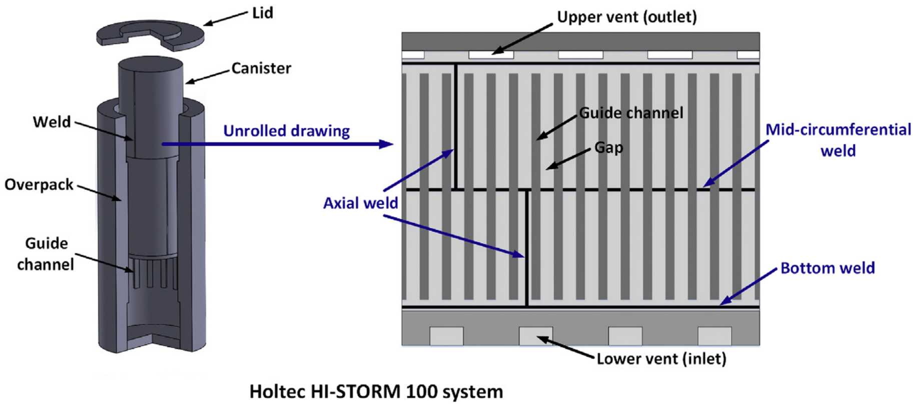

Fig. 1. A 3-D cutaway view of vertical-axis HI-STORM 100 cask and an unwrapped overlay of the canister welds on the overpack inner liner.

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