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Original Article

High-temperature ultrasonic thickness monitoring for pipe thinning in a flow-accelerated corrosion proof test facility

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ABSTRACT

In order to monitor the pipe thinning caused by flow-accelerated corrosion (FAC) that occurs in coolant piping systems, a shear horizontal ultrasonic pitch-catch waveguide technique was developed for accurate pipe wall thickness monitoring. A clamping device for dry coupling contact between the end of the waveguide and pipe surface was designed and fabricated. A computer program for multi-channel online monitoring of the pipe thickness at high temperature was also developed. Both a four-channel buffer rod pulse-echo type and a shear horizontal ultrasonic waveguide type for high-temperature thickness monitoring system were successfully installed to the test section of the FAC proof test facility. The overall measurement error can be estimated as $\pm 10 \mu\text{m}$ during a cycle from room temperature to 200°C .

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1. Introduction

Local thinning in a carbon steel pipe caused by flow-accelerated corrosion (FAC) may occur inside the elbows and a crack or leakage may evolve, which is an important safety issue for ensuring the structural integrity of coolant systems [1–4].

Currently, the manual ultrasonic thickness gauge method is used to measure the FAC in the carbon steel piping in nuclear power plants. The ultrasonic method is a well-known and commonly used nondestructive testing technique to determine the thickness of the piping. However, a manual ultrasonic method reveals several disadvantages: inspections have to be performed during shutdowns with possible consequences of prolonging the down time and increasing the production losses, the insulation has to be removed and replaced for each manual measurement, and scaffolding has to be installed in inaccessible areas, resulting in considerable cost for intervention. In addition, the manual ultrasonic thickness measurement method is inefficient from the viewpoint of data reliability. The thickness data at each shutdown period can be scattered owing to the differences in ultrasonic examiners, ultrasonic device, and data reading conditions, such as the temperature and ultrasonic coupling medium.

To characterize pipe wall thinning, cracking, and leakage from FAC, there is a need to monitor the pipe wall thickness at a high temperature with high accuracy. Conventional ultrasonic thickness measurement techniques cannot be applied to high temperatures of above 200°C , because conventional piezoelectric materials become depolarized at temperatures above the Curie temperature, and the difference in thermal expansion of the piezoelectric materials, coupling medium, and test pieces may cause a failure. Special piezoelectric transducers for specific use at high temperatures have been developed [5–10].

To solve the problems occurring in the propagation of ultrasound at high temperature, one of the possible methods is to put a buffer rod or waveguide (delay line) between the ultrasonic transducers and test pieces [11–15]. In the case of an ultrasonic waveguide technique, the dispersion characteristics of ultrasonic modes of the waveguide during the propagation of an ultrasonic wave should be considered [16]. The shear horizontal vibration mode was chosen because of no dispersion characteristics when the wave propagates in the plate.

An ultrasonic wall thickness monitoring technique using a shear horizontal waveguide has been developed. A dry clamping device with a solid coupling medium for the acoustic contact between the waveguide and pipe surface was designed and fabricated. The shear horizontal waveguides and clamping device result in an excellent signal to noise (S/N) ratio and high measurement accuracy with

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long exposure under elevated temperature conditions. In addition, a computer program for multichannel online monitoring of the pipe thickness at high temperature was developed. The software is integrated to expand up to four channels to monitor several points of the pipe simultaneously, such as intrados and extrados points at the bent region of a pipe. The system has been successfully implemented to monitor the pipe thinning in an FAC proof test facility after a verification test for a long period of time.

2. Considerations for high-temperature ultrasonic thickness measurements

An ultrasonic thickness measurement is typically performed by measuring the transit time between consecutive echoes in a time domain. The thickness of the test piece can be determined using a known value of ultrasonic velocity combined with the transit time. Assuming that there is minimal ultrasonic dispersion, a sharper ultrasonic signal will increase the resolution of the measurement. In general, the most accurate way to perform a temporal measurement is to measure the peak to peak time or to perform pulse-echo overlaps [17]. Because the wall thinning in the carbon steel pipe is generally less than a few tens of μm per year, the measurement error should be kept at a minimum, possibly in the range of μm . Several sources of error in the measurement of the thickness reduction in a pipe can be pointed out: (1) an error in the determination of the peak position of ultrasonic waveforms; (2) errors of ultrasonic velocity in the test pieces owing to a temperature variation or differences in temperature; (3) errors due to the measurement conditions between ultrasonic transducers and test pieces, such as ultrasonic coupling medium, contact pressure and other environmental factors; (4) errors due to the geometrical factors, such as surface roughness and curvature of the test piece; and (5) errors due to the digital signal processing, such as the capability of an analog-to digital converter, or delay by the digital signal processing [18].

Conventional piezoelectric ultrasonic transducers cannot be used at high temperatures because the piezo-ceramics become depolarized at temperatures above the Curie temperature. In addition, as the temperature increases, the signal quality of the piezoelectric transducer can be degraded and an error in determining the peak position of the signals increases. To assure the acoustic contact between the ultrasonic transducer and test pieces at high temperature, a solid type ultrasonic coupling medium should be placed. Occasionally, acoustical contact between the ultrasonic transducer and surface of the test pieces could fail due to the differences in thermal expansion coefficients when the pipe experiences thermal cycling during the plant operation.

3. Development of a high-temperature ultrasonic monitoring system for determination of pipe thinning

3.1. Development of high-temperature ultrasonic thickness monitoring system with buffer rods

High-temperature ultrasonic thickness measurements can be accomplished through the insertion of a buffer rod between the ultrasonic transducer and the pipe, as shown in Fig. 1. The materials for the buffer rod should be acoustically stable and thermally shielded to prevent the temperature rise of the ultrasonic transducer during high-temperature operation. In addition, a general ultrasonic coupling medium, such as glycerin or machine oil, cannot be used for a high-temperature application. A special solid coupling medium, such as a thin gold plate, is required to keep a good acoustic contact between the buffer rod and test pieces. The main problem of this technique is to maintain a good performance

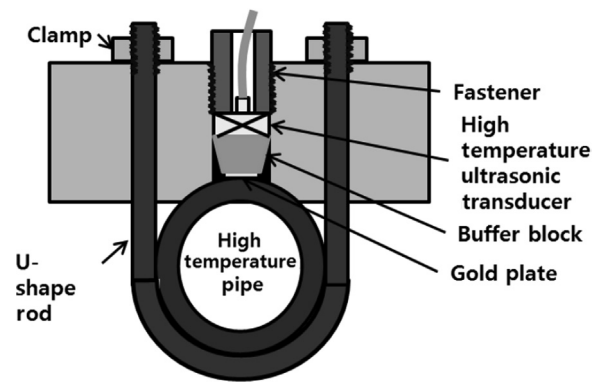


Fig. 1. Schematic drawing of an ultrasonic transducer assembly for high-temperature pipe thinning. The assembly consists of a high-temperature ultrasonic transducer, buffer rod, clamping device, and solid coupling medium for an acoustic contact.

for a long period of heat cycling operation. Occasionally, the ultrasonic energy transfer between the transducer and test piece fails due to a degraded or broken acoustic contact. Fig. 2 shows four-channel high-temperature ultrasonic transducers assembled to a test pipe for the thickness monitoring.

3.2. Development of high-temperature ultrasonic thickness monitoring system with waveguides

Another approach for an ultrasonic thickness measurement at high temperature is using an ultrasonic waveguide. To reduce the probability of acoustical breakage between the ultrasonic transducer and test pieces, an improved approach, an ultrasonic strip waveguide method, was attempted. A pair of shear horizontal transducers and strip waveguides were designed and fabricated. The shear horizontal vibration mode was chosen for proper ultrasonic energy transfer in the strip waveguides. Because the shear horizontal vibration modes in the plate show no dispersion characteristic, i.e., a constant wave velocity within a certain frequency range, the ultrasonic signal in the time domain is sharp and clear. This vibration mode gives an advantage in acquiring sensitive and accurate experimental data at high temperatures [19].

The shear wave transducers are attached to the edge of the waveguides. A 12.5-mm diameter ultrasonic shear transducer was coupled to the far end of the waveguide to excite and receive the shear horizontal mode. It was coupled by a shear coupling medium facing cross section of the strip. The polarization direction of the transducer should be aligned parallel to the width of the strip. A clamping device was designed and fabricated, which could attach two parallel strip waveguides with a separation of 1 mm to the plate, as shown in Fig. 3.

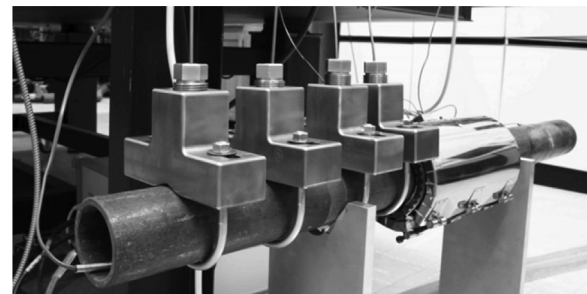


Fig. 2. High-temperature ultrasonic transducers were assembled on a pipe for thickness monitoring.

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