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Development of low frequency high temperature ultrasonic transducers for in-service monitoring of pipework in power plants

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Abstract

In this paper, a low-frequency (20-100 kHz) long-range ultrasonic guided wave transducer for in-service structural health monitoring of high temperature pipework in power plants has been developed. The transducer is designed for continuous operation at a target temperature of 350°C. This paper describes the methodology followed to develop and test the high temperature transducer. The method includes selection of the suitable piezoelectric material and characterisation of their high temperature properties for the desired thickness-shear mode of vibration to validate its performance at the target temperature. The assembly procedure established for manufacturing transducer is discussed. Ultrasonic performance of the developed transducer was examined and has demonstrated its application for in-service monitoring of pipework operating at the target temperature.

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Keywords: Ageing power plants, modified bismuth titanate; high temperature; ultrasonic shear transducer

1. Introduction

The global average age of operating thermal power plants (TTPs) is around 30 years and a majority of them are seeking life extension as they approach the end of their expected service life. Their critical components such as high temperature (HT) pipework are regularly inspected but only during maintenance outages as the current pipe inspection systems are limited to operate at ambient temperatures. This is mainly due to the piezoelectric element of the transducers which suffers depolarisation at HT (Curie temperature, T_c) and can no longer produce ultrasound. This paper presents a low-frequency ultrasonic guided wave (UGW) transducer using modified bismuth titanate which can be permanently mounted (dry-coupled) onto the pipe surface and carry out structural health monitoring (SHM) of HT pipes operating at temperatures up to 350°C. The developed transducers will enable early detection of defects and avoid pipe failure which can have severe consequences.

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2. Methodology

The transducer design established in this paper is based on existing shear transducers used in the Teletest Guided Wave system produced by Plant Integrity Ltd [1]. The current transducers use Lead Zirconate Titanate (PZT) with T_c=350°C as the active piezoelectric material mounted into a stainless steel backing and has a maximum operating temperature of 125°C. In this study, the temperature capability of the transducer is improved through, selection of HT piezoelectric material, HT thickness shear mode characterisation of the selected material, manufacturing of prototype transducers and evaluation of their ultrasonic performance for HT-SHM application.

2.1. Selection of high temperature materials for sensor design

The material selection for the transducer design was carried out to achieve stable ultrasonic performance at the desired operating temperature of 350°C. The coefficients of thermal expansion (CTE) of materials were considered in the process as CTE mismatch can result in material failure. The transducer design comprises of an active piezoelectric element protected by a wear plate and bonded to a backing block using adhesives. As a rule of thumb, piezoelectric materials are recommended to be used up to around half their respective T_c to prevent thermally activated degradation of their electro-acoustic properties.

For the required target temperature, a review on the state-of-the-art HT piezoelectric materials for direct contact ultrasonic transducer indicated bismuth titanate (BIT) and modified bismuth titanate (MBIT) to be the most suitable piezoelectric materials [2]. In previous work, BIT and MBIT have been successfully used as a HT thick film ultrasonic transducer using sol-gel spray technique [3, 4] and also in an ultrasonic thickness monitoring system [5] at temperatures up to 350°C. MBIT material was thus chosen as the piezoelectric element for the transducer. Special HT conductive and non-conductive adhesives were used for the transducer assembly. A customised ceramic was used for the wear plate to act as a heat barrier and to protect the piezoelectric element from wearing. The selected materials had the same order of magnitudes of CTEs and therefore no thermal mismatch was expected.

2.2. Characterisation of the piezoelectric element

To achieve thickness shear mode of vibration, MBIT elements were obtained in dimensions, length (13 mm), width (3 mm) and thickness (0.5 mm) with an aspect ratio of 26, greater than 20 as recommended [6] to obtain a clean shear mode. The samples were gold coated on both length-width faces for parallel electroding. The piezoelectric efficiency of MBIT in shear mode was evaluated through HT material characterisation.

Five MBIT samples were used for HT characterisation, and one of those samples was tested at target temperature overtime. Their piezoelectric performance was investigated using the well-established impedance resonance method [2]. According to BS EN: 50324-2 [7], by knowing the frequency resonance (f_r), frequency anti-resonance (f_a), capacitance value of the element (measured at 1 kHz), dimension and density (ρ) of the piezoelectric material; the elastic, dielectric and piezoelectric properties of the element can be calculated. The f_r, f_a and capacitance of the piezoelectric element were measured using an Agilent 4294A Impedance Analyser.

The exact dimensions of the samples were measured with an accuracy of 0.01 mm using a digital caliper. The density and the CTEs were taken from the material datasheet and the later was used to calculate dimensions for HT calculations. A previously developed purpose built jig [8] was used to hold the samples inside a furnace. The jig was connected to the Agilent 4294A precision impedance analyser using an Agilent 16048A fixture, which was used for impedance measurements in the frequency range of 40 kHz to 4 MHz. The temperature of the furnace was increased 25°C per measurement from 25°C up to 525°C. Before each measurement at elevated temperatures, open and short circuit compensation was performed to remove parasitic impedances [9]. K-type thermocouple connected to a temperature logger was used to record the temperature of the samples before each measurement. The measured impedance resonance spectra and capacitance were recorded at each temperature. The characteristic frequencies from resonance spectra, capacitance, dimensions and density were used to calculate the HT material properties of interest shown in Section 3.1.

2.3. Manufacturing and ultrasonic performance evaluation of the high temperature transducer

A prototype transducer using MBIT was manufactured. Stainless steel block was used as a backing mass to obtain frequency range suitable for long range ultrasonic testing (LRUT). For transducer assembly, HT soldering and diffusion bonding joining methods may be considered but at HT it becomes problematic due to local stresses which can possibly crack the piezo ceramics [2]. In this study the transducer assembly was formed using special HT conductive and non-conductive adhesives. The coated MBIT elements were bonded to the ceramic wear plate of the same dimensions using non-conductive adhesive. This sandwiched element was then attached to pure nickel glass braided wiring using conductive adhesive to achieve a secured electrical connection. Ceramic tubes were used to provide electrical isolation for the wires to avoid any seepage of conductive adhesive. The assembled transducers were then heat treated to cure the HT adhesives prior to evaluating their HT ultrasonic performance.

The ultrasonic performance of the manufactured transducer was evaluated on a steel bar waveguide of thickness 12 mm representing that of a Schedule 40 pipe. The bar was placed on a hotplate and the transducer was dry coupled on the bar with a force of 200 N which was applied through free weights using the transducer holder rig designed in [8]. The experiments were performed in pitch-catch configuration with a reference PZT-5A single element transducer attached at the cold end of the rod. The HT ultrasonic signals were measured and peak to peak signal amplitude and signal to noise ratio (SNR) was analysed to evaluate the reception and transmission quality of the transducer.

3. Results and discussion

3.1. High temperature thickness shear properties of MBIT

The HT impedance measurements were carried out up to the T_c of MBIT as shown in Fig. 1a. The results confirmed piezoelectric behavior of MBIT at temperatures up to 500°C thus exceeding the target temperature. The key thickness shear mode piezoelectric properties (d_{15}, g_{15}, k_{15}) were calculated up to T_c and overall a stable response was observed up to 350°C. The thickness shear coupling factor k_{15} was consistent around 40% up to 450°C. The HT measurement of d_{15} was in good agreement with d_{33} and d_{31} reported in [6] and shown in Fig 1c.

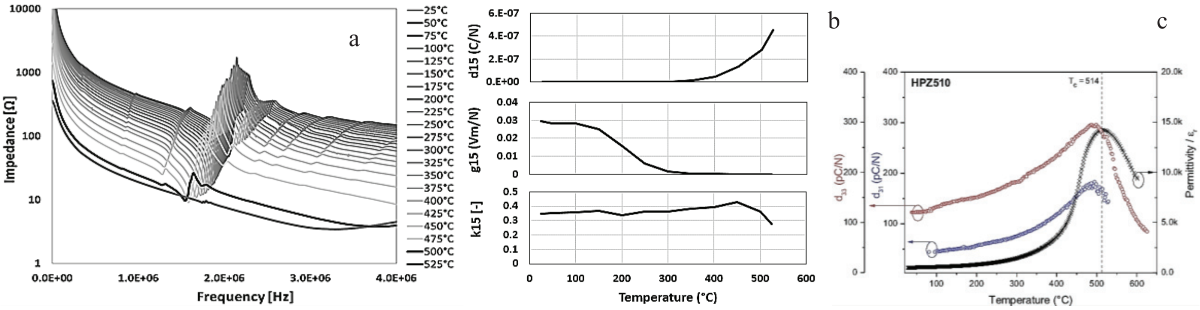

Fig. 1. (a) Electric impedance of MBIT element; piezoelectric properties (b) measured from 25°C up to 525°C.(c) and from a datasheet [6]

3.2. Ultrasonic performance of the manufactured transducer at elevated temperatures

The transducer's ultrasonic response at the target temperature is compared to the response at ambient temperature in Fig. 2a. The through transmission ultrasonic signal received at the target temperature was over 50% than that at ambient temperature. A slight time delay in the signal can also be seen which is accounted for thermal expansion of the waveguide as calculated previously [8]. The ultrasonic response of the proposed design was compared against the existing transducer. The existing transducer shows acceptable response at up to 250°C whereas the proposed design showed good ultrasonic response up to the target temperature of 350°C. A stable HT ultrasonic response up to 350°C was observed (Fig. 2b) and is in good agreement with the HT material properties of MBIT both measured (Fig. 1b) and previously reported [6] in a datasheet (Fig. 1c). The SNR of the transducer was stable up to the target temperature (Fig. 2b) which demonstrates a stable HT ultrasonic performance and defect detection capability at temperatures up to the target temperature of 350°C.

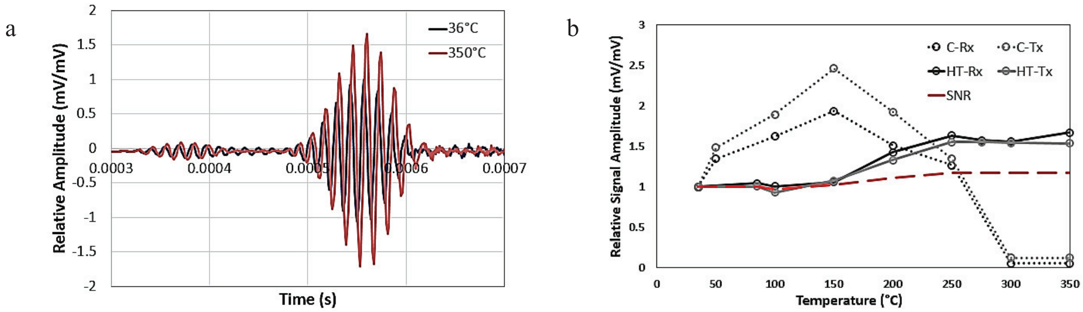

Fig. 2. (a) Ultrasonic response of the transducer at 350°C; (b) Comparison of HT reception & transmission performance with existing transducer.

3.3. Performance of MBIT and manufactured transducer at 350°C over time

To evaluate the thermal stability of MBIT, the corresponding piezoelectric properties were calculated in excess of thirty days and the relative change in the key material properties are shown in Fig. 3a. A stable response was achieved after the first five days. The ultrasonic transmission and reception quality of the transducer were measured at the target temperature over time as shown in Fig. 3b. An initial increase in ultrasonic performance was observed possibly due to adhesives being cured and after about two days the response was stablised.

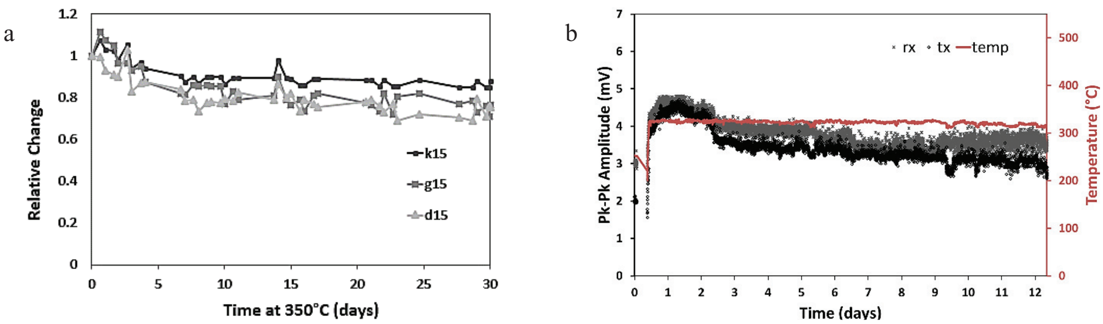

Fig. 3. (a) *Relative change in the piezoelectric properties of MBIT and (b) ultrasonic performance of transducer at 350°C over time.*

4. Conclusion and further work

A HT shear UGW transducer has been developed to achieve a stable ultrasonic performance at 350°C. The thickness shear properties of MBIT were measured up its T_c and will be used to carry out FEA studies to further optimise the transducer design. These outcomes are very encouraging for proceeding with the development of ultrasonic transducers with MBIT for SHM of HT pipes in TPPs at temperatures up to 350°C. Extended thermal stability of the transducers and their sensitivity to defect detection at HT will be investigated to further validate the transducer performance for SHM applications.

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