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High Temperature Ultrasonic Transducer for Real-time Inspection

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Abstract

A broadband ultrasonic transducer with a novel porous ceramic backing layer is introduced to operate at 700°C. 36° Y-cut lithium niobate ($LiNbO_3$) single crystal was selected for the piezoelectric element. By appropriate choice of constituent materials, porosity and pore size, the acoustic impedance and attenuation of a zirconia-based backing layer were optimized. An active brazing alloy with high temperature and chemical stability was selected to bond the transducer layers together. Prototype transducers have been tested at temperatures up to 700°C. The experiments confirmed that transducer integrity was maintained.

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Keywords: High temperature Environment; Ultrasonic Transducer; Real-time Ultrasonic Inspection.

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1. Introduction

Ultrasonic transducers are generally a composite structure, composed of a piezoelectric disc, a backing element and a quarter-wave matching layer. All these components are acoustically coupled together. Typically, piezoelectric materials with high quality factor, show a relatively long ringdown. To broaden the signal bandwidth, the back surface of the piezoelectric element is bonded to a backing element made of an attenuative material. Besides, to improve energy transmission from the piezoelectric element to the test piece, a quarter-wave matching layer is bonded to the front surface of the piezoelectric element.

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A thorough review on high temperature ultrasonic transducers was carried out by Kažys [1], in which various piezoelectric materials and bonding techniques are discussed. At high temperatures, one or more of the components mechanically fail or degrade. Furthermore, stresses at interfaces caused by a difference in thermal expansion coefficients can lead to de-bonding and a loss of acoustic coupling. . 1-3 connectivity composite was made by Z-cut Lithium niobate ($LiNbO_3$) pillars in alumina cement matrix (Cotronics Resbond 989). Compared to single crystal lithium niobate, the composite material produced shorter pulses at temperatures above 400 °C [2]. After cooling from 465°C, the composite disbanded from the metal test block due to a difference in their respective coefficients of thermal expansion (CTE). To resolve the issue, liquid coupling was used to couple $LiNbO_3$ crystal to ceramic backing [3]. The couplant was a solder glass characterized by a low glass transition temperature (T_g~250°C). The major problem was the chemical instability of the couplant which led to the corrosion in transducer components. Recently, direct deposition techniques such as chemical vapor deposition (CVD) process was employed to deposit (002) oriented AlN films with 30MHz center frequency on quartz, sapphire and lithium meta-niobate (LMN) substrates [4]. Due to surface oxidation, high temperature measurements were limited to temperatures below 1150°C. With new developments in high temperature adhesives, they have become an interest in bonding transducer components at high temperatures. X-cut gallium phosphate ($GaPO_4$) was bonded to titanium plate using Contronics 989 [5]. Clear signals were observed in pitch-catch test up 426°C, but they faded away at 480°C. The reason was believed to be the failure of bonding layer between the sensor and substrate.

To date, no successful transducer design has been reported for intermittent operation at temperatures approaching 700 C without the help of any cooling system or buffer rod. In this paper, a new design of ultrasonic transducer suitable for continuous operation at high temperatures (700°C) is presented. 36° Y-cut lithium niobate ($LiNbO_3$) single crystal with 3MHz center frequency is considered as the active piezoelectric element. The concept of porous ceramics as a new high temperature backing element was first introduced by the author [6]. Here, porous zirconia with appropriate porosity and pore size was manufactured to obtain the desired acoustic properties of the backing. Bonding of the piezocrystal to backing and matching layer are investigated using high temperature adhesive and active brazing alloys.

2. Transducer KLM model

To estimate the required acoustic impedance of the backing element (Z_b) to obtain the desired transducer bandwidth, the one-dimensional KLM transducer model [7] was implemented. Alumina ceramic was selected as the matching layer due to its appropriate acoustic properties and high temperature resilience. The close proximity of the coefficients of thermal expansion between the piezocrystal and alumina reduces the chance of de-bonding and cracking at high temperatures.

Table 1 shows the results of KLM model. With increasing Z_b over the range shown in the table, more energy is transferred to the backing element. Therefore, signal bandwidth is widened and transducer output energy decreases. A value of 20-25 MRayls for Z_b was found to yield the desired 3dB bandwidth of 95%-100%.

Table 1. Bandwidth and value of transfer function of the transducer for various values of Z_b

Backing Impedance (MRayls)	$Z_b=5$	$Z_b=10$	$Z_b=15$	$Z_b=20$	$Z_b=25$	$Z_b=30$
3dB Bandwidth (%)	86	87	90	94	100	107
Max. value of transfer function (Pascals/volt)	0.64	0.56	0.51	0.46	0.42	0.39

3. Modeling and manufacturing of porous backing element

Porous ceramics can be employed as thermally-stable backing elements in high temperature ultrasonic transducers [6]. Using the acoustic model for porous media proposed by Kanaun [8], the resulting dispersion equations yield the dependence of acoustic properties on pore size and porosity, when the pores are much smaller than wavelength (Rayleigh scattering region).

To reduce the chance of facture and de-bonding at high temperatures, zirconia was selected as the ceramic matrix for the backing element. Using the results of the acoustic model, porosity value of 25% yields the target acoustic impedance of Z_b=20-25 MRayls. Also, a pore radius of about 160μm provides the required minimum attenuation of 1 dB/mm at the desired central transducer frequency of 3MHz.

Following the procedure described in Ref. [6], porous zirconia backing elements were fabricated. Cylindrical samples were 20mm long and 15mm in diameter. The bottom sharp edge (where each sample joins to the piezoelement) was rounded to deflect any surface and lateral waves toward the far end of the backing element. An exterior grove was placed along the side of each backing element to hold the positive "hot" wire lead connected to the piezocrystal electrode.

4. Bonding of layers

To obtain good acoustic coupling between the piezocrystal and matching and backing elements, an active brazing technique was employed. Active brazing foil TiBrazeAl-665 (Titanium Brazing, Inc., OH) with 50 micron thickness was used to bond the layers. To obtain strong bonding between the brazing alloy and ceramic backing, the surface of the backing element was polished with diamond paste to achieve an average roughness of 1µm. To control the concentricity of the components, the backing and piezocrystal were placed inside a customized receptacle. The components were gently pressed together to induce the brazing material to spread on the surfaces and form a uniform layer. After bonding the ceramic backing to the piezocrystal, the alumina matching layer was bonded to the piezocrystral using same brazing foil.

5. Transducer performance analysis

A prototype transducer (Fig.1) was mounted on a 10mm thick stainless-steel test plate with high temperature couplant SONO 1100 (Sonotech, Illinois). The assembly was placed into a furnace and heated to 600°C with steps of 100°C. Backwall echoes were captured and signal bandwidth was computed at each step. Up to 200°C, clear signals were obtained, while the signal was lost at higher temperatures. The reason was found to be the chemical instability of the couplant and consequently; the lack of acoustic coupling between the transducer and the test plate. The recorded signals and the corresponding Fourier transform are depicted in Fig.2 and 3, respectively.

After heating up to 600°C and cooling to room temperature, the transducer was found functional and all the components remained bonded. Further investigation is required to find a proper acoustic coupling between the transducer and the test piece

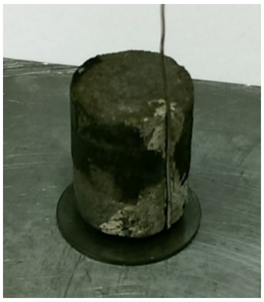

Fig.1. Transducer components bonded together using the brazing foil

6. Conclusion

A new design of ultrasonic transducer suitable for high temperatures (700°C) is introduced. 36° Y-cut $LiNbO_3$ with 3MHz was chosen as the active element. Porous zirconia with 25% porosity and pore diameter of 160µm was manufactured as the backing element. Alumina plate with quarter-wave thickness was used as the acoustic matching layer. The selection of the materials reduces the shear stresses due to the difference in thermal expansion coefficients.

Active brazing foil TiBrazeAl-665 was used to obtain acoustic coupling between the piezoelement, backing and matching layer. High temperature test results show the stability of the components as well as the bonding integrity. The design procedure can be adjusted to transducer with various center frequencies and signal bandwidth.

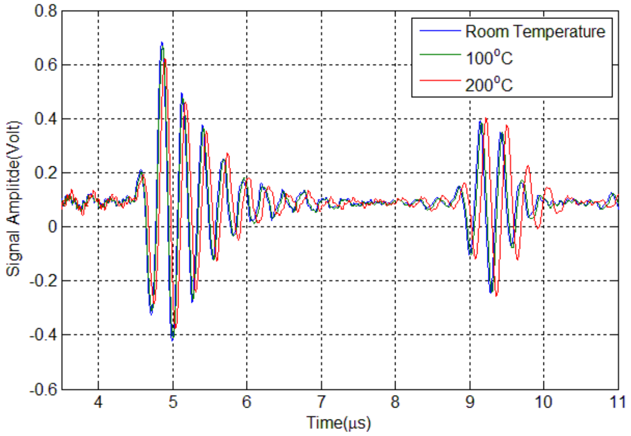

Fig.2. first and second back-wall echoes from the stainless-steel test plate at various temperatures

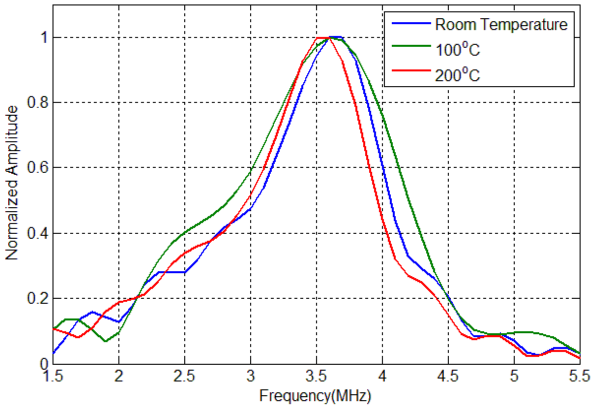

Fig.3. Frequency spectrum of the recorded back-wall echoes at various temperatures

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