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High Temperature Guided Acoustic Wave Transducers Using Mechanical Gratings

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Abstract— **Integrated and flexible guided acoustic wave transducers have been made using line shape mechanical gratings together with sol-gel fabricated integrated ultrasonic transducers at the opposite side. They can be used to generate and receive guided surface and plate acoustic waves and to operate up to 150°C. Preliminary results show the potentials of them for non-destructive evaluation and structural health monitoring applications.**

Keywords- *flexible ultrasonic transducer, mechanical gratings, array, high temperature, structural health monitoring, NDE*

I. INTRODUCTION

Guided acoustic waves are of attraction for structural health monitoring (SHM) and nondestructive evaluation (NDE) applications because they may inspect parts or structures, in particular, made of metals of a large area within a short time period using a few ultrasonic transducers (UTs) [1, 2]. For aerospace industry such SHM and NDE may require that the UTs operate from -80°C to 100°C. In other areas the operation temperatures may be required to be higher [3, 4]. Guided waves may be surface (SAW) or plate acoustic waves (PAW).

Mechanical line-shape gratings have been used to effectively convert bulk longitudinal (L) waves to surface acoustic waves (SAW) [5, 6]. The main applications were aimed at high frequency SAW filters. However, in the last decade such gratings have been also applied as mode converters from L to SAW or PAWs and as reflectors for the touch screen panels (or displays) made of glass substrates [7-9]. Such touch screen panels are widely used at many major transportation industry stations, department stores, different institutions, etc and become a convenient tool involved in human daily living. The main motivation of this research is to regard the touch display panel as an approach for SHM or NDE of a large part, however, the panel is made of metals. The analogy is that any defect is initiated or propagated within this panel the guided SAWs or PAWs propagating in the entire panel can detect the defect location and even the size. In this investigation thin and light weight integrated and flexible guided acoustic wave transducers involving the use of line-shape mechanical gratings only as mode converters are studied for the SHM and NDE application at temperatures up to 150°C.

II. TRANSDUCER FABRICATION

The line mechanical gratings are machined with a line width of 0.3 mm, an aperture of 10 mm and different depths

and number of gratings using electrical discharge machining (EDM). The gratings will be used to convert L waves into SAWs [6, 7] and PAWs depending on the substrate thicknesses. Piezoelectric lead-zirconate-titanate composite (PZT-c) films served as L wave integrated UTs (IUTs) were made by a sol-gel sprayed technique [4, 10] onto the opposite surface of the metallic substrate having the mechanically gratings. The merit of this approach is that IUT can be at the internal surface of a structure and mechanical gratings at the external surface. If the substrates are 75 μ m thick membranes, then it is a flexible UT (FUT). FUTs may be attached or bonded to metal parts even with curved surfaces and used for guided wave NDE and SHM.

The sol-gel spray fabrication method of the PZT-c film consists of six main steps [4, 11]: (1) preparing a high dielectric constant PZT solution, (2) ball milling of piezoelectric PZT powders to a submicron size, (3) film spraying using slurries from steps (1) and (2) to produce a layer of slurry film onto thin metal membrane substrates, (4) heat treatment to produce a solid PZT-c film on the metal substrates, (5) corona poling to obtain piezoelectricity of the composite ceramic film, and (6) electrode painting of electrical connections. Steps (3) and (4) are performed multiple times to produce the proper film thickness for optimal IUT and FUT ultrasonic operating frequencies. One main merit of the sol-gel spray technique is to offer the on-site fabrication capability for IUTs. Also on-site installation ability using gluing and brazing [12] can be provided by FUTs which may be mass produced in the laboratory.

III. RESULTS AND DISCUSSIONS

In this section the experimental and numerical simulation results of SAW and PAW generation and receiving using line mechanical gratings and mode conversion from L waves to SAWs and PAWs, respectively will be presented up to 150°C.

A. Integrated guided SAW transducers on a SS plate

In order to show the capability of integrated guided SAW transducer line-shape mechanical gratings as shown in Fig. 1 with a line interval of 0.6 mm, a width of 0.3 mm, a depth of 0.06 mm, an aperture of 10 mm and 6 gratings have been made onto the grating side of 10 mm thick SS plate. According to [5] the optimum depth of the grating is 0.6 mm, but here 0.06 mm is chosen for easy machining. The gratings may be made to have symmetrical or anti-symmetrical shape to increase the

efficiency of mode conversion and directivity [5]. PZT-c films have been also made as IUTs at the direct opposite side of these gratings and their thicknesses are about $82\ \mu\text{m}$ thick which corresponds to a center frequency of an L wave of 7.9 MHz with a 6 dB bandwidth of 4 MHz. The dimensions of the top electrodes are about 9 mm by 3.5 mm which covers about 6 gratings area.

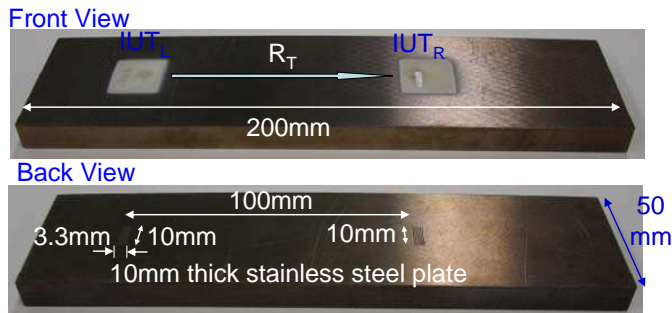


Figure 1. Line-shape mechanical gratings with a line interval of 0.6 mm, a width of 0.3 mm, a depth of 0.06 mm, an aperture of 10 mm and 6 gratings have been made onto a 10 mm thick SS plate. PZT-c films with $82\ \mu\text{m}$ thick were deposited on the opposite side of gratings directly.

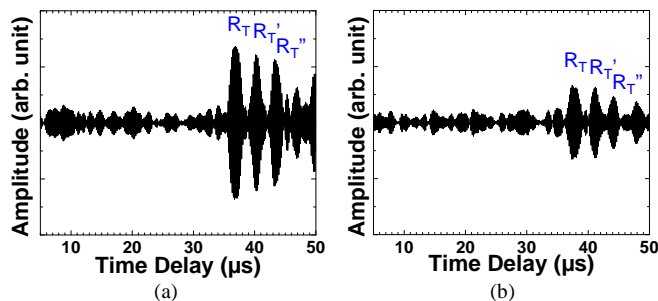


Figure 2. Ultrasonic performance of the IUTs shown in Fig. 1 and operated in transmission mode (a) at room temperature (b) at 150°C .

At room temperature the measured V_L and V_S of this SS substrate are 6056 m/s and 3328 m/s, respectively. Using these data and the calculated SAW is 3022 m/s with 5 MHz of center frequency in this design of 0.6 mm wide line interval grating. Fig 2 shows the measured ultrasonic signals in transmission mode in time domain of the measurement (a) at room temperature and (b) at 150°C . The data shown in Fig. 2(a) and 2(b) were filtered with a band pass filter centered at 5 MHz. R_T is the first SAW arrival signal. Because of the 10 mm thick SS plate, bulk L waves generated and received by the IUT also traverse back and forth from the top and bottom surfaces of this plate. The large echoes R_T' and R_T'' follow the echo R_T come from such reverberation with a time delay of about $3.3\ \mu\text{s}$. Such echoes R_T' and R_T'' can be significantly reduced if the incident L waves toward the line gratings is at an inclined angle or the SS plate has a non-parallel top and bottom surfaces. At room temperature the measured SAW is 3012 m/s which agrees well with the theoretically calculated value of 3022 m/s. At 150°C , as shown in Fig. 2(b), the measured SAW velocity is about 2905 m/s. Fig. 3 shows the numerical simulated results of this configuration at room temperature using Wave3000 commercial available software which agree well with the experimental result shown in Fig. 2(a). In addition the center frequency of the received signal in Fig. 3 is also around 5 MHz.

Figs. 2(a) and 2(b) provide the possibility of high temperature guided SAW generation and receiving for 150°C NDE and SHM.

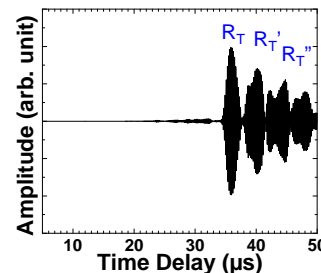


Figure 3. Numerically calculated SAW signals in time domain at room temperature in the SS plate as shown in Fig. 1.

B. Flexible guided plate acoustic wave transducers on $75\ \mu\text{m}$ stainless steel membranes

Since the grating has been approved to be able to generate and receive SAW at room temperature [5, 6] and at 150°C as demonstrated above, it is also of interest to study whether flexible guided PAW grating transducer can be developed if the above 10 mm thick SS plate is replaced with a $75\ \mu\text{m}$ SS membrane. The IUT can be still deposited at the opposite site of the line grating. Using SS membrane high temperature high efficient bulk L wave FUT were reported in [4, 12]. For guided PAW grating FUTs line-shape mechanical gratings with a line interval of 0.6 mm, a width of 0.3 mm, a depth of ~ 0.03 mm, an aperture of 10 mm and 17 gratings have been made onto SS membranes of $75\ \mu\text{m}$ thick by the EDM. The depth of ~ 0.03 mm of the grating is almost a half of the membrane thickness. Again these mechanical gratings are made in symmetrical shape because of convenience in machining. PZT-c films have been made as IUTs at the direct opposite side of these gratings and their thicknesses are about $62\ \mu\text{m}$ thick which corresponds to a center frequency of an L wave of 15 MHz. In this investigation such transducers are named as PAW grating FUTs.

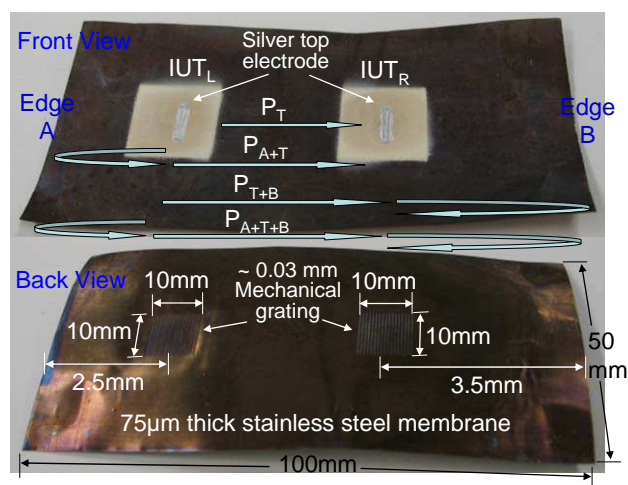


Figure 4. A $75\ \mu\text{m}$ thick SS membrane with two $62\ \mu\text{m}$ thick PZT-c films. Line-shape mechanical gratings with a line interval of 0.6 mm, a width of 0.3 mm, a depth of ~ 0.03 mm, an aperture of 10 mm and 17 gratings have been made onto the SS membrane.

At first, ultrasonic measurements in transmission mode were carried out. In Fig. 4 IUT_L was used as the transmitting IUT and IUT_R as the receiver. The ultrasonic signals obtained in this transmission configuration at room temperature with the IUT top electrode which covers 3, 7 and 10 line-grating areas are shown in Figs. 5, 6 and 7, respectively. In these figures the time and frequency domain signals are given in (a) and (b), respectively. As expected [5] the higher number of line gratings provides narrower bandwidth of the PAWs. The propagation paths of echoes P_T, P_{A+T}, P_{T+B}, and P_{A+T+B}, are indicated in Fig.4. Because the edges of the SS membrane serve as PAW reflectors, for example, the propagation path of echo P_{A+T} starts from the IUT_L together with the mechanical grating to the Edge A and reflected and received by IUT_R together with the mechanical grating. It also means that pulse-echo capabilities of such PAW grating FUT transducers have been demonstrated as well. From the time delays of P_T, P_{A+T}, P_{T+B}, and P_{A+T+B} the velocity of the PAW is 4870 m/s which indicates the first symmetrical mode S₀ [13, 14] for the SS membrane used. The signal-to-noise ratio (SNR) of the received signal P_T in Figs. 5(a), 6(a) and 7(a) is 17 dB, 16.6 dB and 8.7 dB, respectively. The anti-symmetrical mode propagation, in particular, the first A₀ was also expected to be generated and received by such PAW grating FUTs, however it was weak. Their arrival time comes much later because of the slow velocity and interfered by the later arriving of multiple echoes of the symmetrical mode traversing back and forth within the SS grating FUT membrane. It will be studied further in the future.

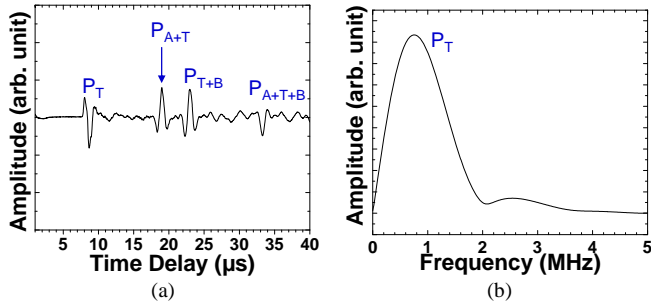


Figure 5. Ultrasonic performance of the IUTs shown in Fig. 4 and operated in transmission mode. 3 line-grating area is covered by silver top electrode.

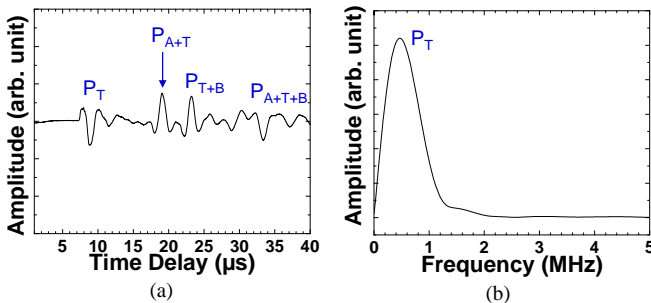


Figure 6. Ultrasonic performance of the IUTs shown in Fig. 4 and operated in transmission mode. 7 line-grating area is covered by silver top electrode.

In order to demonstrate the high temperature operation capability the whole PAW grating FUT membrane shown in Fig. 4 was directly put on top of a hot plate. Figure 8 shows the

ultrasonic signals obtained in transmission mode at 150°C with IUTs covering only 3 line-grating areas (~9 mm by 2 mm). The SNR of the received signal P_T is 11.4 dB. The choice of 3 line-grating was because it gave the broader bandwidth of the received signal.

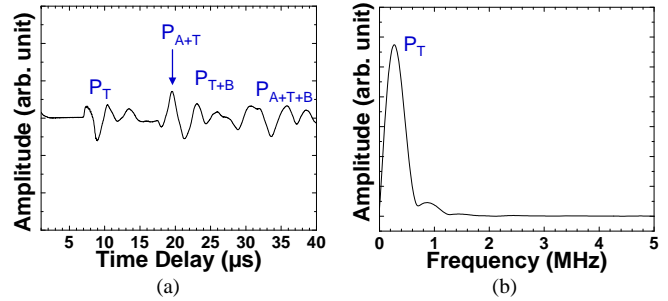


Figure 7. Ultrasonic performance of the IUTs shown in Fig. 4 and operated in transmission mode. 10 line-grating area is covered by silver top electrode.

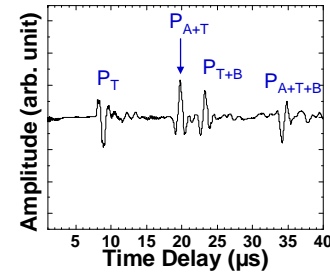


Figure 8. Ultrasonic performance of the IUTs shown in Fig. 4 and operated in transmission mode at 150°C. 3 line-grating area (~9 mm by 25 mm) is covered by silver top electrode.

C. Flexible guided plate acoustic wave transducers generate and receive PAW in a SS plate

In order to demonstrate the potential of using grating FUT guided PAW transducer for SHM and NDE, the grating FUTs shown in Fig. 4 were cut into two. Each part consisting of one grating with IUT below serves as guided PAW grating FUT. These two PAW grating FUTs were placed at the two ends of a 1.9 mm thick 100 mm long 50 mm wide SS plate as shown in Fig. 9(a), and their ultrasonic signal obtained in transmission mode is shown in Fig. 9(b). The SNR of the received signal is 20 dB. Then an artificial line defect with 1 mm depth and 1 mm width across the entire width 50 mm of the SS plate was made onto the middle of the SS plate, and the measured ultrasonic signal P_T was 3.4 dB weaker than the measured signal on SS plate without line defect. The line defects on plate can be detected by the amplitude change of ultrasonic signals, generated and detected by the grating FUTs, in transmission mode. The guided PAW grating FUT transducers could be attached or bounded onto plate structure like the bulk L wave FUTs reported in [12] for high temperature SHM or NDE.

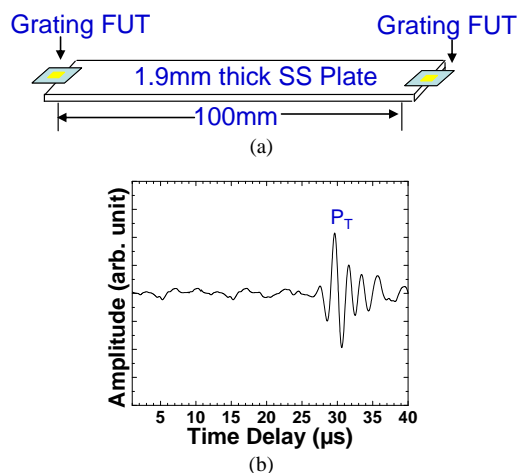


Figure 9. (a) Ultrasonic performance of PAW Grating FUTs shown in Fig. 4 are placed at the two end of a 1.9 mm thick stainless steel plate. (b) Ultrasonic performance of measurement setup in (a). The two grating FUTs were operated in transmission mode.

IV. CONCLUSIONS

Integrated and flexible guided acoustic wave transducers have been made using line shape mechanical gratings made by EDM together with sol-gel fabricated IUTs at the opposite side. IUTs served as bulk L wave transducers and these L waves were converted to SAW or PAW when they interacted with the line mechanical gratings depending on the substrate thickness. Guided SAW grating IUTs have been made and for such transducers IUTs are made directly under the line gratings in a 10 mm thick SS plate. The measured SAW velocity and frequency agreed well with the theoretical and numerical calculation. When the SS substrate is 75 μm thick which is flexible, the gratings together with IUTs served as guided PAW grating FUTs. The experimental results indicated that the more is the number of line gratings, the narrower is the bandwidth of the PAW. In this study symmetrical S_0 mode was generated and received. The detection of an artificial line defect created on a 100 mm long 50 mm wide SS plate was also demonstrated in a transmission mode using two guided PAW grating FUTs. These FUTs may be attached or bonded to parts even with curved surfaces. The preliminary results have indicated that they may be used for NDE and SHM purposes [12].

ACKNOWLEDGMENT

Financial support from the Natural Sciences and Engineering Research Council is acknowledged.

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