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Ultrasonic condition monitoring using thin-film piezoelectric sensors

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Thin-film low-profile sensors have been investigated for ultrasonic condition monitoring. The sensors are made by growing a thin film of aluminium nitride onto the component to be monitored. The transducers can be engineered to operate in passive or active mode from 200 kHz to 400 MHz. New or existing applications based on ultrasonic pulse-echo techniques or acoustic emission testing can make use of the sensors, including monitoring of high-temperature plant or machinery. The sensors have been demonstrated on various component materials such as stainless steel, ferritic steel, aluminium, titanium and silicon carbide. The piezoelectric material used, aluminium nitride, has a very high Curie temperature so the devices can be used up to 600°C. Examples are presented of devices operating in pulse-echo and passive detection modes, which could be used for permanent monitoring of parts which would normally require maintenance outage in order to be inspected. In addition, because the typical thin-film transducers are only 8-40 µm thick, sensors can be placed in locations previously impossible to access. The operating frequency of the thin-film devices has been investigated by simulation using an equivalent circuit model.

1. Introduction

An important trend in condition monitoring is to pre-instrument machine elements with sensors in order to provide the user with real-time monitoring capabilities. Piezoelectric transducers have been used for many years for non-destructive evaluation of components using pulse-echo techniques and recently their application has extended into condition monitoring by recording acoustic emissions from damaged parts. Probes used for these inspections are typically bulky discrete devices which, in some cases, are unable to fit into awkward locations or survive in the environment where the part is operating. Conventional active transducers have not been employed greatly in condition monitoring systems, possibly because of their bulky nature and the relative expense of installing many sensors on each critical component in an industrial plant.

In this work, active and passive transducers have been investigated which are fabricated from piezoelectric thin films deposited directly onto the component to be monitored. Aluminium nitride (AlN) thin films were used, deposited by RF magnetron sputtering under vacuum[1]. By this technique, a polycrystalline film a few microns thick is formed and, unlike usual piezoceramic materials, does not require poling. Devices have been made on different types of substrate material including glass, aluminium, stainless steel, chromium steel, silicon and silicon carbide. Surface preparation of the substrate was by grinding or by grinding and polishing. Direct deposition of AlN onto components has the advantage of producing very low profile devices with very good acoustic coupling, which are capable of high-temperature operation because of the high Curie temperature of AlN and the absence of fluid couplant[2]. A typical device structure is shown in Figure 1.

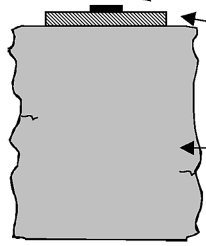

Figure 1. Structure of piezoelectric thin-film transducer for ultrasonic condition monitoring applications. The thin film is deposited directly onto the component to be monitored and therefore no couplant is required

The thin-film transducers do not operate in a $\lambda/2$ thickness resonant mode like traditional piezoelectric transducers. Instead, they operate far below their resonant frequency in a regime where the input signal, plus electrical and mechanical effects, controls the electro-acoustic characteristics of the device[3]. By correct choice of device parameters and electrical excitation, it is possible to operate the devices at frequencies in the range 200 kHz to 400 MHz. Therefore, with only a few microns of piezoelectric material, acoustic waves suitable for ultrasonic testing and monitoring can be generated and detected. Higher frequency ultrasonic transducers can also be reliably made for special applications. Examples from other authors of piezoelectric film sensors for monitoring have been reported[4,5,6,7], however these were operated in a resonant regime and much thicker piezoelectric films were used.

In this paper, we demonstrate some applications of thin-film piezoelectric transducers in ultrasonic condition monitoring of industrial components using pulse-echo techniques or passive sensing. We also discuss the principles of operation of the transducers.

2. Applications

To demonstrate the potential of thin-film piezoelectric transducers in ultrasonic condition monitoring, we produced transducers on mechanical parts such as ball bearings, face seals and thick metallic parts. In these devices, thin-film transducers are used to generate and/or detect ultrasound in place of the usual commercial piezoceramic transducers. The thin-film transducers are small, low profile and high-temperature resistant in the 200-600°C range. Thus they can be used very close to the source of ultrasound in acoustic emission or the potential defect location for pulse echo. They also have the capability to continue to operate whilst machinery or plant

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is running at high temperatures, significantly above the standard range for the use of piezoelectric transducers.

2.1 Thickness of lubrication layer in ball bearings by ultrasonic pulse-echo technique

In the lubrication layer thickness monitoring application, an instrumented bearing with a thin-film transducer was incorporated into a research test-rig formerly operated using commercial ultrasonic transducers. The advantages of using a thin-film transducer for oil film thickness monitoring in research or industrial applications are the following: miniature devices can be incorporated into components close to critical lubricated interfaces; the operating frequency suits the measurement regime for very thin oil films; the transducers give good spatial resolution of the lubricated contact; and good coupling of the transducer to the component gives good signal strength.

Failure of a bearing can be linked to the collapse of the oil film at the lubricated contact where the mechanical load is transferred[8]. The ultrasonic measurement technique uses a high-frequency pulse to interrogate the lubricated contact area, which in ball bearings is a narrow ellipse only a few mm^2 travelling at high speed. To obtain information that comes specifically from the contact area and not from the surrounding thicker oil layer requires very good spatial resolution. This necessitates the use of a narrow and collimated beam or a tightly focused beam and was previously achieved using a focused transducer installed in a water bath and focused on the steel/oil interface[9]. Measuring the oil film in this way required major modifications to the bearing housing. This meant that, whilst of interest in laboratory work, the approach could not be used in industrial applications. Thin-film transducers can provide a significiant advantage in this respect since only minor modifications to the bearing are required. For this work, a type 6016 deep-groove ball bearing from FAG, Germany, was instrumented with a transducer, as shown in Figure 2. A 5 µm-thick thin film of AlN was sputtered onto the external surface of the outer raceway and made into a narrow rectangular transducer with an active area of 3 x 0.3 mm^2 and a centre frequency of 200 MHz. This resulted in the output of a fine collimated beam of similar dimensions to the electrode.

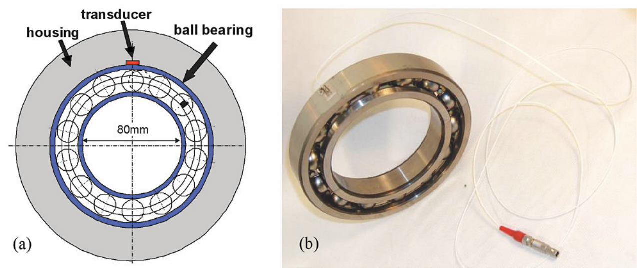

Figure 2. Instrumented ball bearing, type 6016 FAG, 80 mm inner diameter: (a) schematic showing transducer location; (b) photograph showing thin-film transducer fabricated on a small machined flat on the outer surface of the outer raceway

The ultrasonic measurement technique uses the change in the reflection coefficient R of a specific frequency of longitudinal ultrasonic wave at the steel/oil interface. The lubrication layer thickness is calculated from R by modelling the oil film as a spring with stiffness dependent on film thickness[10]. Reflected signals obtained when the contact region passes the measurement location are shown in Figure 3. The reflected signal drops as the contact point passes the measurement point and then recovers to the original value. Note that the oil film is less than 1 µm thick under normal operation in the elastohydrodynamic regime.

Results given in Figure 4 demonstrate that the lubricant layer thickness could be measured to improved accuracy using thin-film transducers compared to conventional transducers. In Figure 4, oil film thickness is measured at various values of radial load, W, and shaft speed, ω, and compared with the thickness calculated

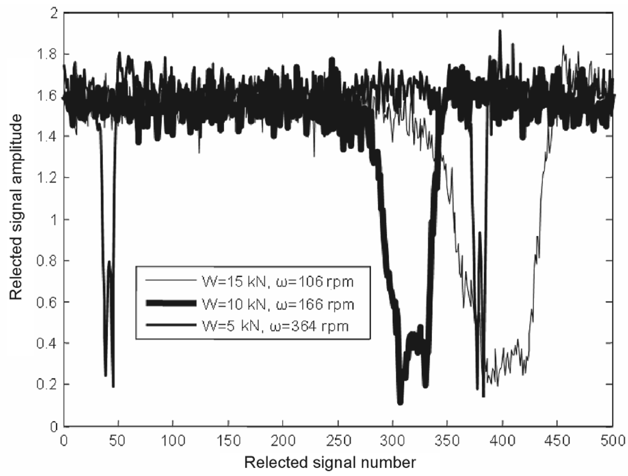

Figure 3. Amplitude of reflected ultrasonic signal falls and recovers as the ball passes the measurement location. Results for different applied load, *W*, and shaft speed, *ω*. Horizontal axis relates to time

from elastohydrodynamic theory[11]. Results from the thin-film transducer and the focused transducer are shown, with the thin-film transducer providing measurements closer to the expected value, with less scatter. The improvement when using the thin-film transducers is attributed to a shorter pulse, higher frequency and a narrower ultrasonic beam more accurately directed onto the lubricated contact.

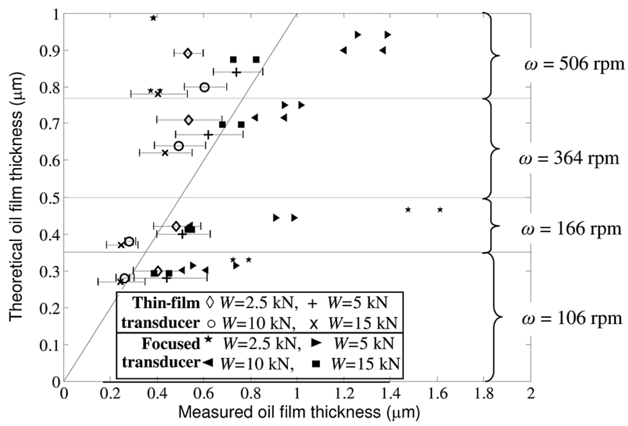

Figure 4. Experimentally measured oil film thickness compared to expected thickness from elastohydrodynamic theory[11] at various values of radial load (*W*) and shaft speed (*ω*). Results from thin-film transducer (open symbols) show improved fit compared to focused transducer (solid symbols)

2.2 Acoustic emission testing

Acoustic emission (AE) is a well-known technique to monitor structures and mechanical parts by listening for acoustic events indicating structural failure or machine malfunction. Typically, AE sensors operate in the 200 kHz to 1 MHz range. Use of thin-film acoustic emission sensors could enable permanent monitoring of components and machines, with particular advantages at high temperatures or where there is limited space to install standard sensors.

Thin-film transducers were tested in two experimental configurations, as shown in Figure 5. In both cases the signal from the transducer was amplified using the 'through' channel of a JSR DPR300 pulser receiver and acquired using an Agilent 54641A digital oscilloscope set to trigger at a threshold. The Fourier transform of the acoustic events was obtained using the oscilloscope FFT function.

In the first experiment the substrate was an 8 mm-thick stainless steel coupon (50 x 50 mm^2). The transducer was made from a

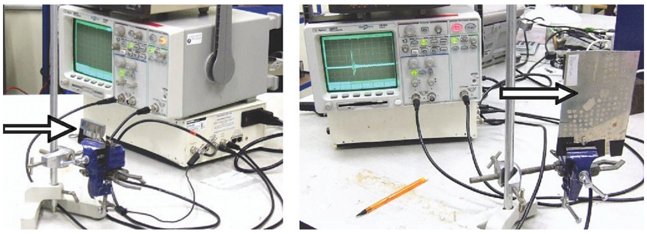

Figure 5. Set-up for AE tests of (a) 8 mm-thick steel plate and (b) 2 mm-thick aluminium plate (test samples arrowed)

4-6 μm-thick piezoelectric film and had an active area 3 x 8 mm². To generate an AE event the steel coupon was hit with a small spanner. The gain of the DPR300 was 50 dB and the band-pass filter was set to 0-35 MHz. Results are shown in Figure 6.

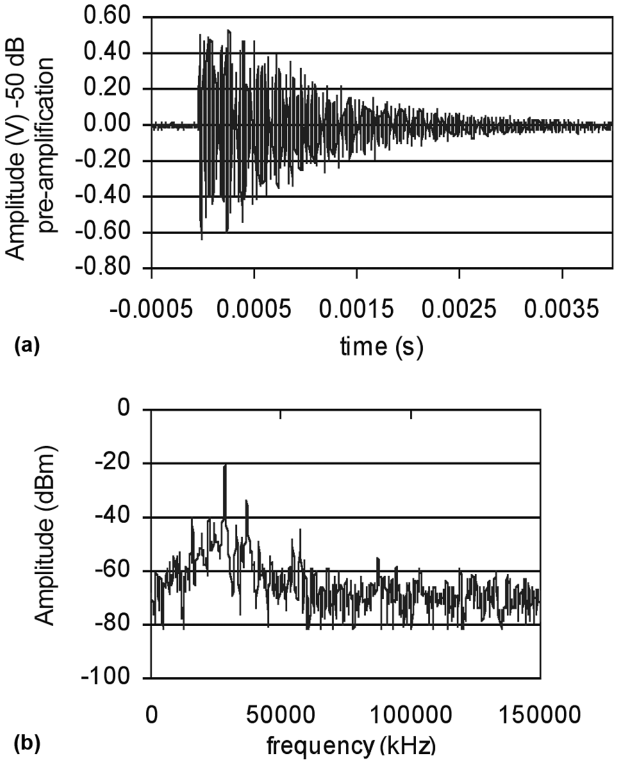

Figure 6. AE event recorded on steel sample: (a) time domain; and (b) FFT

In the second experiment the substrate was a 2 mm-thick aluminium plate (180 x 120 mm²). The piezoelectric film was again 4-6 μm thick and the transducer active area was 6 mm diameter. An AE event was simulated by a pencil lead break on the back of the aluminium plate. The DPR300 amplifier gain was 30 dB and the band-pass filter was set to 0-50 MHz. AE events recorded in this way showed a long ringing tail at low frequency (Figures 7(a) and (b)) but also a very sharp attack with MHz range harmonics (Figure 7(c)).

These results demonstrate that the thin-film transducers are able to function as AE sensors, with a broadband response from 20 kHz to over 5 MHz. Performance could be optimised depending on the substrate material under test and the type of AE events to be monitored.

2.3 High-temperature ultrasonic monitoring of plant in service

Thin-film transducers were investigated for online condition monitoring, for example of corrosion or growing cracks in high temperature plant[12]. Pulse-echo results were obtained from the inside wall of a section of ferritic steel steam pipe 65 mm thick and, in addition, a high temperature probe was developed for tests on live plant. It was possible to use the thin-film transducers with standard

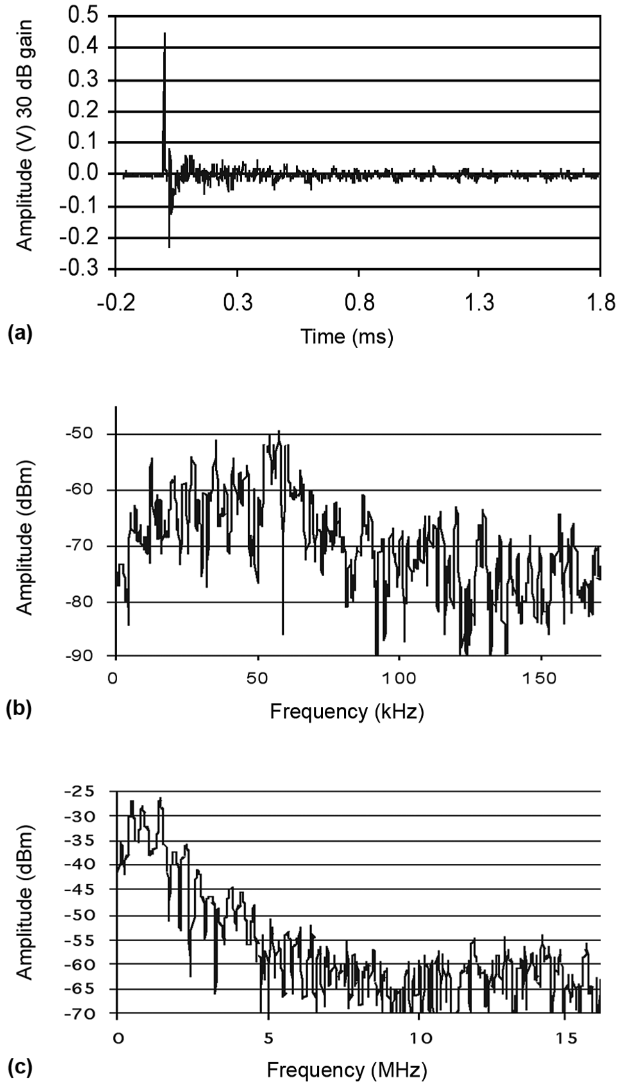

Figure 7. AE pencil lead break event recorded on aluminium substrate. Gain = 30 dB, BW = 0-50 MHz: (a) time domain; (b) FFT; (c) FFT of start of band-limited AE event on aluminium substrate (peak harmonic at 1.45 MHz)

flaw detectors. High-temperature tests were conducted using a sample consisting of a 1 cm-thick steel substrate, a 4 μm thin-film transducer, a sputtered gold electrode and a 'backing' of Cotronics Corp 940 zirconia-based ceramic adhesive rated for applications up to 1100°C. A-scans were recorded up to 600°C (Figure 8).

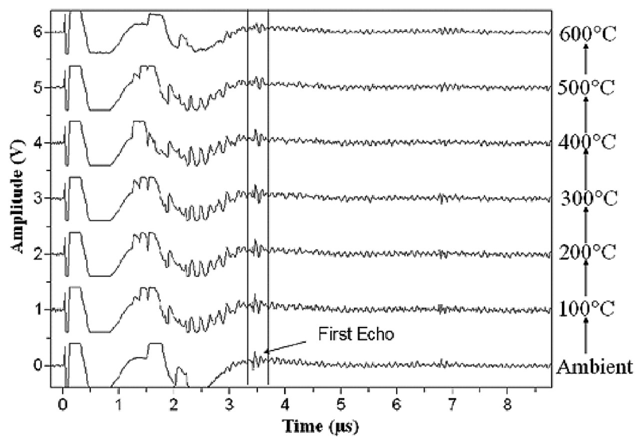

Figure 8. High-temperature ultrasonic trials on 10 mm-thick steel substrate. The thin-film transducer had a sputtered gold electrode and a high-temperature cement backing layer

3. Transducer frequency control

From the experimental results and applications given above, it is apparent that despite the small thickness of the piezoelectric element, the thin-film transducers can operate over a wide frequency range. Investigations into how to control the operating frequency showed that the response to pulse excitation is governed by both electrical and mechanical effects, plus the harmonic content of the excitation pulse. The natural thickness mode resonance of the thin-film transducers is of the order of GHz, therefore in these ultrasonic condition monitoring applications the transducers are operating in a non-resonant (below resonance) mode. 1-D simulations using a PSpice equivalent circuit model[13] and PZFlex finite element simulations have been used to explain how to engineer the frequency of operation. The situation has similarities to below resonance operation of a bulk piezoelectric transducer described in[14].

For below resonance operation, the thin-film transducer is in 'actuator' mode, where the strain generated by the piezoelectric material replicates the electrical signal it receives. Unlike the case for resonant operation, the mechanical output of the transducer is not amplified or filtered by the transducer's own mechanical resonance characteristics. The signal which arrives at the transducer is, however, modified by the electrical properties of the transducer and the system. The nanosecond electrical excitation pulse commonly used in ultrasonic imaging and non-destructive testing cannot be regarded as a true impulse because its maximum frequency is much lower than the ~GHz resonant frequency of the thin film. By particular design of the excitation pulse, the transducer can be induced to operate at the required frequencies. This is demonstrated by results obtained using NDT flaw detectors to generate excitation pulses at 1-10 MHz.

Effects were seen experimentally which have been attributed to the mechanical structure of the thin-film transducer. In particular, the behaviour was different when thin Cr/Au back electrodes were used instead of thick Ag paint. Shear waves were found to dominate for transducers with low mass back electrodes (evaporated Cr/Au). FE simulations show the shear waves originating from the edges of the transducer. Note that the thin-film transducers are solid-coupled to the substrate, so shear waves can propagate directly from the transducer.

Longitudinal mode operation in high-temperature transducers was induced by 'mass loading' the back electrode with high-temperature cement or by electroplating with Au or Ag. Figure 9 demonstrates the effect of using jewellery-maker's brush electroplating to grow a 2 μm Ag layer on an 8.3 μm-thick piezoelectric film on a ferritic steel substrate. In this case the excitation was by a JSR DPR300, receiver gain 70 dB, receiver bandwidth 2.5-50 MHz. Originally, only a shear wave echo could be recorded (Figure 9(a)). After Ag plating the back electrode, improvement in the penetration of the longitudinal waves is clearly visible (Figure 9(b))[15]. The peak frequency of the longitudinal mode echo is at 9.9 MHz.

4. Summary and conclusions

In summary, we have developed ultrasonic transducers made using thin piezoelectric films for applications in ultrasonic condition monitoring and non-destructive testing. The transducers have the advantages of being low profile, broadband and high-temperature resistant. The thin-film sensors have shown to have distinct benefits in use. Control of the operating frequency of the thin-film transducers is now fairly well understood and design techniques can be applied when a device is needed for a specific purpose.

The transducers have been demonstrated in ultrasonic measurements in pulse-echo mode, through-transmission mode and as passive sensors. Thin-film transducers can enable the pre-instrumentation of components and parts of systems in order to build equipment able to be monitored during operation. This provides a new way to add functionality to existing systems or to provide technical solutions where standard ultrasonic transducer technology is difficult or impossible to use.

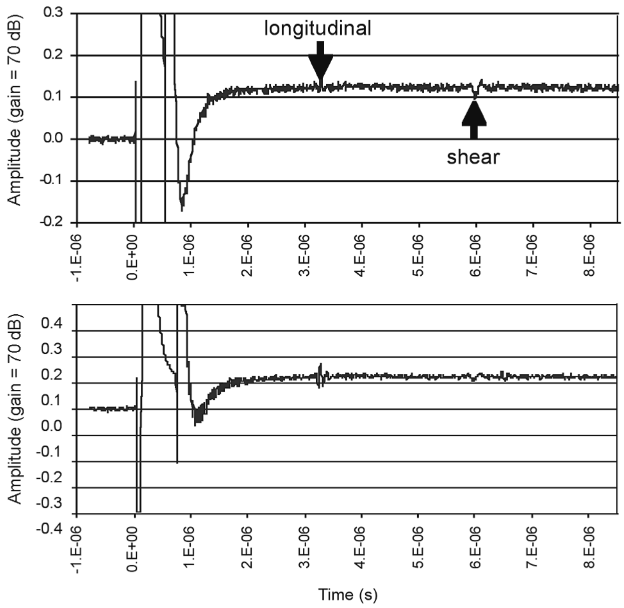

Figure 9. Pulse-echo results for thin-film transducer on ferritic steel coupon showing detection of longitudinal and shear wave modes: (a) thin-film Cr/Au electrode (100 nm); (b) thick Ag electroplated electrode (0.5-2.5 μm)

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The measured locations of the crack tip in the images before and after processing are compared with the destructive testing result for a typical weld crack in Figure 9. The horizontal axis in the plot corresponds to the scanning surface and the zero of the horizontal coordinate, which is set beforehand, represents the midpoint of the B-scan path. The vertical axis represents the buried depth of the tips from the scanning surface in the specimen. The measured and actual locations of the tips are shown in the corresponding plots. The measurement errors in the raw and the final processed image can be compared. Ten measurements were taken on the original images and the data from the final processed image was obtained from one measurement.

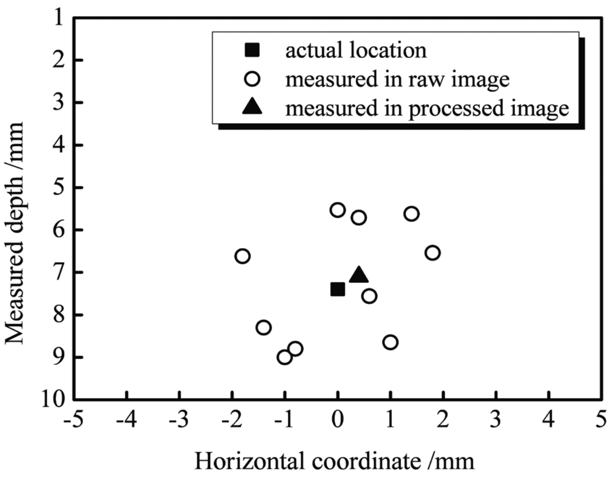

Figure 9. Location results for weld crack tip

5. Conclusions

In this paper, the forward problem of ultrasonic TOFD imaging was studied and B-scan testing results were simulated. The experimental results show that the simulated data, including A-scan lines and B-scan images, are in good agreement with the measured data.

The SAF algorithm was developed and applied to improve the lateral resolution of the ultrasonic TOFD B-scan image. Forward synthesis can validate the SAF algorithm and solve the inverse problem of non-destructive testing.

In the final processed images, the buried depth and lateral location of weld crack tips can be determined within an error of 0.5 mm. Measurements can be taken on the final processed images more rapidly and with higher accuracy than on the raw images.

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