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Improvement of bulk acoustic wave hammer for vibration testing of microstructures using 1-3 composite transducers

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Abstract

Improvement of a bulk acoustic wave (BAW) hammer for vibration test of microstructures using 1-3 composite transducers is presented. The characteristics of a BAW hammer produced with the 1-3 composite transducer were simulated by commercial software PIEZOCAD. The composite transducer excited by the pulse waveform acted as a BAW hammer will be evaluated by the vibration testing of microstructures. The experimental results of a BAW hammer with composite structure agree well with the simulation predictions. Moreover, based on the vibration testing result of silicon dioxide beams, 1-3 composite transducers excited by a pulse can improve the waveform duration and bandwidth of BAW hammer used in the vibration testing. Furthermore, the program code can be exploited to design the composite BAW hammer to excite the interested frequency range of the microstructure. The BAW hammer produced by the 1-3 composite transducers is also applicable to the on-line testing of microstructures.

Keywords: Bulk acoustic wave hammer; 1-3 Composite transducers; Vibration test; Microstructure

1. Introduction

Ultrasonic transducers have been extensively used in industrial and medical applications. The ultrasonic transducer has several characteristics such as high operating frequency (KHz–MHz), large output force, and fine positioning (nm–μm) with extremely high accuracy. In this regard, the ultrasonic transducer can be exploited as not only a detector but also an actuator. Because the operating frequency of the ultrasonic transducer is close to the natural frequencies of microstructures, it is especially suitable for the application of MEMS testing. For instance, various harmonic excitation techniques are using PZT discs as the driving source to determine the dynamic response of microstructures [1–3]. In this manner, the measured resonance of the microstructure may be shifted when it is near the resonance of the PZT discs. To avoid the interference of PZT dynamics during vibration test, a novel bulk acoustic wave (BAW) hammer is exploited to excite the microstructure [4]. A bulk PZT ultrasonic transducer generates the BAW. This transducer has longer waveform duration due to the radial modes of the bulk PZT ceramic. Although the backing layer of transducer can slightly reduce the effect of these radial modes, these lower radial frequencies still couple with the dynamic response of microstructures.

The design and manufacturing of 1-3 connectivity composite transducers, comprising an assembly of active piezoceramic rods embedded within a passive polymer, has been extensively investigated over the past 10 years [5–8]. These articles are focused on the study of 1-3 composite transducers under different PZT volume fraction and passive polymer material. Generally, the performance of the composite transducer including bandwidth and waveform duration is better than that of the bulk PZT. However, higher cost and complicated fabrication processes are also required for the composite transducers.

Broad bandwidth and constant amplitude are two basic requirements for the impact hammer during vibration test. In this regard, the BAW hammer used in [4] is not an ideal impact hammer for the vibration test. The 1-3 composite transducer is employed in this study to improve the characteristic of a BAW hammer for vibration testing of microstructures. The 1-3 composite transducer was driven by pulsed voltage to generate a BAW to excite the microstructures. According to the commercial software PIEZOCAD [9], the electrical impedance, transmit impulse waveform and spectrum of the 1-3 composite BAW hammers will be predicted. Thus, the BAW hammer consists of PZT material and polymer filler were designed and fabricated.

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The vibration test of micromachined silicon dioxide beams was conducted to demonstrate the feasibility of the proposed concept.

2. Design of the BAW hammer using 1-3 composite transducer

As illustrated in Fig. 1a, a broad bandwidth ultrasonic transducer is used to generate a BAW. The transducer, acting as an impact hammer, is employed to generate an impulse excitation to excite the microstructures during the vibration test [4]. A typical impulse waveform and power spectrum of the transducer acted as a BAW hammer is shown in Fig. 1b and c. The waveform and frequency spectrum of the BAW hammer used in this study has been defined by the American Society for Testing and Materials (ASTM) code E1065.

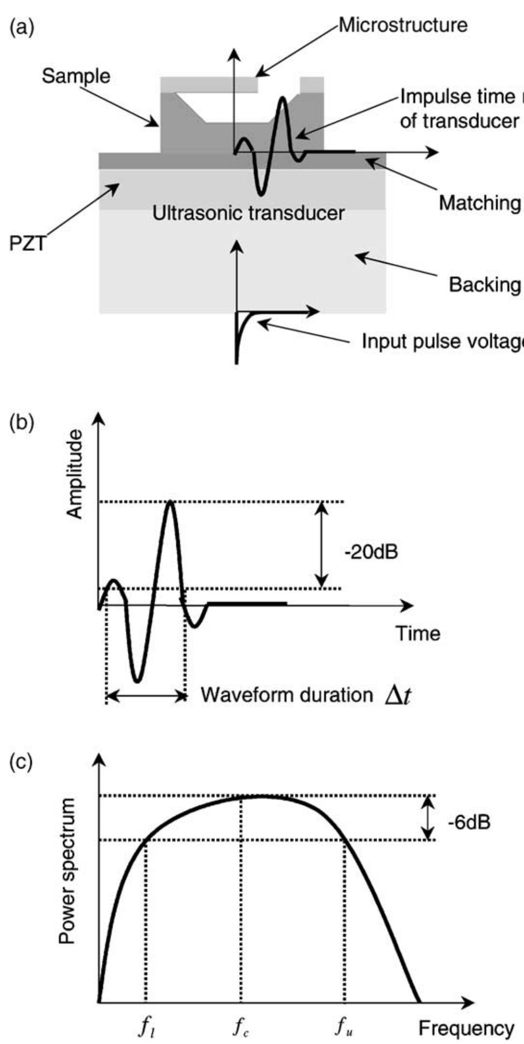

Fig. 1. A schematic diagram of the bulk acoustic wave (BAW) hammer applied to microstructures using pulsed broad bandwidth ultrasonic transducer: (a) the proposed BAW hammer model, (b) the impulse time response of transducer, and (c) the impulse frequency response of transducer.

According to this code, the waveform duration Δt is defined as the -20 dB level amplitude of peak, as shown in Fig. 1b. The central frequency f_c in the frequency response of the waveform is expressed as $f_c = (f_u + f_l)/2$. As indicated in Fig. 1c, the parameters f_u and f_l are upper and lower frequencies where the power spectrum drops 6 dB from its peak. The bandwidth BW of the BAW hammer is defined as $\mathrm{BW} = 100 \times (f_u - f_l)/f_c$. However, the energy level of the transducer required for the impulse test is not restricted to -6 dB. Hence, the effective bandwidth for impulse test is wider than BW. The natural modes of the microstructure within the effective bandwidth will be excited.

The impact hammer is exploited to apply an impulse to the structure for conventional vibration test [10]. The impulse with specific amplitude A and duration Δt can excite all the vibration modes of the test structure within a certain frequency range. Thus, the dynamic characteristics including natural frequencies, mode shapes, and modal damping of the structure are determined. In this test, the frequency range over which the amplitudes are essentially constant is inversely proportional to the waveform duration Δt of the impulse. It is necessary to generate a pulse with a shorter Δt to excite the microstructures at a higher frequency range. In other words, the requirement of the ultrasonic transducer when acting as a BAW hammer is to have a broad bandwidth spectrum with constant load.

The characteristic of the proposed BAW hammer will be highly dependent on the design of broad bandwidth ultrasonic transducer. As indicated in Fig. 1a, the transducer consists of the active component and the passive components. The present study intends to improve the performance of BAW hammer using 1-3 composite transducers. Fig. 2

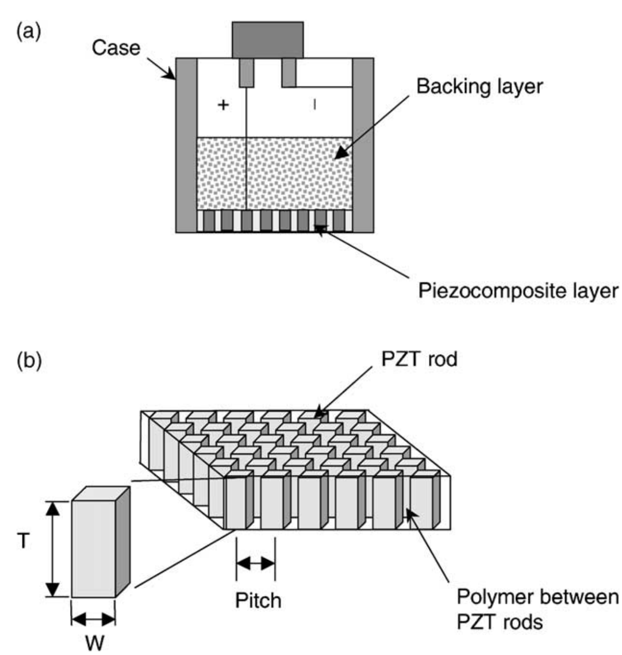

Fig. 2. The schematic diagram of a BAW hammer produced by (a) 1-3 composite transducer and (b) the close-up of the 1-3 piezocomposite layer.

shows the design of 1-3 composite transducer employed in this study. As indicated in Fig. 2a, the primary components of the transducer are the active 1-3 piezocomposite layer, and the passive backing layers. Fig. 2b shows the close-up of the active piezocomposite layer that comprises various PZT rods. The space between the PZT rods was filled with passive polymer. These piezocomposites, typically in volume fraction of 20–70% PZT, have a lower acoustic impedance (4–25 MRayl) [11]. The aspect ratio of the PZT rod (*W*/*T*), the pitch between the PZT rod, and PZT volume fraction V_{PZT} will significantly affect the performance of BAW hammer. Moreover, the design of passive element such as backing layers can also improve the bandwidth of the composite BAW hammer. The backing can suppress the waveform duration Δt of the BAW hammer, whereas, it will also reduce the vibration amplitude. Furthermore, the acoustic impedance of the piezocomposite layer material can be adjusted by its composition. In this study, the acoustic impedance of the piezocomposite layer is approximately the same as that of the silicon substrate and silicon oxide (16.7 MRayl) [12]. Hence, there is no need of the design of the matching layer of the 1-3 composite BAW hammer in the present study.

3. Analysis of composite BAW hammer

The 1-3 composite ultrasonic transducer acting as the BAW hammer has three ports, with one electrical port representing the terminals of the piezoelectric material, and two identical acoustic ports representing the front and rear surfaces. The PZT rods were regarded as one-dimensional model since their width (*W*) is much smaller than their height (*T*), as shown in Fig. 2b. The polymer matrix in this case can be regarded as an equivalent mechanical damping (quality factor) to the vibration of PZT rods. In application, the thickness mode of the piezocomposite transducer in Fig. 2 is driven by pulse voltage to excite the microstructures. Therefore, the piezocomposite transducer can be considered as a homogeneous material with equivalent properties. Thus, the commercial software PIEZOCAD can be exploited to simulate the performance of BAW hammer based on the modified KLM model [13–15]. Both of the front and rear loading of BAW hammer are applied to the air before mounting the testing sample. Based on the input parameters of piezoelectric material, backing layer, and loading condition, the performance of the composite BAW hammer including the electrical impedance, transmitted waveform and spectrum can be predicted simultaneously.

Fig. 3a shows the simulation results of the impedance for a 1 MHz 1-3 piezocomposite disc. The material properties including velocity, acoustic impedance, and attenuation of the kerf-filling polymer are 2584 m/s, 3.02 MRayl, and 24 dB/(cm MHz), respectively. To achieve good electromechanical coupling coefficient and sensitivity of piezocomposite material, the volume fraction V_{PZT}, *W*/*T* ratio, and pitch of PZT5A rod are designed to be 44%, 0.2 and 0.4 mm, respectively [5–8]. The diameter, thickness and acoustic impedance of the piezocomposite disc is 20 mm, 1.67 mm and 12.8 MRayl, respectively. The quality factor of 1-3 piezocomposite disc is approximately 15, which is much smaller than that of bulk PZT disc. In other words, the BAW hammer actuated by the pulsed 1-3 piezocomposite disc will exhibit broader bandwidth than the bulk PZT disc.

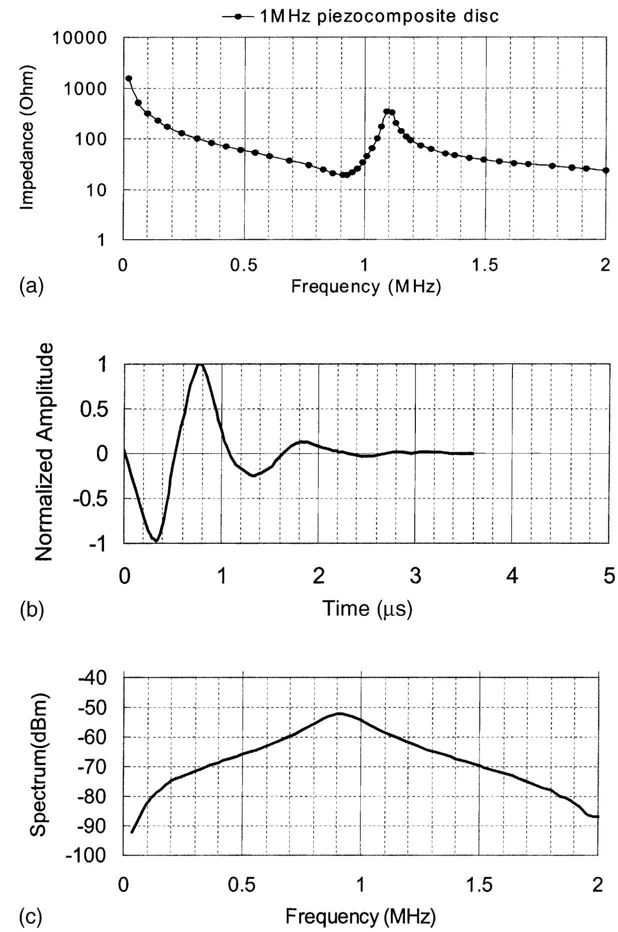

Fig. 3. The predicted response of BAW hammer produced by the 1 MHz 1-3 composite transducers: (a) electrical impedance curve of the 1-3 piezocomposite layer, (b) waveform, and (c) power spectrum of 1-3 piezocomposite layer plus backing layer design.

The simulation results of a BAW hammer composed of the 1 and 5 MHz composite transducers (piezocomposite layer plus backing layer) are indicated in Figs. 3 and 4. The volume fraction V_{PZT} of the 1 MHz composite transducer is still 44%, and that of the 5 MHz one is 25%. The acoustic impedance and velocity of backing material is 5.6 MRayl and 1280 m/s, respectively. The −6 dB bandwidth of 1 and 5 MHz transducer is 97 and 168%, respectively. The simulation results revealed that the impulse response of the 1-3 composite transducers is similar to that of the conventional hammer [10], even at the megahertz range. Consequently, the composite transducer will be an ideal BAW hammer for the impulse vibration test of microstructures. The excitation frequency for vibration test of microstructure can be increased to megahertz range.

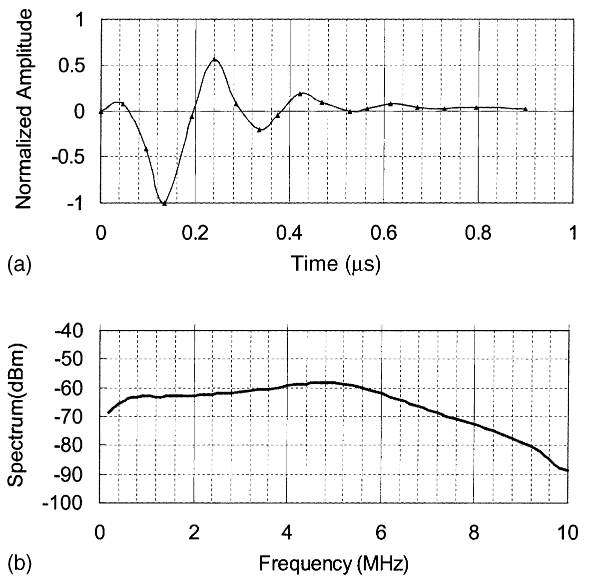

Fig. 4. The predicted response of BAW hammer with 5 MHz 1-3 piezocomposite disc plus backing layer design: (a) waveform and (b) power spectrum.

4. Experiments

The active layer of the 1-3 composite ultrasonic transducer was fabricated through the wafer level batch processes shown in Fig. 5. In Fig. 5b, the PZT5A disc was diced into the matrix rods using dicing saw firstly. The width of kerf can be controlled by the thickness of the saw-blade. As shown in Fig. 5c, the kerf was then filled using the polymer (epoxy resin) to form the piezocomposite layer. In Fig. 5d, the piezocomposite layer was lapped to the desired thickness after the polymer was cured. Finally, the electrode material of the piezocomposite disc was patterned using sputtering machine, as shown in Fig. 5e. Fig. 5f shows the photograph of a 1-3 composite disc fabricated through above processes.

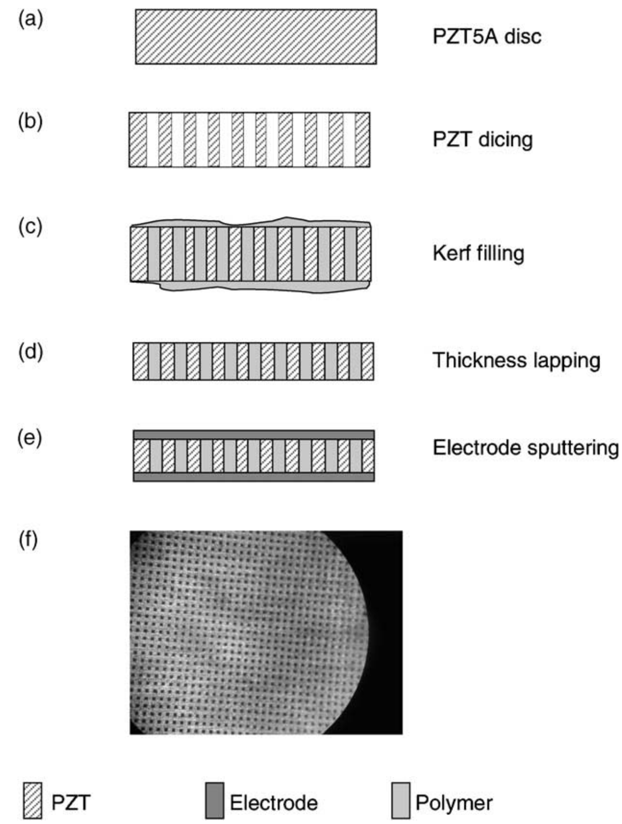

Fig. 5. The manufacturing process and schematic diagram of the 1-3 piezocomposite layer: (a) PZT5A disc, (b) PZT dicing, (c) kerf filling, (d) thickness lapping, (e) electrode sputtering, and (f) typical photograph of the 1-3 piezocomposite layer.

In application of the proposed ideal BAW hammer produced by 1-3 composite ultrasonic transducer, silicon dioxide cantilever beams were fabricated on the (1 0 0) oriented silicon substrate. The thermal oxide film was grown on the (1 0 0) wafer first. The oxide film was patterned into dif-

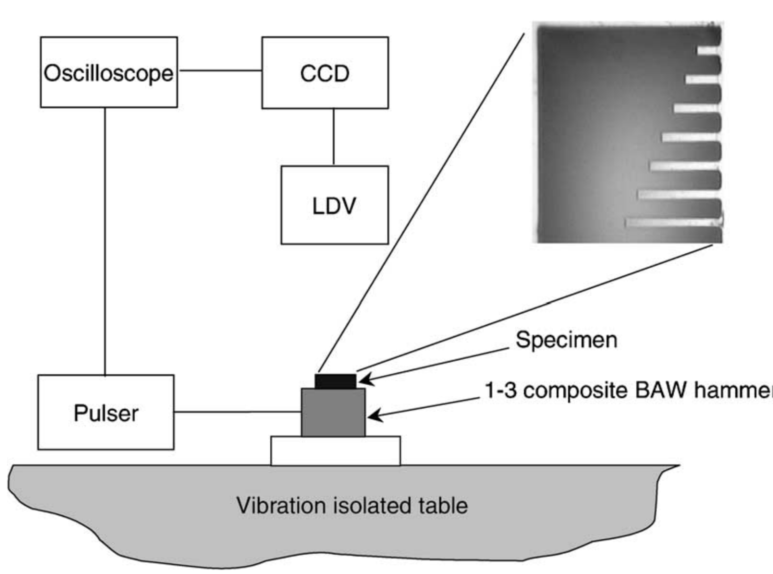

Fig. 6. The experimental setup for BAW hammer test.

ferent geometry by buffered HF after photolithography. The substrate under the microstructures was etched anisotropically by TMAH solution. The inset in Fig. 6 shows the photograph of typical cantilever beams fabricated through above processes. These test micro cantilevers were 6 μm wide and 1.1 μm thick, and their lengths were ranging from 20 to 80 μm. The gap between micro cantilevers and the substrate was 55 μm after the bulk etching to prevent the squeeze film effect.

The experimental setup for recording the dynamic response of BAW hammers and microstructures is illustrated in Fig. 6. The dynamic response of the BAW hammer was characterized individually before the test. Moreover, the impedance characteristic of the BAW hammer was measured using HP 4194 impedance analyzer. The test sample as indicated by the inset was mounted on the transducer by wax or sticky tape. The high voltage pulse generator in Fig. 6 was used to produce a very short pulse voltage shown in Fig. 1a to provide broad bandwidth frequency spectrum to the ultrasonic transducer. The transducer generated a BAW after excited by the pulse voltage. After that, the sample will experience an excitation with a broad bandwidth frequency range. The pulser in Fig. 6 can also be replaced using a function generator together with a power amplifier. Finally, the dynamic response of transducer and microstructure was measured by the Laser Doppler Vibrometer system. The time and frequency response of BAW hammers and microstructures were recorded and analyzed by the oscilloscope or frequency analyzer.

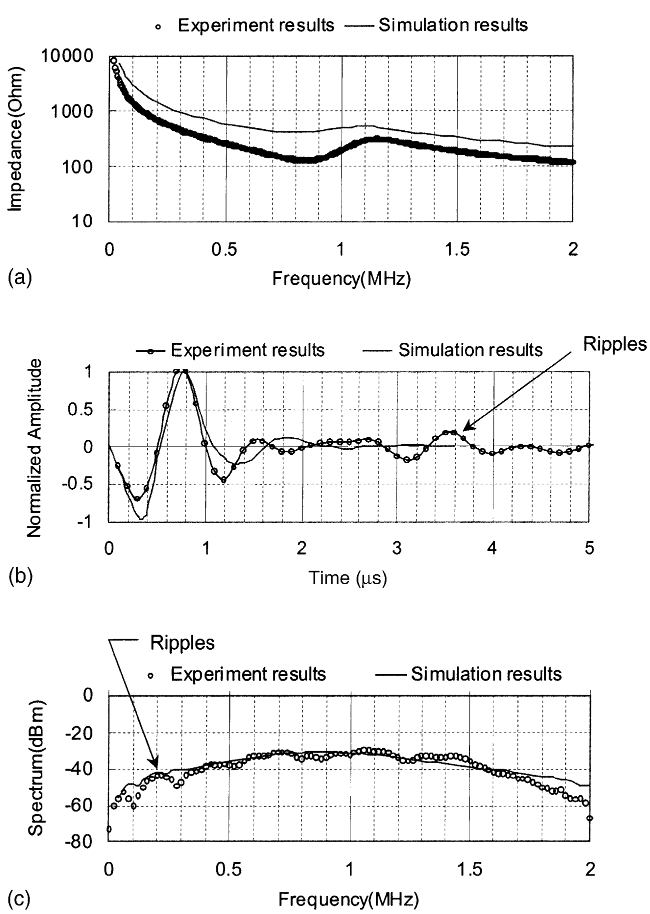

Fig. 7. Comparison of simulation and experimental results for the BAW hammer with 1 MHz piezocomposite layer plus backing layer design: (a) electrical impedance response, (b) impulse waveform, and (c) impulse spectrum.

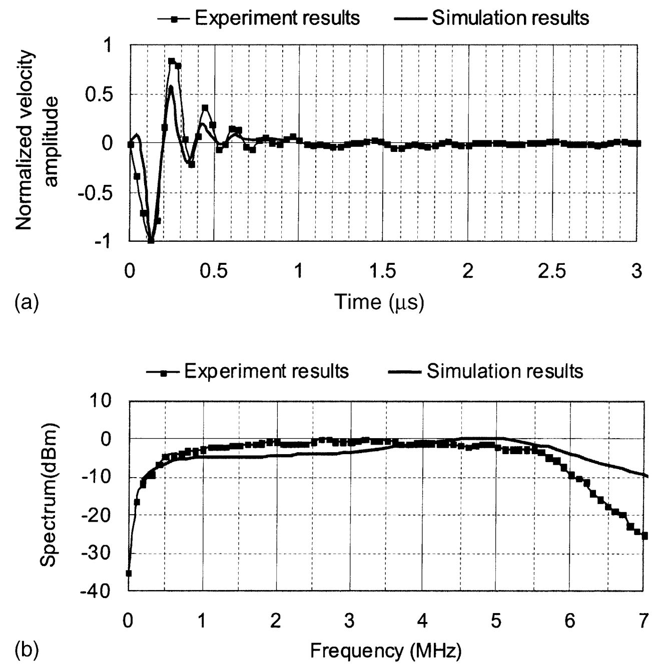

Fig. 8. Comparison of simulation and experimental results for the BAW hammer with 5 MHz piezocomposite layer plus backing layer design: (a) impulse waveform and (b) impulse spectrum.

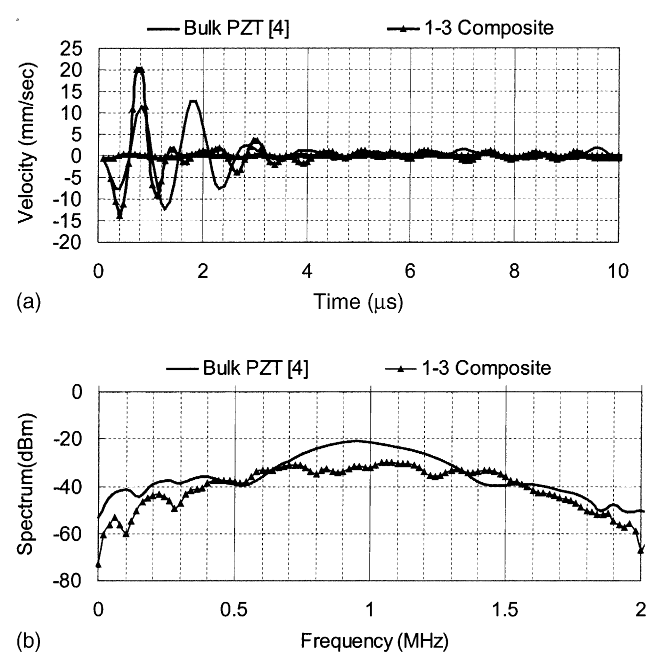

Fig. 9. Comparison of BAW hammer produced by bulk PZT and 1-3 composite design: (a) impulse waveform and (b) impulse spectrum.

Table 1
Summary of the performances of BAW hammer produced by three different ultrasonic transducers

Items	Compositions	Center frequency (MHz)	Predicted −20 dB waveform duration (μs)	Experimental −20 dB waveform duration(μs)	Predicted −6 dB bandwidth (%)	Experimental −6 dB bandwidth (%)
BAW hammer 1	PZT5A plus backing [4]	1	3.997	6.5	39	35
BAW hammer 2	44% V_{PZT} composite plus backing	1	1.87	2.9	97	100
BAW hammer 3	25% V_{PZT} composite plus backing	5	0.39	0.42	168	167

5. Results and discussion

The pulse voltage applied on the composite BAW hammer was 175 V, 1 KHz pulse repetition rate, and 0.1–0.23 μs pulse width time. Figs. 7 and 8 show the experiment and simulation results for 1 and 5 MHz piezocomposite discs plus backing layer. The simulation results agree well with the experimental ones. In Fig. 7a, there are no radial modes before thickness extensional mode. However, as indicated in Fig. 7b, there are still several ripples for the 1 MHz 1-3 composite BAW hammer. These ripples as indicated in Fig. 7c resulted from the radial modes of piezocomposite layer. As shown in Fig. 8, these ripples were successfully removed through the 5 MHz 1-3 composite transducer. Fig. 9 shows the difference between the bulk PZT [4] and 1-3 composite BAW hammer for both pulsed waveform and the associated frequency spectrum. It is evident that the 1-3 composite BAW hammer has shorter waveform and wider bandwidth than the bulk PZT one. In close, Table 1 summarizes the impulse response of different BAW hammer. The experimental waveform duration was much longer than the predicted ones due to the radial modes effect of BAW hammer. The predicted bandwidth results agree well with the experimental ones. The results demonstrate that the 1-3 composite transducer indeed has a broader bandwidth, and will become a better impact hammer for vibration test. Consequently, the performance of BAW hammer for vibration test of microstructures can be significantly improved using 1-3 composite transducers.

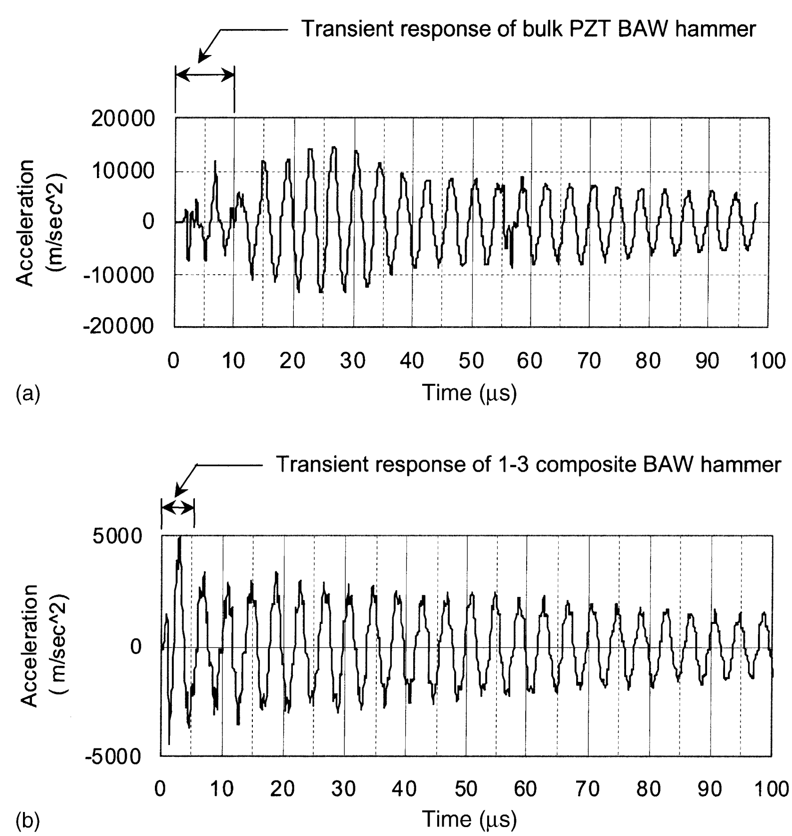

Fig. 10. The measured impulse time response of a 1.1 μm thick, 6 μm wide and 60 μm long test cantilever excited by (a) 1 MHz bulk PZT transducer and (b) 1 MHz 1-3 composite transducer.

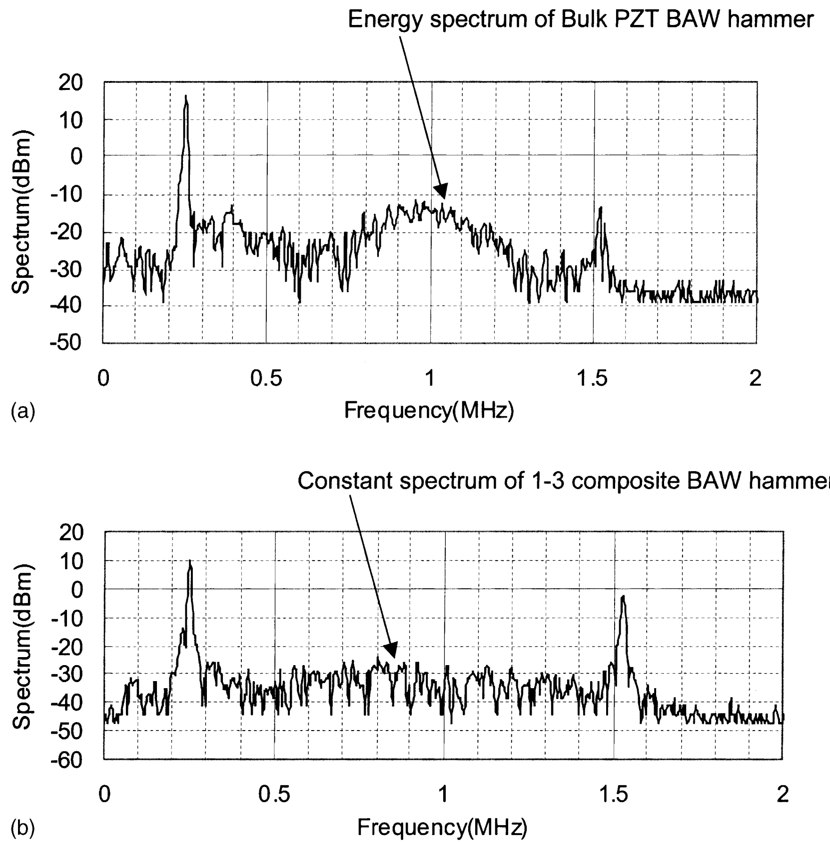

Fig. 11. The measured impulse frequency response of a 1.1 μm thick, 6 μm wide and 60 μm long test cantilever excited by (a) 1 MHz bulk PZT transducer and (b) 1 MHz 1-3 composite transducer.

To demonstrate the improvement of BAW hammer using composite transducer, the vibration test of microstructures was conducted. As shown in Fig. 10, the free vibration of the test cantilever excited by an impulse was recorded by the oscilloscope. The transducers used to generate the impulse excitation include a 1 MHz conventional bulk PZT transducer and a 1 MHz composite transducer. The first few cycles of the measured response were due to the dynamics of the transducer. The transient responses of bulk PZT transducer and composite transducer are for about 10 and 5 μs, respectively. The spectrum of the transient response of the microstructures is shown in Fig. 11. An additional peak indicated in Fig. 11a was caused by the bulk PZT transducer. However, this problem was prevented by the composite transducer, as shown in Fig. 11b. In close, it shows that the 1-3 composite BAW hammer has shorter waveform duration and constant power spectrum.

6. Conclusion

In this research, the improvement of a BAW hammer for vibration testing of microstructures using a 1-3 composite transducer was studied. The performance of a 1-3 composite transducer including the electrical impedance, transmit waveform, and spectrum can be simulated using the PIEZOCAD software. Experimental results of the composite ultrasonic transducer agree well with simulation ones. The result also revealed that 1-3 composite transducer had shorter waveform duration and broader bandwidth than bulk PZT one. Consequently, the 1-3 composite transducer is a better source to act as a BAW hammer for the vibration test of microstructures. The BAW hammer produced by the 1-3 composite transducers is also suitable for on-line testing of microstructures under batch production.

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