Investigation of ultrasonic vibrations of wire-bonding capillaries

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Abstract

Ultrasonic energy is widely used in wire bonding for microelectronics packaging. It is necessary to ensure that the maximum ultrasonic vibration displacement occurs at or near the tip of the bonding tool (capillary) for optimal performance. In this study, amplitude profiles of ultrasonic vibrations along capillaries were measured with load using a laser interferometer. This provided valuable information in understanding and improving capillary performance. The method was applied to real time applications to optimize capillary designs and bonding processes for specific bonding applications. First, the application of a new capillary material with different zirconia compositions was evaluated. The new material with certain amount of zirconia composition showed that it was the capillary material of choice for ultra-fine pitch wire bonding. Next, comparative analysis was conducted to investigate the ultrasonic energy transfer of a new 'slimline' bottleneck and the conventional bottleneck. The actual bonding response of the molded slimline bottleneck showed comparable performance with the ground conventional bottleneck using the same bonding parameters. Finally, optimization of a 60-μm-bond-pad-pitch process was performed on a wire bonder. Within the optimized parameter ranges, the ultrasonic displacement of the capillary was monitored. For all possible combinations of bond force and bond power, the ultrasonic displacement of the capillary increased with increasing bond power, without drastic changes caused by bond force changes. This indicated that the selected process window was located in a stable region.
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1. Introduction

The increasing demands for high pin count, high electrical performance and miniaturization have led to significant advances in IC (integrated circuit) fabrication and microelectronics packaging [1–6]. Processing of silicon wafers also plays an enhanced role in manufacturing of microelectronics and micro-electro-mechanical systems [7].

Wire bonding is the most widely used technology in the microelectronics industry as a means of interconnecting IC chips and substrates [8]. Today, more than 90% of IC chips used in the world are with wire bonds because the high-speed automatic wire bonders meet most of the needs of microelectronics devices to the next-level packaging interconnection [9]. Today's demands for speed, accuracy and reliability are fulfilled with modern cameras, ingenious

optics and illumination, modern digital signal processors and intelligent algorithms [10].

A cost analysis [9] has also revealed that wire bonding cost per die decreases with pad pitch increases. Wire-bonding cost per die decreases with chip size decreases. For peripheral array chips, wire bonding is cheaper than flip chip [11,12] if the chip size and the pad pitch are very large.

Microelectronics packaging has sparked intensive interest in ultra-thin packages in which the body thickness is less than 1 mm [13]. This is forced by the demand of assemblies such as Smart Cards and MCMs (multi-chip modules). The emphasis is placed on the interconnect between the chip and its interconnection system. The bond loop height is one of the dominating parameters in reducing the thickness of the ultra thin package [14].

Besides the most commonly used Au wires, Al–Si wires are also used for interconnection in microelectronics devices, including RF power transistors in cellular base stations [15]. To improve the performance of advanced ICs, a transition from Al to Cu metallization is in progress. Despite its many advantages, implementation of Cu poses

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a challenge for integration, even in the case of conventional Au wire bonding technologies [16].

Ultrasonic wire bonding is playing an important role in making interconnections in the microelectronics packaging industry. High quality of the bonds is vital to the performance of an IC chip. Therefore, a proper bonding quality control system is desirable. It is known that the bonding quality can be distinguished by observing the change in vibration amplitude of the fundamental frequency of the transducer [17].

The connections at the bond pad and lead are made by welding the wire to the metal with a combination of ultrasonic energy, pressure, and heat. This task is done with a wire-bonding machine, which has several parameters to set, such as temperature, ultrasonic power, and bond force. The parameter settings for successful wire bonding depend on many factors, including wire size, pad material and geometry, package size, tool type, and the capabilities of the machine. These require expert knowledge to optimize critical process characteristics [18].

Ultrasonic technology can be used for many applications [19,20] by appropriately utilizing its sound wave and high-frequency mechanical energy. In ultrasonic metal welding, the use of ultrasounds allows metals to be cold-welded, i.e. two metals can be welded together remaining at a temperature far below the melting temperatures of the two metals [21]. Ultrasonic energy is used to improve the structure of materials in metallurgy. The acoustic irradiation of molten mass improves degasification and the finer grain structure during the hardening process. To achieve a high level of wire bonding performance and quality, appropriate bonding process parameters must be accurately identified and controlled. Process engineers must identify and control these parameters to obtain desired wire bonding quality for optimizing multiple responses (e.g. maximum ball shear strength, wire pull strength, and appropriate ball size), based on their experience or equipment provider's recommendations [8].

Ultrasonic energy and the normal force to the bonding surface generate the metallurgical interaction causing the atoms of the wire to diffuse into the bonding site. The principal bonding process parameters such as bonding time, normal force, resonant frequency, ultrasonic power, and the amplitude of the tool can affect the bonding quality [22].

In recent years, there are increasing research efforts in the quantitative understanding of the wire bonding process mechanism to relate it to bonding quality. With the application of ultrasonic waves and a static tool tip force, a solid-state weld joint is produced between the wire and the terminal surface. A decisive factor for the electrical and mechanical proprieties of the bond is the vibrational behaviour of the bonding tool, which transmits the ultrasonic energy to the contact zone [23].

Ultra-fine pitch wire bonding [24] and copper bonding require a higher stability and robustness of the ultrasonic vibration generated by the transducer compared with current ultrasonic horns. No theory that can describe and clarify why higher frequencies can modify the results of the wire bonding process has been developed. The reason for the frequency increase of the transducers is that, at higher frequencies, the same bond results can be achieved at a lower bonding temperature reducing the thermal stresses and drifts in wire bonders, and in a shorter bonding time increasing the speed of wire bonders [25].

Ultrasonic welding is a type of deformation weld in which the metal is first softened by the ultrasonic energy. The clamping force deforms the softened wire or ball against the equivalently softened bonding pad, sweeping aside brittle surface oxides and contaminants, leaving clean surfaces in contact. Because little deformation takes place in the center of the weld, the oxides and contaminants remain there, and this area is often observed to remain unwelded. Presumably, the same energy transfer mechanism that softens the metals without significant heat generation also supplies the required activation energy for interdiffusion. This forms the metal-to-metal (atomic) bonds within a few milliseconds [26].

Therefore, in wire bonding, the bonding-tool (capillary) vibration amplitude is one of the most important parameters that influence the energy delivered to the bond zone. It is necessary to ensure that the maximum ultrasonic vibration occurs at or near the tip of the capillary for optimal performance. However, the quantitative understanding of the ultrasonic bonding mechanism still remains insufficient and therefore will continue to pose a huge challenge for future research work.

In this study, ultrasonic amplitude profiles along capillaries were measured using a laser Doppler interferometer. Measurement could be performed with load or in free air without load. To simulate actual bonding conditions, measurements were performed with load in this study. This provided valuable information in understanding and improving capillary performance. The method was applied to real time applications to optimize capillary designs and bonding processes for specific bonding applications. First, the application of a new capillary material with different zirconia compositions was evaluated. Next, comparative analysis was conducted to investigate the ultrasonic energy transfer of a new 'slimline' bottleneck and the conventional bottleneck. Finally, optimization of a 60-μm-bond-pad-pitch process was performed on a wire bonder and within the optimized parameter ranges, the ultrasonic displacement of the capillary was monitored.

2. Experimental setup

A laser Doppler vibrometer is an optical instrument that employs laser interferometric principles to measure velocity and displacement of points on a vibrating structure. The mobile unit of the laser vibrometer, which included a camera, a scanning unit, and an optical sensor head,
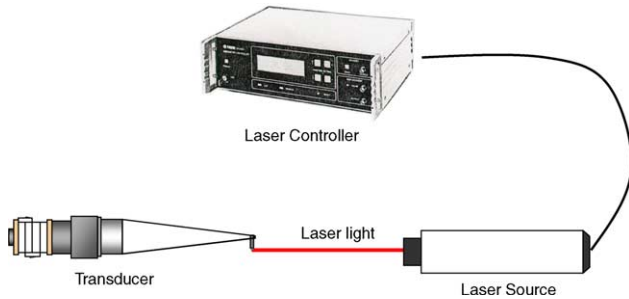
Fig. 1. Measurement of ultrasonic vibration of a capillary using a laser interferometer.

Fig. 2. Transverse vibrations of two capillaries.

was mounted onto a tripod. The laser beam from the optical sensor head was directed perpendicularly to a vibrating capillary as shown in Fig. 1. With the reflection from the vibrating capillary, the laser beam traveled back towards the mobile unit and was detected by the sensor head. An electronic signal processor in the vibrometer then demodulated the signal. Using an FFT algorithm, the vibrometer software converted the velocity of the transverse vibration (time domain) to displacement amplitude (frequency domain).

To understand the characteristics of the capillary during bonding, measurements of the displacement were carried out along the external profile of the capillary with certain amount of load applied by the capillary on the bond pad.

Using the vibrometer controller software, the laser beam can be directed at various points along the axial length of the capillary, hence allowing the displacement amplitude at any point along the axial length to be measured. The external profile of the capillary can be mapped out prior to the measurement. In operation, the laser beam was directed according to the mapped out location using the X, Y, and Z motor control to perform the measurement. Data were then tabulated and a graph of displacement amplitude versus the position along the capillary length was produced.

3. Vibration characteristics of capillaries

A decisive factor for the electrical and mechanical properties of the wire bond is the vibrational behaviour of the capillary, which transmits the ultrasonic energy from the transducer to the interface of the bonding media. The ultrasonic displacement causes the capillary to vibrate in a back and forth manner or sinusoidal motion. Depending on the bonded ball size requirement and the bond power and force settings used, the actual displacement of the capillary tip during bonding can vary from 0.56 to 3 μm. The higher the displacement is, the larger the bonded ball size is.

The capillary vibrates along the node point, which determines the amount of movement at the capillary tip. Depending on the design of the capillary, the node point can be positioned nearer or further away from the capillary tip. By moving the node point away from the capillary tip, larger
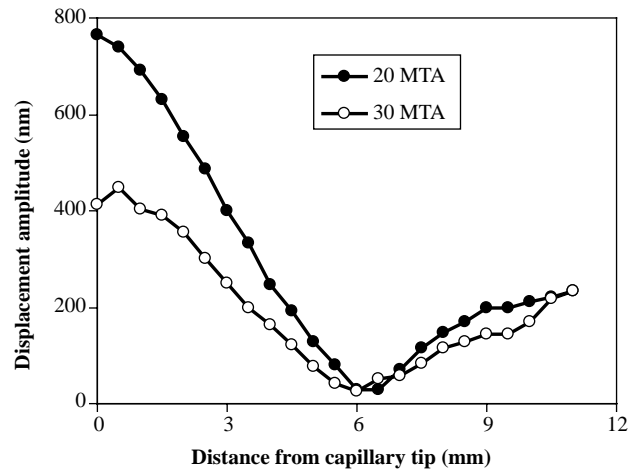
tip displacement amplitude can be achieved. As compared in Fig. 2, a 20MTA (main taper angle $=20°$) design has a higher tip displacement than a 30MTA (main taper angle $=30°$) design. The amount of tip displacement has a direct effect on the bond quality and the setting of process parameters on the bonder.

Although, the vibration characteristic of a capillary depends on the location of the node point, the overall length of the capillary has a significant effect on the vibration behavior, which directly affects the bonding performance. Currently, the $0.437''$ series with a length of 11.1 mm is the most common length used. Depending on bonding applications, a capillary length of 16 or 19 mm is also available for deep access bonding to prevent the transducer from hitting the device during bonding. Such capillaries are used for hybrid device bonding with specially designed transducer to match the resonance frequency.

Other factors, such as the tip diameter, internal taper angle and the bottleneck height, also affect the vibration characteristics of a capillary. These dimensions change the displacement amplitude at the tip of a capillary, which is directly responsible for the bond quality of ball and stitch bonds. Fig. 3 shows measured ultrasonic vibration waveforms of a capillary using low and high ultrasonic power settings. A higher ultrasonic displacement of a capillary requires a higher bond power setting.

An experiment was carried out to determine the effect of the capillary tip diameter on the displacement amplitude with respect to the change in bond parameters. As shown in Table 1, a smaller capillary tip diameter requires a lower bond power and bond force to produce equivalent vibration displacement compared to a larger tip diameter. Based on the assumption that the same ball size requirement is needed, a capillary with a tip diameter of 80 μm will require less bond power to achieve the equivalent bond quality than a tip diameter of 100 μm.

From the displacement measurements, it was found that the effect of bond power on vibration displacement was
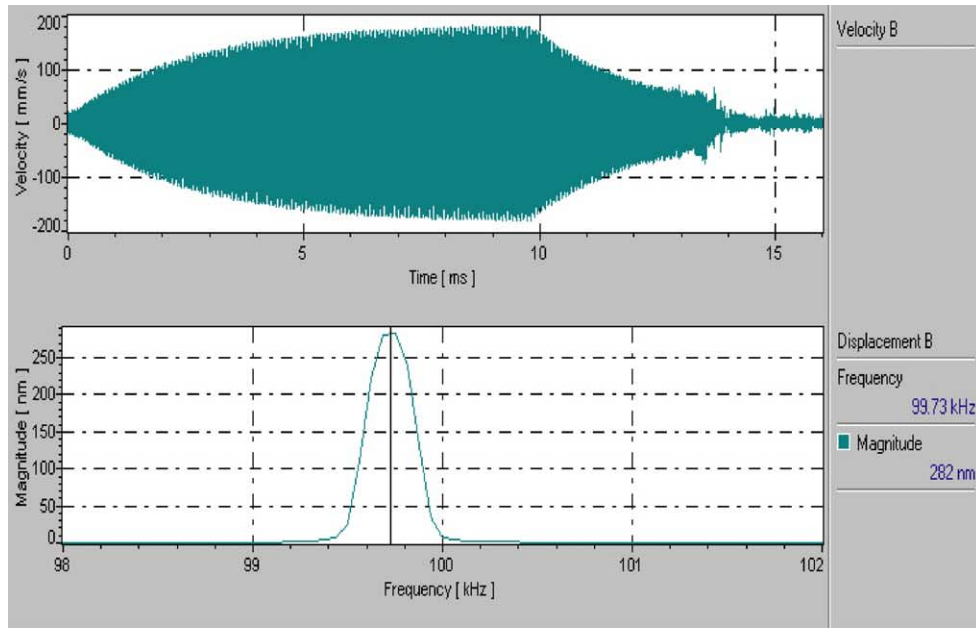
(a) Ultrasonic power = 70mW
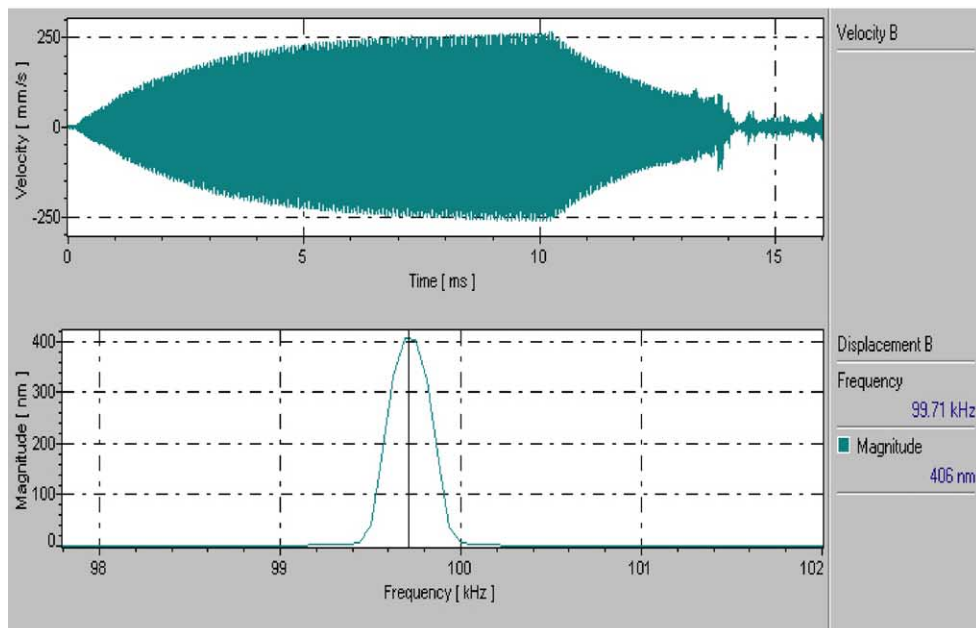
(b) Ultrasonic power = 90mW

Fig. 3. Measured ultrasonic vibration waveforms of a capillary using (a) low and (b) high ultrasonic power settings.

Table 1
Amplitude of oscillation for different capillary diameter, bond power and force combinations

Tip diameter (μm)	Bond force (mN)	Bond power (%)	Amplitude of oscillation (nm)		
			Min.	Max.	Ave.
100	500	18	480	520	500
	300	12	440	460	447
	300	18	640	660	647
80	180	10	520	540	527
	100	5	280	320	300

more significant compared to the bond force. Vice-versa, higher bond force with the same bond power would reduce the ultrasonic energy transfer, because the capillary was pressed harder onto the bond pad, which restricted the movement of the capillary during bonding. To a certain extent, this could result in lifted or non-stick ball bond.

4. Real-time applications

Using the laser vibrometer to investigate the vibration characteristics of capillaries has provided valuable information in understanding and improving the performance of capillaries. The knowledge can be applied to real time applications to optimize capillary designs and bonding processes for specific bonding applications.

4.1. Capillary material comparison

With the decrease in the bond pad pitch (BPP), subsequent decrease in capillary tip diameter has made the bottleneck tip more prone to breakage. The standard ceramic (SC) material consisting of pure ceramics can only support bonding applications with BPPs not smaller than 80 μm. With BPPs smaller than 80 μm, due to further decreased capillary tip diameter and bottleneck, the brittleness of the SC material results in high occurrence of tip breakage during bonding. In addition, it is not possible to economically manufacture such capillaries due to high yield loss.

A new material with zirconia additive has exhibited higher toughness values with much better resistance to tip breakage compared with the SC material. However, it was not certain how the capillary would behave during bonding with different zirconia compositions (ZC). An oscillation test using the laser vibrometer was conducted to determine if there was any difference in the vibration amplitude response between the SC and the new ZC materials. This test provided useful information for fine-tuning of the desired material composition before actual bonding tests.

In this test, the application of the new material with different zirconia compositions was evaluated. The zirconia composition increased for ZC1–ZC3 materials. The test was carried out on an ESEC wire bonder with the bonding parameters optimized for using the SC capillaries. As shown in Fig. 4, the vibrational displacement amplitude decreased as the amount of zirconia composition increased. This was because a larger amount of zirconia composition made the capillary material less rigid. During the test, the body of the capillary tended to be more flexible but the applied load restricted the movement at the tip of the capillary. It can be predicted that higher bonding power is needed during wire bonding to achieve satisfactory bond quality. The flexibility of the capillary can result in difficulty to define an acceptable process window.

In this test, the ZC1 material with the least amount of zirconia composition has shown that it is the capillary
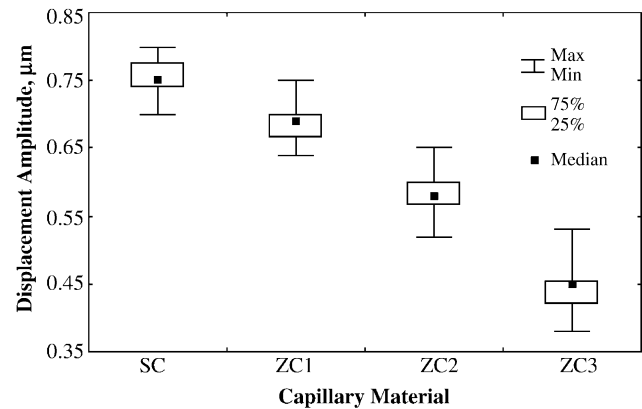

Fig. 4. The vibrational displacement amplitude decreased as the amount of zirconia composition increased.

material of choice for ultra-fine pitch wire bonding although the vibrational displacement amplitude is about 15% lower compared to the SC material. By bonding parameter optimization, the ZC1 material is capable of exhibiting a bonding response comparable to that of the SC material.

4.2. External profile comparison

The continuous shrinking of IC chips with closer pad-to-pad pitches has led to an increase in demand of special wire bonding capillaries for fine pitch and ultra fine pitch applications. As tips of capillaries become smaller, there is a need to redesign the external profiles of capillaries to provide consistent ultrasonic energy transfer during wire bonding. Currently, most of the capillaries used in the microelectronics industry are ground to shape. This grinding process, however, limits the repeatability, accuracy and wall thickness consistency of the capillary taper, resulting in a weakened bottleneck taper. Furthermore, it stresses the ceramic material and creates initial micro-fractures that proliferate during wire bonding.

A robust taper called slimline bottleneck taper has been designed (Fig. 5). The ceramic injection molding technology has been utilized to mold the capillary, which provides a stronger bottleneck taper because no grinding stresses are generated. In addition, the smooth transition from the taper to the bottleneck minimizes the chances of tip breakage during set-up and wire threading.

Comparative analysis was conducted to investigate the ultrasonic energy transfer of the slimline and conventional bottlenecks. Design optimization of the slimline bottleneck capillary was performed based on the vibration measurement results followed by wire bonding tests. The main objective of such design optimization was to provide consistent ultrasonic energy transfer to the tip of the capillary for good bonding stability. As shown in Fig. 6, the vibrational displacement at the tip of the slimline bottleneck capillary is about 5% lower than that of the conventional bottleneck capillary. This is because

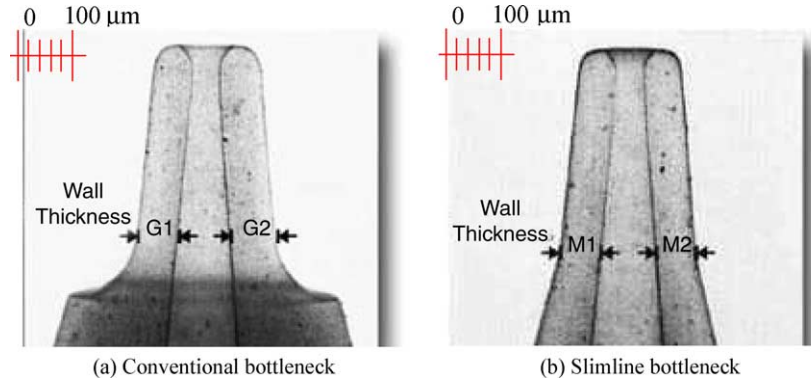(a) Conventional bottleneck (b) Slimline bottleneck

Fig. 5. The conventional and slimline bottleneck capillaries.

the thinner wall slightly restricts the amount of ultrasonic energy transfer to the tip of the slimline bottleneck capillary.

During bonding tests, the actual bonding response of the molded slimline bottleneck showed comparable performance with the ground conventional bottleneck using the same bonding parameters. Although, the ball shear readings were slightly lower, the 5% difference in the vibrational displacement did not change the bonding responses drastically. This benefits microelectronics manufacturers to shift between two different types of bottlenecks without any significant changes in bonding parameters and performance.

4.3. Process optimization

In wire bonding, it is important to achieve a robust process within the defined operating window. This means that within the specified parameter ranges there should not be any drastic change in the bonding responses with regard to the ball geometry and bond destructive tests. Currently, the only way to observe this is inspecting and testing after wire bonding. The situation can be improved by incorporating the laser vibrometer as a monitoring system to study

the ultrasonic displacement of the capillary during wire bonding.

Optimization of a 60-μm-BPP process was performed on an ESEC wire bonder, and the defined process window was bond power = 8.4–10% and bond force = 140–170 mN. Within the optimized parameter ranges, the oscillation amplitude of the capillary was monitored and the results are shown in Fig. 7. For all possible combinations of bond force and bond power, the oscillation amplitude of the capillary increases with increasing bond power, without drastic changes caused by bond force changes. This indicates that the selected process window is located in a stable region.

Based on the assumption that fixed ultrasonic displacement of the capillary produces fixed bonded ball size, by getting the same ultrasonic displacement, similar ball deformation can be obtained even though the bonder settings are different. By creating a data base of ultrasonic displacement responses of capillaries to different bond power and bond force settings, ranges of process windows can easily be determined without going through the tedious procedure of performing various wire bonding experiments.
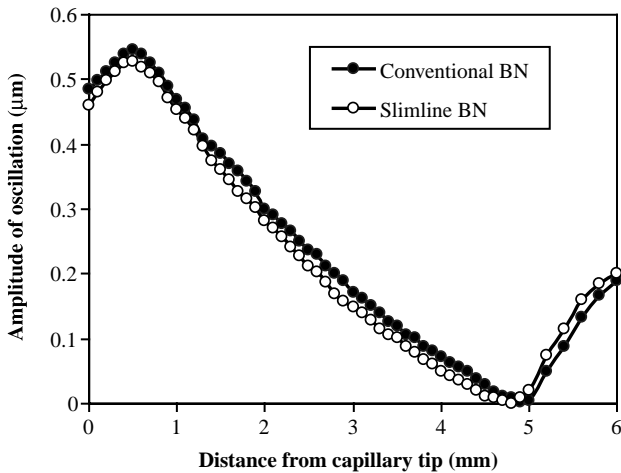

Fig. 6. Measured vibrational displacement amplitude of the conventional bottleneck (BN) and slimline BN capillaries.
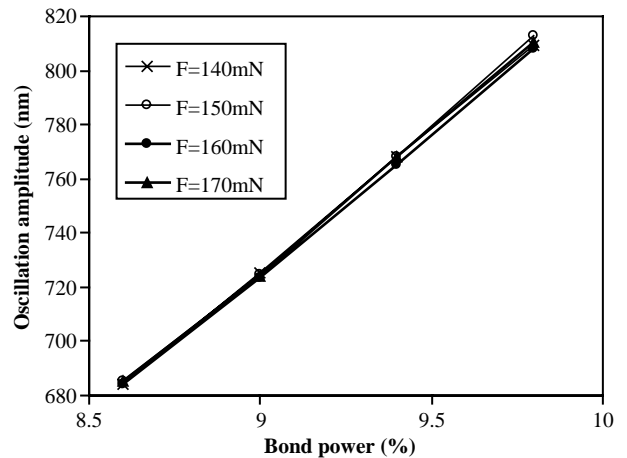

Fig. 7. Oscillation amplitude of the capillary for different bond power and bond force (F) combinations.

5. Conclusion

Amplitude profiles of ultrasonic vibrations along capillaries were measured using a laser interferometer. This provided valuable information in understanding and improving capillary performance. The method was applied to real time applications to optimize capillary designs and bonding processes for specific bonding applications.

First, the application of a new capillary material with different zirconia compositions was evaluated. The new material with certain amount of zirconia composition showed that it was the capillary material of choice for ultra-fine pitch wire bonding. Next, comparative analysis was conducted to investigate the ultrasonic energy transfer of a new slimline bottleneck and the conventional bottleneck. The actual bonding response of the molded slimline bottleneck showed comparable performance with the ground conventional bottleneck using the same bonding parameters. Finally, optimization of a 60-µm-bond-pad-pitch process was performed on a wire bonder. Within the optimized parameter ranges, the ultrasonic displacement of the capillary was monitored. For all possible combinations of bond force and bond power, the ultrasonic displacement of the capillary increased with increasing bond power, without drastic changes caused by bond force changes. This indicated that the selected process window was located in a stable region.

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