S. Z. Dushkes

A Design Study of Ultrasonic Bonding Tips

Abstract: The standing wave on ultrasonic bonding tips and the tendency of the lower end to fold back upon itself, termed "lug-down," have been measured under actual bonding conditions. These phenomena have also been modeled on a computer. Lug-down can be a major contributor to bonding failures in designs having an overly slim tip. One definition of a "bonding failure" is the production of a bond between wire and monolithic circuit pad which lifts, when the wire is pulled at 90° to the pad, under a wire tensile force less than 25% of the ultimate tensile strength of the wire. Improper location of nodes can also contribute to bonding failures. A tapered tip has been shown by mathematical analysis to possess a higher resonant frequency and fewer nodes than a tip of uniform cross section. Using the newly developed taper tip, means were found for minimizing lug-down. With judicious trade-offs, it is now possible to optimize tip geometry for a particular bonding application.

Introduction

This paper analyzes the required geometry of a tapered tip that terminates the amplifying horn used for ultrasonic bonding of fine wires to small electronic circuit boards. The special application of the ultrasonic bonding technique described here is for circuit boards of extremely high wire density, where the slender bonding tip must penetrate the circuit network to bond a wire to a pad without disturbing the neighboring bonds.

This application differs from the usual use of ultrasonic power for bonding Al or Au wires to semiconductor chips or circuit boards. In such applications the wire is ordinarily ≤ 0.002 inch in diameter and requires clamping forces < 50 gm and ultrasonic power levels < 2 W. In semiconductor work the length of the tip extension to the amplifier horn is generally a small fraction of an inch. The present study concerns the design of tips that are required to be about one-half inch long for bonding Au-plated CuBeO wires 0.002 inch in diameter to closely spaced pads of Au-plate Cu set in an epoxy substrate. This wire had been selected for its high ultimate tensile strength (~ 140 gm) and it required much higher clamping forces and ultrasonic power levels than are generally used. Under such conditions of ultrasonic bonding there developed a strong tendency to "lug-down," i.e., for the lower end of the tip to fold back upon itself during bonding. When the tip length and geometry were changed in order to eliminate bonding failures, new problems arose.

For these reasons, the analyses were made to determine optimum bonding tip configurations for the special application. Although the mathematical properties of ultrasonic amplifying horns have been published [1–5] and are well known, the properties of the bonding tip are seldom mentioned in the literature. Since the resonant frequency varies inversely as the square of the length of the tip, and since the choice of resonant frequency will affect the number and location of nodes, a study was made of standing-wave phenomena. It will be shown how a light-section microscope was used to measure the motion of the bonding horn and tip, both in the unloaded condition and during bonding. An expression is derived for the resonant frequency of the tip, obtained by equating kinetic and potential energies. The relation between proper tip geometry and the lug-down and bonding effectiveness will then be shown.

Power train

The ultrasonic bonding power train shown in Fig. 1 consists of a stable power supply, magnetostrictive element, driver, mount, amplifying horn, and bonding tip. The magnetostrictive element deforms mechanically in response to an ac signal from the power supply. Mechanical movement is transmitted along the driver and is amplified by the tapered horn. The gain of the horn in wire bonding applications is generally of the order of 2 : 1. The horn is intended more to provide access to the entire surface of the circuit board than to provide signal gain. A transverse tip, clamped securely at the end of the horn and long enough to penetrate the wire maze, transmits the energy to the wire to be bonded. This wire is gripped by a longitudinal groove in the tip. As the wire oscillates, atoms move across the interfacial boundary between wire and board to produce a mechanical and electrical bond.

The literature describes the general characteristics of the process and the horn [1–5]. Transducer and power supply designs have been highly refined by several manufacturers.

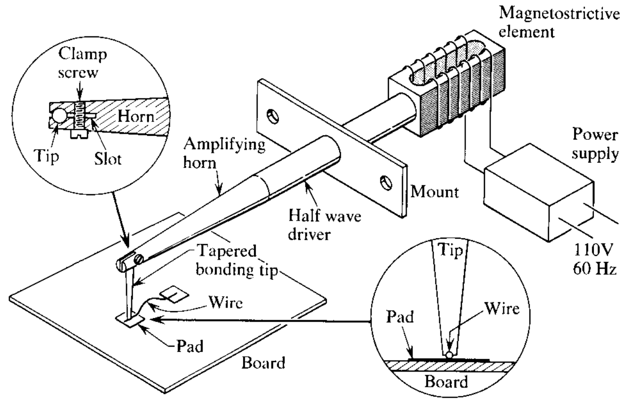


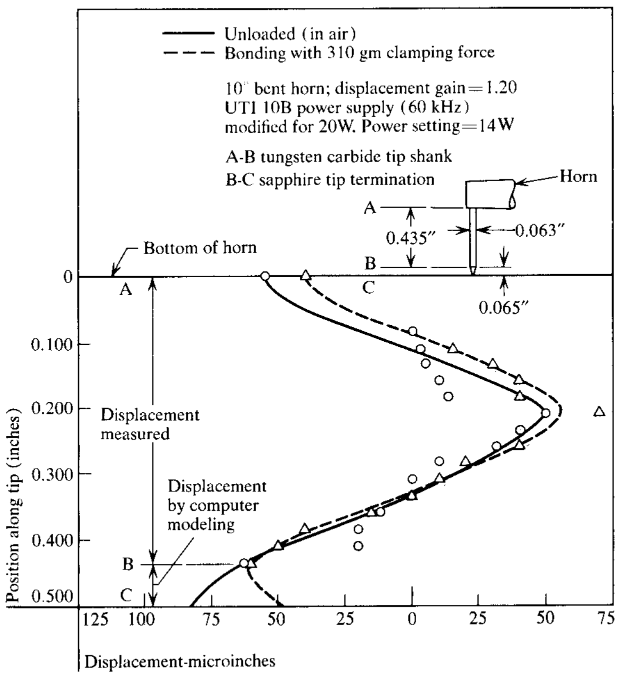
Figure 1 Optimal design developed for the ultrasonic bonding power train.

Standing-wave phenomena along uniform cross section tips

Figure 2 shows measured standing waves along a tip of conventional configuration, i.e., of uniform circular cross section. Data are given for a low fundamental resonant frequency of 8 kHz for both the unloaded condition in air and the loaded condition during bonding. The waves are characterized by two nodes and provide some amplification at the lower end of the tip shank. The displacement measurements were made using a light-section microscope which provided a resolution of approximately ± 10 microinches (see Appendix). The advantage of the light-section microscope relative to other methods lies in the fact that displacement measurements are made directly by optical means. Thus, no data reduction is required and the standing wave on a tip may be profiled in a matter of minutes. This is accomplished at the expense of accepting the ± 10 microinch resolution. In order to enter the wire maze and to bond a wire to a pad without disturbing adjacent bonds on the same pad, it is necessary to terminate the tip by tapering the lower extremity from the shank dimensions to a flat approximately 0.004 in. wide $\times$ 0.008 in. long (single groove) for 0.002 in. diameter wire. This tip termination, because of its slenderness, tends to cause lug-down during bonding. The motion characterization was determined for the tip by computer modeling and is shown in Fig. 2. Direct measurement in this zone by the light-section microscope was not possible because this portion was inclined to the vertical and, being made of unpolished sapphire, was not sufficiently smooth to reflect a narrow beam of light.

The location of the lower node is highly dependent upon tip length for a given diameter and material, and the length must be adjusted to insure that the node is adequately distant from the bonding end. Lug-down is quite sensitive to viscous damping between wire and pad. Wire surface and pad surface conditions affect viscous damping and can cause bonding failures if the tip tapers gradually, to the lower end. The transition from the tip shank dimensions to the very small dimensions of the bonding flat should be accomplished over as short a tip length as possible to avoid a needle-like lower end

Figure 2 Motion characterization (peak-to-peak in direction parallel to major axis of horn) of conventional uniform circular cross section tip for $\omega_0 = 8$ kHz.



design. The latter design would flex excessively when viscous damping is high and would reduce effective tip motion at the location where it matters most—at the tip-wire interface.

Resonant frequency elevation effect of tapered tips

It is possible to raise the resonant frequency of the tip and thereby reduce the number of nodes to 1 or 0 by uniformly increasing the tip shank diameter from bottom to top. Such a tip will have a resonant frequency higher

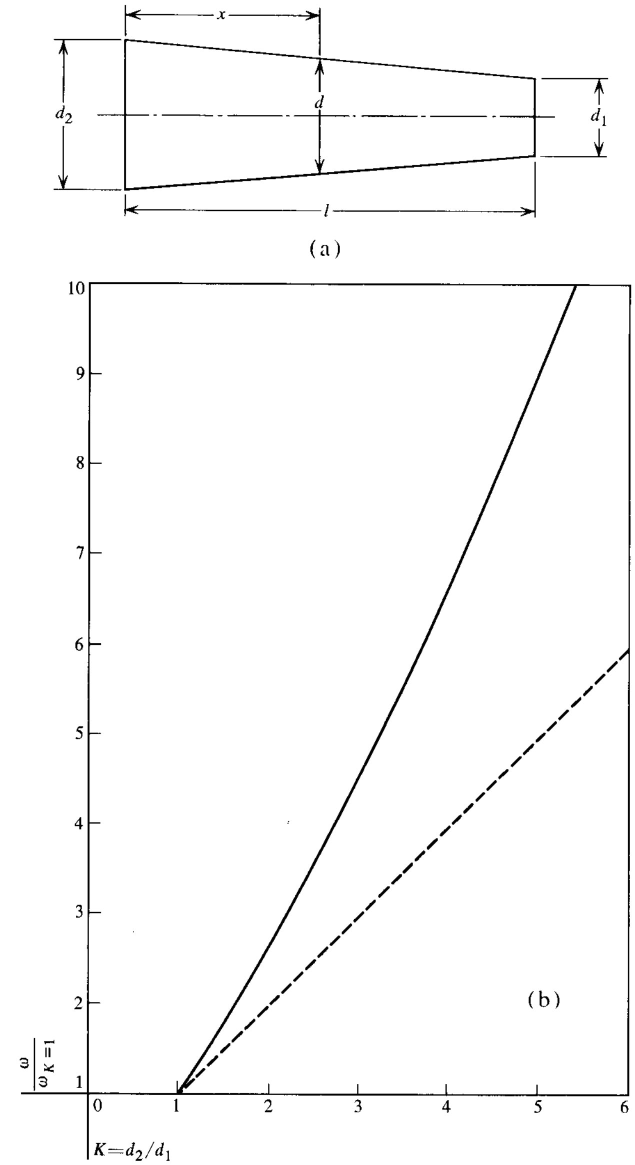


Figure 3 (a) The tapered cantilever beam. (b) Resonant frequency elevation as a function of diameter ratio.

than even one of large, constant diameter. Since the lower extremity of the tip shank has the smaller diameter, initial penetration of the wire maze will be no more difficult to accomplish than with a uniform cross section tip of the smaller diameter.

The resonant frequency of a tapered tip built in at one end and free at the other (the unloaded case) can be solved by equating kinetic and potential energy and performing the necessary integrations [6]. The loaded case could also be solved by a similar approach. The derivation for the tapered cantilever beam (Fig. 3a) follows.

The kinetic energy, K.E., at any distance x along the axis of the beam is given by

$$\text{K.E.} = \frac{1}{2}\mu\omega^2 \int_0^l y^2\,dx = \frac{1}{2}\rho\omega^2 \int_0^l Ay^2\,dx, \tag{1}$$

where ω is the frequency in rad/sec, μ is the mass per unit length and ρ is the mass density of the material. The cross-sectional area A is computed from

$$A = \frac{\pi}{4}d^2 = 0.785\left[-(d_2 - d_1)\frac{x}{l} + d_2\right]^2$$

$$= 0.785\,\frac{d_1^2}{l^2}[-(K-1)x + Kl]^2, \tag{2}$$

where $K = d_2/d_1$. The transverse deflection y of the beam (assuming a quarter sine wave; i.e., the fundamental resonant mode) is calculated from

$$y = y_0\left(1 - \cos\frac{\pi x}{2l}\right). \tag{3}$$

Substituting Eqs. (2) and (3) into Eq. (1), one obtains the expression

$$\text{K.E.} = \frac{\rho}{2}\omega^2 \int_0^l 0.785\,\frac{d_1^2}{l^2}[-(K-1)x + Kl]^2 y_0^2 \left(1 - \cos\frac{\pi x}{2l}\right)^2 dx \tag{4}$$

$$= \rho\omega^2 d_1^2 y_0^2\, l(0.0043K^2 + 0.0224K + 0.0621).$$

The potential energy P.E. of the system can be expressed as

$$\text{P.E.} = \frac{E}{2}\int_0^l I\left(\frac{d^2y}{dx^2}\right)^2 dx, \tag{5}$$

where E is the modulus of elasticity and I, the moment of inertia at a cross section, is

$$I = \frac{\pi}{64}d^4 = 0.049\,\frac{d_1^4}{l^4}[(K-1)^4x^4 - 4Kl(K-1)^3x^3 + 6K^2l^2(K-1)^2x^2 - 4K^3l^3(K-1)x + K^4l^4]. \tag{6}$$

Substitution of Eq. (6) into (5) produces

$$\text{P.E.} = \frac{y_0^2\pi^4}{16l^4}\,\frac{E}{2}\,0.049\,\frac{d_1^4}{l^4} \int_0^l [(K-1)^4x^4 - 4Kl(K-1)^3x^3 + 6K^2l^2(K-1)^2x^2 - 4K^3l^3(K-1)x + K^4l^4]\left(\cos^2\frac{\pi x}{2l}\right)dx$$

$$= \frac{Ey_0^2 d_1^4}{l^3}[0.0268K^4 + 0.0217K^3 + 0.0143K^2 + 0.0085K + 0.0031]. \tag{7}$$

Finally, setting K.E. = P.E., and solving for ω yields

$$\omega = \frac{d_1}{l^2}\sqrt{\frac{E}{\rho}}\,[(0.0268K^4 + 0.0217K^3 + 0.0143K^2 + 0.0085K + 0.0031)/(0.0043K^2 + 0.0224K + 0.0621)]^{\frac{1}{2}}. \tag{8}$$

For $K = 1$ (uniform rod),

$$\omega = 0.915\frac{d_1}{l^2}\sqrt{\frac{E}{\rho}}. \tag{9}$$

The coefficient of 0.915 agrees precisely with the value that is obtained by solving for the uniform cross section case directly. For the uniform case, $d_1 = d$.

Handbooks [7] generally give a coefficient about 3.8% lower, based on experimental evidence.

Equation (8) has been solved for various values of K and the resulting resonant frequencies normalized by dividing ω by the resonant frequency for $K = 1$. The resulting curve of resonant frequency elevation as a function of diameter ratio is plotted in Fig. 3(b). Note that the curve passes through the point (1, 1) by definition. A 2 : 1 diameter ratio would increase the resonant frequency to 2.6 times that of the uniform cross section tip cut to the smaller diameter. The dashed line shows how the resonant frequency would increase if the diameter were kept uniform all along the tip shank and increased according to the scale of abscissas. The rectangular cross section case has also been solved and shown to possess some marginal advantages. The circular cross section, however, lends itself much more readily to manufacture.

Tips having high resonant frequency

In an effort to produce a tip without nodes, a design for high fundamental resonant frequency (high E/ρ, short length, large diameter ratio) was produced [Fig. 4(a)] and made entirely of sapphire. The tip was tapered uniformly from point of exit from horn to bonding flat without going through a sharp transition zone, yielding a diameter ratio of 10.4 : 1. Resonant frequency of the tip was calculated to be 148 kHz. The front edge was vertical and the surface highly polished to facilitate displacement measurements with the light-section microscope down to the interface with the wire. The lower extremity of this design, however, was so overly slim that bonding results were highly erratic because of lug-down [see Fig. 5(a)]. Although the tip motion of about 70 $\pm$ 10 microinches during bonding appears adequate the gradient is so steep (3.6 microinches/mil) that realizable variations in viscous drag could cause it to drop well below 50 microinches. The air characteristic as shown in Fig. 5(a), on the other hand, was misleadingly good, and so the tips had to be

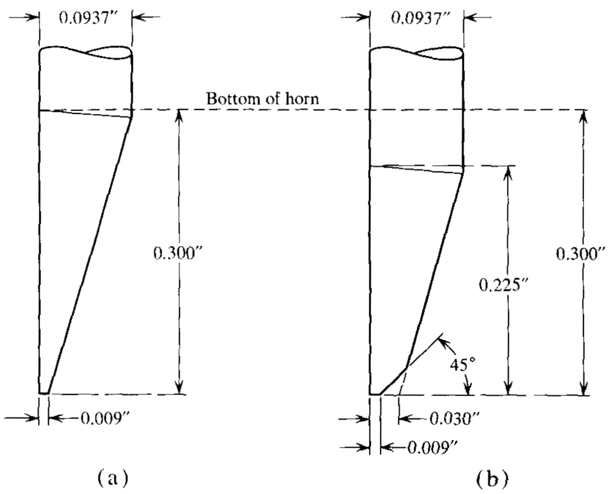


Figure 4 Tip having high resonant frequency. (a) Original sapphire tip. (b) Modified tip.

characterized under actual bonding conditions. To reduce the lug-down effect, the lower end of the tip was modified as shown in Fig. 4(b), resulting in the characteristic of Fig. 5(b). Although the resonant frequency is reduced to 103 kHz (the taper ratio now being 3.1 : 1), the lug-down effect is no longer apparent and there are still no nodes. The lower end design, however, is too bulky for practical use.

- *Compromise designs*

Sapphire proved to be unsuitable for bonding tips, even as an insert in a tungsten carbide carrier, primarily because of its tendency to fracture at the high clamping force levels, which ranged up to 310 gm. Power required was higher than 10 W. Wire motion and tip motion are substantially the same only when the tip groove material adequately grips the wire. Sapphire is not the best material in this respect. As already mentioned, a tip length of 0.5 inch was necessary to penetrate the maze of wires. Accordingly, designs were finally evolved using tungsten carbide shanks with inserts of a proprietary material furnished by Microminiature Technology, Inc., Redwood City, Calif. The use of this material apparently gave better transfer of energy from tip to wire. More modest taper ratios of the order of 2 : 1 and a relatively short transition zone to the narrow bonding flat were employed in a trade-off among lug-down effect, resonant frequency and ease of penetrating the network of wires. The resulting resonant frequencies were below the drive frequency of 60 kHz but reduced the number of nodes from two to one, as shown by a typical curve in Fig. 5(c) obtained by computer modeling.

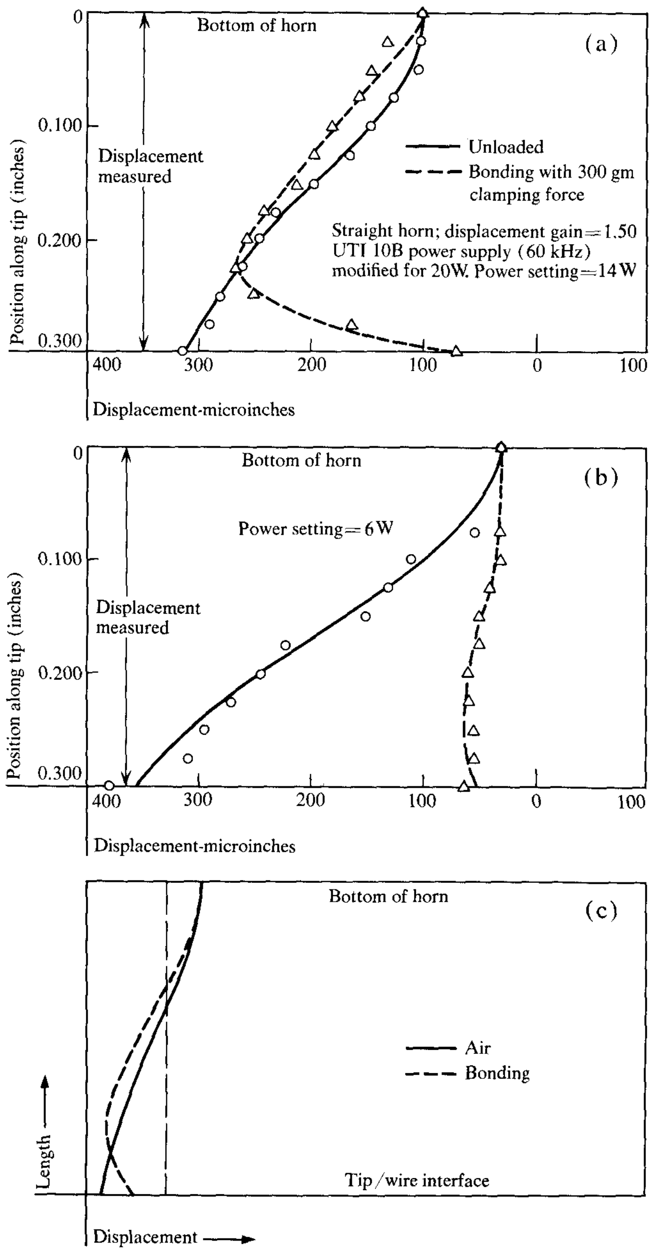


Figure 5 (a) Motion characterization (peak-to-peak in direction parallel to major axis of horn) of tapered all-sapphire tip for $\omega_0 = 148$ kHz. (b) Motion characterization of modified tapered all-sapphire tip for $\omega_0 = 103$ kHz. (c) Motion characteristic of a compromise tip design.

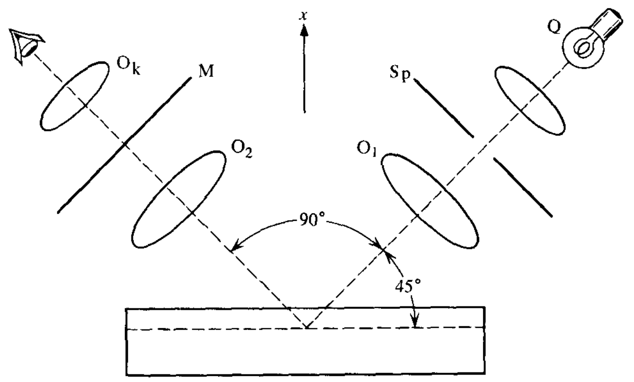
Bonding results in the laboratory have been consistently good with these tips. The bond "failure" criterion for a wire being pulled at an angle of 90° to the pad was lifting the wire under a tensile force less than 25% of its ultimate tensile strength. Three samples produced 10,000 to 20,000 bonds each without a single failure to bond. Bond pull strengths averaged 70% of the ultimate tensile strength of the wire and showed standard deviations of <10 gm. It is believed that raising the resonant frequency to move the node away from the tip-wire interface and the minimizing of lug-down have contributed importantly to this result.

Conclusions

This paper shows a design solution for the ultrasonic bonding tip needed in a modern application in densely wired circuit boards. A relation was found between the tapered tip configuration, resonant frequency, placement of nodes and bonding effectiveness for the wire material used. This quantization of the design of bonding tips permits system performance to be predicted. As might be expected, design tradeoffs were necessary, and it is not possible to optimize all characteristics in a single design. Any specific design will depend on the particular bonding application.

Appendix—The light section microscope

Extensive measurements have been made of the x-axis motion of the end of a bonding horn and of the bonding tip, both in air and during bonding, using a light-section microscope. Use of this technique was based on experience with the light-section microscope in measuring surface roughness. With a highly polished surface, the light beam is quite narrow when the surface is stationary, being ~120 microinches. When the reflective surface vibrates the light beam widens. The difference between the dynamic and static values of beam width represents the peak-to-peak amplitude of the excursion of the surface. The measurement obtained is an average over many cycles at the ultrasonic frequency. The measuring principle of the microscope is indicated by the following illustration:



In the above schematic of the light-section microscope, Q is the light source, Ok the ocular, M the reticle, Sp the slit, and O_1, O_2 a pair of objective lenses.

Acknowledgments

The experimental work described was undertaken on the recommendation of Dr. Ralph E. Meagher. Without his continued support, this study would not have been possible.

The use of the light-section microscope to profile the bonding tip was based on a suggestion by Rohinton J. Surty, San Jose SDD Laboratory. The drafting group and model shop of the San Jose SDD Laboratory provided needed assistance.

The computer modeling of the bonding tips was performed by J. R. Bernacchi employing a program of mechanical analysis refined by J. F. Potts, IBM San Jose.

Note added in proof

The analytical work reported here relating to raising the resonant frequency of the bonding tip by tapering was completed in 1967. Later an experimental program was undertaken to profile the standing wave on both uniform and tapered tips using the light-section microscope, both in air and under actual bonding conditions. This work, including the study of the lug-down effect, was completed subsequently. The nodal locations and displacement amplitudes relating to uniform tips were later confirmed, first by J. R. Bernacchi at the IBM San Jose Laboratory using a Photonic Sensor and subsequently by Dr. Byron Martin and co-workers at the IBM Endicott Laboratory using laser interferometry.

Two related papers have been presented at the IEEE Ultrasonics Symposium in San Francisco, October 21, 1970: A. D. Wilson, B. D. Martin and D. H. Strope, "Holographic Interferometry Applied to Motion Studies of Ultrasonic Bonders," and B. D. Martin and A. D. Wilson, "An In-line Laser Interferometer Applied to Ultrasonic Bonder Characterization."

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The author is at the IBM Systems Development Division laboratory at San Jose, California.