BDX-613-996

ULTRASONIC TINNING OF
COMPONENT LEADS

Technological Spinoff Report

W. A. Mulholland, Project Leader

Prepared February, 1971
Released September, 1973

Prepared for the
United States Atomic Energy Commission
Under Contract Number AT(29-1)-613 USAEC

**Kansas City
Division**

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Department 814**

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ULTRASONIC TINNING OF COMPONENT LEADS

BDX-613-996, UNCLASSIFIED Technological Spinoff Report, September 1973

Prepared by W. A. Mulholland, D/814

Ultrasonic soldering was investigated to eliminate the need for using strongly activated solder fluxes during the hot-tinning of component leads. The results indicate that the technique is suitable for tinning the difficult-to-solder materials encountered in production.

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THE BENDIX CORPORATION

KANSAS CITY DIVISION

KANSAS CITY, MISSOURI

A prime contractor for the
Atomic Energy Commission
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SUMMARY

Many metals resist joining with solder. Although strongly activated rosin-base fluxes can usually overcome this resistance, the fluxes can create additional problems if not completely removed. These problems include corrosion and current leakage.

Ultrasonic soldering is a process where ultrasonic vibrational energy is used to clean the basis metal, permitting the solder to alloy with it. Solder fluxes are not used so the problems associated with highly activated fluxes are eliminated.

Representative electrical conductor materials of nickel, Kovar (Fe-Ni-Co), Alloy-52, aluminum, gold-plated Kovar, and gold-plated nickel were ultrasonically solder dipped and evaluated. Evaluation was both visual and metallographic.

The results obtained by ultrasonic soldering dipping are impressive. Solder wicking is eliminated, gold-embrittlement is eliminated, and the resulting solderability of the difficult-to-solder materials is excellent.

The use of ultrasonic solder pre-tinning will minimize solderability failures and their related problems.

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DISCUSSION

SCOPE AND PURPOSE

The assembly of electrical products often requires the formation of a solder joint between metals, one or both of which are difficult to solder. The difficulty arises from the presence of a resistant, naturally present oxide film. The resistance can usually be overcome with highly activated fluxes which remove the oxide. However, residual fluxes, if not removed from the assembly, can cause corrosion and current leakage. Other procedures involve chemical re-activation of a metal to restore solderability.

Another approach to soldering these metals, one that has been reported to be successful, is ultrasonic soldering. Here, the objects to be soldered are dipped into an ultrasonically agitated solder pot.¹ Cavitation from the ultrasonic energy scrubs the oxide film away, allowing the solder to wet the metal. The solder coated parts can then be soldered together with conventional techniques using rosin fluxes, thereby eliminating the potential problems associated with stronger fluxes.

The purpose of this project was the evaluation of ultrasonic soldering for use at Bendix. Test pieces of difficult-to-solder metals were tinned ultrasonically and visually evaluated for the completeness and quality of the solder coating. The solder coatings were also evaluated by metallography. The project was carried out during the period November 16, 1970 to February 16, 1971. The tinning was done at the applications laboratory of the Branson Sonic Power Company and the metallography and evaluation were done by Bendix Materials Engineering.

PRIOR WORK

Ultrasonic tinning of component leads was evaluated in a study of wave soldering. The lead materials were Dumet (Cu clad Fe-Ni), Kovar, and nickel. The tests were made using functional components (diodes, resistors, capacitors). After the tests, the quality of the solder coating was evaluated and the components were tested for the presence of functional damage caused by the ultrasonic energy. The solder coatings were good and the components

¹ Ultrasonically activated soldering irons were not studied in this project.

were undamaged. The ultrasonic pretinning of component leads was recommended, but the recommendation has not been adopted.

ACTIVITY

Experiments

Representative samples of difficult-to-solder electrical conductors and component leads (Table 1) were ultrasonically solder dipped and evaluated metallographically and visually. No pre-soldering cleaning was performed. Insulated, stranded wire samples were included to verify vendor claims of no solder wicking. Gold plated samples were included to verify the vendor claim that gold-embrittlement is eliminated. Intentionally aged materials were included to simulate a worst case.

The specimens were taken to the Branson Sonic Power Company, Danbury, Connecticut, and were tinned in their applications laboratory using their equipment. The ultrasonic soldering parameters used are listed in Table 1.

Pure tin was used for the aluminum samples because a high-zinc alloy solder was not available. A better alloy is probably eutectic Sn-Zn.

Results

All samples had 95-100 percent coverage except the fine diameter (0.003 in. [76 μ m]) stranded aluminum wire bundles.

Low generator power levels and short immersion times were required to tin aluminum. Longer exposures resulted in the aluminum being completely dissolved. In the fine diameter stranded aluminum wire, the outer wires were solder covered but the inner wires were not. This is probably due to the sonic vibrations being attenuated and dampened by the non-rigid bundle. Possibly, if these wires were less flexible or if the wire bundles were rigidly supported during the soldering operation, they would exhibit 98-100 percent solder coverage throughout the bundle.

Metallographic investigation of the gold-plated specimens revealed that the gold was completely removed and the brittle AuSn_4 compound layer was not present. A continuous interface between basis metal and the solder was present.

The insulated stranded wire samples, prepared for solder dipping in accordance with 9913000 except that solder flux was not used, were ultrasonically solder dipped, and metallographic investigation revealed that the solder alloy

Table 1. Soldering Materials, Conditions, and Parameters

Material	Condition	Ultrasonic Soldering Parameters
Nickel	As received	A
	Aged 9 months	C
Alloy-52	As received	A
Kovar	As received	A
Copper	As received	A
Aluminum	As received	B
Gold plated nickel*	As received	A
Gold plated Kovar*	As received	A
Stranded aluminum wire	Aged 3 months	B
Stranded copper wire	As received	A
Stranded, silver-plated copper wire	As received	A
Nickel clad FR-45 laminate	As received	A
	Aged 9 months	C
Copper clad laminate	As received	A
	Aged 14 months	C
<p>A. 60 Sn - 40 Pb at 500°F (260°C) for 3-4 seconds.</p> <p>B. Pure tin at 500°F for 1-2 seconds.</p> <p>C. 60 Sn - 40 Pb at 500°F for 5-7 seconds.</p> <p>*The gold-plating was nominally 50-100 microinches (1.3-2.5 μm) thick.</p>		

penetrated throughout and wet the wire bundle. Moreover, the solder was not wicked under the insulation of the wire. The solder alloy only wet the wire where the ultrasonic activation was present.

Metallographic examination of all the samples revealed that a perfect metallurgical interface was established. The thickness of the solder coating was about 85 microinches ($2\text{ }\mu\text{m}$). This is somewhat dependent on the withdrawal rate.

Conclusions

Ultrasonic soldering will permit the tinning of difficult-to-tin metals without the use of flux. The process is quick, simple, and reliable. It is a substantial improvement over the processes presently used.

Recommendations

It is recommended that ultrasonic tinning be used on all electrical components that are to be soldered and that, in their natural state, require the use of fluxes stronger than rosin-in-alcohol. However, it is also recommended that the process be evaluated with respect to each type of component for possible mechanical damage to the component by the ultrasonic energy.

ACCOMPLISHMENTS

Ultrasonic tinning was proved feasible on component lead materials which had heretofore been difficult or impossible to solder.

FUTURE WORK

Future work is planned to evaluate the effect, if any, of ultrasonic energy on components during tinning of leads. Also, a less aggressive solder for tinning aluminum will be sought.

BIBLIOGRAPHY

Aluminum as a Substitute for Copper in Electrical Conductors. AD-290888.
Chrysler Corp., Missile Division, 1957.

Aluminum Joining Processes for the Electrical Industry. Alcoa, 1968.

Bozarth, R. M. Ferromagnetism. New York: D. Van Nostrand Co., Inc., 1951.

Bulat, T. J., Dr. "Sonic Energy as a Production Tool." ASTME Journal, Volume 60, Book 1, Paper 270, 1960.

Bulat, T. J., Dr. The Role of Cavitation in Sonic Energy Cleaning. ASTM Conference Paper, 1962.

Bulletin MT-100. Branson Sonic Power Co.

Bulletin SB-5. Aero Projects (Sonobond), Inc., 1955.

Bulletin 101. Bendix Pioneer, Central Division.

Carlin, B. "Techniques in Ultrasonic Soldering." Proceedings of the National Electronics Conference. Institute of Radio Engineers, Volume XI, 1955.

Carlin, B. Ultrasonics. New York: McGraw-Hill Book Co., Inc., 1949.

Daniels, H. P. C. "Ultrasonic Welding." Ultrasonics, October, 1965, pp 190-196.

Design Parameters for Sonic Energy Cleaners. Bendix Pioneer, Central Division, 1962.

Glennite Piezoceramics. Gulton Industries, Inc., Catalog H-700.

Hueter, T. F., and R. H. Bolt. Sonics. New York: John Wiley & Sons, 1955.

Industry and Welding. "Ultrasonic Fluxless Soldering," 1957.

Life Test Evaluation of Fairchild FD-621 After Ultrasonic Tin Dipping. AD-438577. 1963.

Lyons, L. J. Transducer Parameters Affecting Sonic Cleaning. ASTM Conference Paper, 1961.

Mason, W. P. Piezoelectric Crystals and Their Application to Ultrasonics. New York: D. Van Nostrand Co., Inc., 1950.

Mechanism of Ultrasonic Absorption in Liquids and Ultrasonic Perturbation of Nuclear Magnetic Resonance Lines. AD-104646. 1953-1956.

Neppiras, E. A. "Ultrasonic Welding of Metals." Ultrasonics, July, 1965, pp 128-135.

Osterman, H. F. "Cavitation Erosion of Sonic Radiating Surfaces," Institute of Radio Engineers National Convention. Institute of Radio Engineers, 1959.

Rosenberg, L. D. "On the Physics of Ultrasonic Cleaning." Ultrasonic News, Volume IV, Number 4, pp 16-20.

Strength and Corrosion Resistance of Ultrasonically Soldered Aluminum Joints. AD-98324. March, 1956.

Technical Report No. 220. Bendix Pioneer, Central Division, 1963.

Ultrasonic Soldering of Aluminum. AD-60697. Aero Projects, Inc., Research Report No. 55-24, 1955.

Ultrasonic Soldering of Aluminum. ASTM Special Publication-189.

Wenk, P., and H. Boljahn. "Tinning and Soldering of Aluminum by Ultrasonics." Zeitschrift fur Metallkunde, Volume 43, Number 9, 1952, pp 322-324.

Wise, Boyd. Design of Nickel Magnetostrictive Transducers. The International Nickel Corp., Inc., 1957.

Appendix

BACKGROUND INFORMATION ON ULTRASONIC SOLDERING

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BACKGROUND INFORMATION ON ULTRASONIC SOLDERING

INTRODUCTION

Sonic energy is the basic force present in all sound waves. As the frequency of sound waves is increased, the pitch rises until it passes into an inaudible, or ultrasonic range. This inaudible level varies from person to person, but rarely exceeds 16 kHz. However, whether the sound is audible or not, sonic energy is present to the degree imparted by the sound wave source.

Maximum cavitation intensity, with a uniformly high distribution of cavitation throughout the ultrasonic active region, can only be achieved through proper acoustical and mechanical design of the ultrasonic soldering equipment. The critical areas which must be considered in the design of any sonic energy unit are threefold:

- The transducer,
- The method of bonding the transducer, and
- The generator supplying the high frequency power.

In order to have a working knowledge of ultrasonic soldering, an understanding of cavitation must first be obtained. It is from this phenomenon that the basic energy of ultrasonic soldering is obtained.

MECHANISMS OF CAVITATION

Sound pressures generated by a sonic system fall far short of attaining the negative pressures required to initiate cavitation. Yet in a properly designed sonic unit, heavy cavitation can be obtained. The reason for this paradox lies in the fact that a liquid contains many weak spots which serve as nuclei for cavitation inception. The nuclei are mainly in the form of microscopic bubbles mechanically stabilized in the liquid. Nuclei of this type (e.g., air, dust) can provide a locus for cavitation inception at pressures lower than one atmosphere.

Cavitation processes begin when a bubble enters a sound field. A bubble trapped in a sound field begins to expand and contract as it is acted upon by the vibrations (compression waves). As these oscillations proceed at the

frequency of the induced sound waves, the bubble begins to grow. This process is known as rectified diffusion. It occurs because gas is being expelled from the bubble when it is being compressed and absorbed when it is expanding. The surface area of the bubble is greater during expansion than during compression thus providing more area for absorption. The net effect is that more gas is taken into the bubble than is being expelled. The bubble, therefore, grows. If the area of sound intensity is low, the bubble will continue to oscillate and will remain pulsing with the sonic frequency. It may reach resonant size or coalesce with similar bubbles and become visible to the naked eye. This type of bubble is often trapped in a standing wave where it can be seen moving rapidly about. This is gaseous cavitation. It is the beginning of a force for cleaning because its pulsating action effects a scrubbing action on surfaces which it contacts. Gaseous cavitation, however, plays only a minor role in ultrasonic soldering.

It is the vaporous cavitation which plays the major part. Vaporous cavitation results when the pulsating bubble reaches resonant size and moves into an area of intense sound. At this point it will vibrate violently, then collapse. The cavity or void left by this implosion is instantaneously filled with surrounding liquid driven by external pressures. The resulting pressures generated at the loci of these implosions can attain 1000 atmospheres (101.3 MPa).

During the period of violent vibration, shock waves are emitted of an amplitude which significantly exceeds the amplitude of the induced sound wave. The combined effect of the two sources of sound pressure is exhibited in the formation of thousands of microscopic cavities which appear as a burst in the vicinity of the cavitation nucleus. The motion of this dense cloud of micro-cavities appears as streamers which dart erratically throughout the solution. This is often called streaming cavitation.

It is the implosion of the vaporous cavitation and the collapse of the micro-cavities which provide the most effective mechanisms for sonic cleaning.

PHYSICAL PARAMETERS INFLUENCING CAVITATION

There are several physical ways to increase cavitation. Most important of these are frequency and power. Basically the frequency determines the intensity of the cavitation implosion and the power level determines the amount of cavitation per unit of time.

Frequency

The lower the frequency, the more violent the cavitation and, therefore, the greater the potential for cleaning. The lower frequency produces a larger

bubble for cavitation than does high frequency. At low frequencies there is a greater time interval between the compression and rarefaction waves than there is at a high frequency. This allows more time for the bubble to grow before pulsing or imploding. The larger the bubble, the greater the force of the implosion. A low frequency level for cavitation has never been established.

Cavitation occurs when the bubble reaches resonant size. The higher the frequency the smaller is the resonant size of the bubble. Another important fact is that the lower the frequency of a sound wave the greater the penetrating power.

These factors point out the advantage of using low frequency sound waves for soldering. Yet there are practical limits on how low a frequency should be used. When the fundamental frequency is dropped much below 20 kHz, sound begins to enter the audible range. The noise created may be objectionable to personnel. It has also been empirically determined that fragile items may be susceptible to damage below 20 kHz.

Power

As stated above, the ratio of the maximum bubble size to its original size influences cavitation intensity. The amplitude of the sound wave (power) is also of prime importance.

It appears logical that as power is increased over the critical threshold, the amount of cavitation should increase proportionately. There are many factors which will alter this. As an example, if too much power is fed into a transducer, it will produce heavy cavitation at the face of the transducer horn. The cavitation voids and gas pockets thus formed will then act to impede the ensuing sound waves. In a pot which is overpowered, cleaning will be excellent at the face of the transducer horn but it will be weak or ineffective in the main body of the solder alloy. A general statement as to proper amount of power to use cannot be made. Effective power levels will differ with the acoustics of each unit design as well as the type and design of the transducer.

In order to effect cavitation, the sound pressure must exceed the hydrostatic pressure (external pressure). Increased hydrostatic pressure will suppress the amount of cavitation. This is due to the fact that the intensity of the cavitation is determined by the ratio of the original size of the bubble to the maximum size it attains. This ratio is controlled by frequency, not by power. The net effect is a suppression because less nuclei are available for cavitation under this environment. Conversely, if a vacuum is pulled over the soldering system, the power threshold for cavitation onset is lowered. This does not change the intensity of any single cavitation implosion, but it

does increase the number of cavitation events which occur in a given period of time.

One unique feature of cavitation is that it can be generated anywhere a sound wave of sufficient intensity can penetrate. This means that cleaning action will occur deep within the interstices of a part or assembly with a complicated geometric configuration. Surfaces which are seemingly smooth to the naked eye have microscopic pores and grain boundaries. The specific action of cavitation penetrates these minute areas and results in a cleanness at the microscopic level which can be equalled by no other known method.

EVALUATION OF ULTRASONIC SOLDERING EQUIPMENT

A sonic system is composed to two basic parts: a transducer, and a generator. The function of the generator is to supply electrical energy to the transducer. The electrical energy provided must be at the resonant frequency of the transducer.

The Transducer

Considerations

The transducer converts the electrical energy supplied by the generator into mechanical energy in the form of vibrations. Because the transducer is the heart of the sonic system, it will be described in detail.

Transducers fall into two main classes: piezoelectric (electrostrictive) and magnetostrictive. In the first instance, a material which changes dimension in the presence of an electrical field is utilized; in the second, the material is influenced by a magnetic field. Due to the large difference in conversion efficiencies (70 to 95 percent for electrostrictive compared with 20 to 50 percent for magnetostrictive), the transducers used in this project are of the electrostrictive type.

The choice of a transducer depends directly upon the sonic energy application it will be used for. Generally speaking, the crystal or ceramic transducers are used for low power and relatively low frequency applications. When ceramic transducers are driven at high power levels for extended periods of time, they can undergo natural degradation. The magnetostrictive transducer is used where high power application is needed for extended periods of time without loss in efficiency.

A piezoelectric transducer is composed of a natural crystal such as quartz, or a specially produced ceramic, which will emit sonic vibrations under the

influence of an impressed voltage. The magnetostrictive transducer is composed of a magnetostrictive metal (e.g., cobalt, nickel, iron). A magnetostrictive metal is one which undergoes dimensional change when subjected to a magnetic field. When the magnetic field is relieved, the metal returns to its natural dimensions. In a magnetostrictive sonic system, the transducer is vibrated through dimensional changes by introducing an interrupted or alternating magnetic field.

Sound waves produced by either piezoelectric or magnetostrictive transducers can be used in gas, solid, or liquid media.

Piezoelectric Elements

Initially barium titanate was used as the active material, but it had two major drawbacks: its inability to operate continuously above 160°F (71°C) (imposed by a 240°F [115.5°C] curie point) and poor maintenance characteristics from the standpoint of transducer rebuilding. The curie point is that critical temperature where a transducer material loses its ability to convert electrical or magnetic energy into mechanical vibration.

The use of a relatively new ceramic, lead zirconate titanate, has eliminated these problems. Although somewhat more expensive than barium titanate, it is capable of handling much greater power inputs. A unique sandwich design has yielded a transducer element with the following characteristics:

- High electrical to mechanical conversion efficiency (95 percent compared with 70 percent for barium titanate),
- High operating temperature (in excess of 200°F [93.3°C]), and
- Low maintenance cost.

Transducer elements in their manufactured form cannot be used directly in a liquid. The sound waves are directed into the liquid media through a specially designed coupler. Transducer elements are attached to these couplers by special bonding techniques that combine high mechanical strength with good acoustic efficiency. The section of the coupler that is in contact with the liquid on one side and the elements on the other is called the radiating surface.

Returning to the fact that ultrasonic soldering is accomplished through mechanical erosion, the horn attached to the coupler will erode. The equipment used has been designed to increase horn life to 100-150 hours of continuous operation as opposed to earlier designs that had horn life of only a few hours.

Another important feature of lead zirconate titanate elements is that transducers utilizing them can be rebuilt at 20 percent of their initial cost. This compares with 80 percent rebuilding costs for older type transducers.

Transducer Material Selection

The selection of the type of transducer material to be used in a sonic energy system is dependent upon many considerations. Table A-1 was compiled in an attempt to relate the various transducer materials and their more important characteristics. The following transducer materials are the most common in use today: ammonium dihydrogen phosphate, barium titanate, ferrite, lead zirconate titanate, lithium sulfate, nickel, Permendur, quartz, Rochelle salt, and 4 percent cobalt nickel. The most important characteristics of these materials with respect to a sonic soldering system are the following: reliability, frangibility, cost, coupling coefficient, operating temperature, bondability, availability, impedance stability, internal losses, power capability, and fabrication.

In Table A-1, the above criteria for evaluation are given. The maximum quality points for the criteria are found at the top of the chart under each criterion heading. Each material was evaluated against the criteria in a left to right chart flow.

The total quality points assigned each material are found in the last column at the right of the chart. It appears then that material selection would follow this order: nickel, 4 percent cobalt nickel, Permendur, lead zirconate titanate, barium titanate, quartz, ferrite, Rochelle salt, ammonium dihydrogen phosphate, and lithium sulfate. The apparent analysis is that no material is available that possesses all of the desired criteria. This is evidenced by the fact that the high value is only 80. Also, the quality totals of some materials are relatively close in value, showing that the actual selection is not simple. This is due to the fact that although a particular material may excel in one criterion, it may be weak in others. It is obvious, then, that the total quality indicated is only as accurate as the selection of criteria and the assignment of relative maximum quality points. It is re-emphasized that this method only aids in the selection of a transducer material.

Reliability

After selection of a material suitable for the application, the over-all design must be such that the applied use of the material results in a reliable and efficient system, with predictable long life. This quality of reliability is most important in that field performance and user satisfaction provide the final justification of any design. Reliability encompasses all other criteria and indicates how long the material, in its final form, will retain its original

Figure A-1. Transducer Material Selection

Materials	Reliability	Coupling Coefficient	Frangibility	Operating Temperature	Bondability	Availability	Cost	Impedance Stability	Power Capability	Internal Losses	Fabrication	Total Quality
Maximum Quality Points	12	12	12	10	10	10	10	7	7	6	4	100
A-D-P	5	5.5	3	1	3	4	9	2	1	2.5	1	37.0
Barium Titanate	7	8.6	6	1	5	10	10	4	2	3.5	4	61.1
Ferrite	5	5.5	5	5.5	5	7	6	4	2	2.5	4	52.5
Lead Zirconate Titanate	6	12	6	3	5	9	8	5	3	6	6	68.0
Lithium Sulphate	4	6.4	3	0.5	3	4	8	1	1	2.5	1	35.4
Nickel	12	3	12	3.7	10	10	10	7	6	2.3	4	80.0
Permendur	12	2.3	12	10	10	4	4	7	7	1	2	71.3
Quartz	9	1.9	8	6	5	5	3	6	6	1	3	53.9
Rochelle Salt	3	10	2	0.5	3	8	9	2	1	2.5	1	42.0
4 Percent Cobalt-Nickel	12	5.5	12	4.1	10	9	9	7	4	2.7	3	78.5

qualities. Reliability can usually be improved by design simplification. True reliability can only be derived by accurately derating the transducer materials and associated components due to the influence of all environmental operating conditions.

Frangibility

If the material selected is fragile, it must be protected through adequate design to withstand thermal cycling, severe shock, and operational conditions. Thermal cycling is normally prevalent in most soldering applications in that solder temperature usually ranges from 360 to 800°F (182 to 427°C). In the case of piezoelectric materials, compression loading should be considered so that the material is never in tension due to mechanical shock. Compression loading also prevents tension on the transducer material throughout each dynamic vibration cycle. This construction allows the piezoelectric material to be driven at more suitable power levels to effect better sonic cleaning. Metallic transducer materials such as Permendur and nickel, possess much greater tensile stress limits, and therefore do not present problems regarding shock loading or dynamic fatigue.

Bondability

The method of attachment of the transducer material to its mating surface or elements should be consistent with the static, shock, and dynamic stresses imposed during normal operation. If the transducer and mating elements are metallic, the apparent advantage of a metallic joint, such as that produced by silver brazing or welding, should be employed.

The bond problems usually associated with ceramic materials are more severe in that it is virtually impossible to attain the stress quality of a metallic joint. Ceramic materials are generally polarized before attachment, and the high temperature (approximately 1400°F [760°C]) normally associated with brazing would affect this polarization. Therefore, low temperature (approximately 300°F [149°C]) curing adhesives such as epoxy resins are generally used to bond ceramic transducer materials. If an adhesive is used, life tests should be conducted under operating conditions in order to determine the reliability of the bond. This is necessary since high temperature, aging, and vibration may influence the quality of an adhesive bond.

In sandwich type piezoelectric transducers the ceramic transducer may be sandwiched between two metal blocks. The metal block can then be metallurgically bonded to the coupling material.

Whether using a metal joining or adhesive process, it is essential that the mating surfaces be cleaned thoroughly. A void in the joint or bond will affect

the usable driving area of the transducer. If a void is present, heat will be generated in this area due to the friction losses. A large void or defective bond will also affect the resonant frequency of the particular element involved. Therefore, in multiple element systems, if defective bonds are present the individual transducers will be driven at unequal power levels, causing poor energy distribution.

Energy Transfer

It is necessary to effectively couple the energy stored in the vibrating transducer element into the liquid load of the sonic cleaner. This is essentially a fourfold problem: the transducer must be allowed to vibrate in a complete sinusoidal action similar to that produced by a swinging pendulum; the mechanical configuration of the transducer should be considered; the transducer should be matched to the liquid load in such a manner that the required sonic energy is transferred; and the efficiency of power utilization should be considered.

Vibratory Action. A basic transducer material normally changes shape in one direction when an electrical signal is impressed. Therefore, usable mechanical energy could be obtained on each half cycle of an alternating signal, causing pulses of mechanical power to be delivered. Such a transducer would actually vibrate at twice the supply frequency since it would not distinguish the polarity of the input signal. This of course would be an extremely inefficient use of the supplied power and the material, since the vibration imposed is not smooth. It does not match the sinusoidal swing of the normal supply signal which resembles the action of a pendulum. In order to obtain a smooth swing the transducer material must be polarized. (This term is analogous to the bias used in amplifier circuitry.) In a transducer application, the bias is a mechanical consideration where the material is partially changed in shape so that an imposed ac signal results in a change of shape in two dimensions. This results in both lengthening and shortening action when driven with an ac signal.

In magnetostrictive transducers, for example, a permanent magnet may be inserted in the normal magnetic path, resulting in material contraction. When an alternating field is applied to the transducer coils, one half-cycle opposes the magnet resulting in elongation while the other half-cycle aids the magnet, resulting in further contraction. In this manner, the full ac signal is employed to promote a sinusoidal oscillation. The magnet used should have a low value reversible permeability so that it is not easily demagnetized. This type of magnet allows a constant mechanical bias in the presence of an ac field. An alternate method of accomplishing polarization with magnetostrictive material is to employ a steady state dc signal superimposed on the ac signal delivered to the transducer coils. Either case represents an external polarization. Because of this external polarization, high-temperature operation even up to the curie point of the metal will not destroy the polarization; the polarization

returns as the magnetic quality improves while descending below the curie temperature.

In piezoelectric transducers, an internal bias is obtained by means of the application of a high potential polarization voltage. The voltage necessary to induce polarization in barium titanate, for example, is approximately 12,000 V/cm or 30 V/mil. This method does not provide a permanent polarization since the material will tend to return to its original mechanical shape with age. Also, in the presence of high ambient temperatures, or if internal losses create excessive heat, the polarization is decreased; when the curie temperature is reached, the polarization is lost and does not return when the temperature is lowered. In order to obtain a polarization that is more stable, impurities are added to material such as barium titanate; for example, through the additions of a small percentage of lead in the form of lead titanate, higher operating temperature, with more stability, may be achieved.

Mechanical Dimensions. In general, the dimensions and normal shape of ceramic elements are not limited. Associated processing and application problems do, however, impose restrictions. Since this type of material is a poor heat conductor, large sizes are usually avoided. The thicker the minimum dimension of the element, the more complex the oven baking process, since heat penetration is impeded. Also, the thicker the polarization dimension, the higher the necessary polarization potential. There is a further restriction on size due to the heat losses within the materials (under power), which must be conducted away to be dissipated. For these reasons ceramic elements such as barium titanate are usually fabricated in flat disks, short blocks, or thin tubes. Many other shapes are possible, of course, depending upon the application. The normal resonant frequency of the ceramic elements is from 40 to 100 kHz. The resonant frequency of a transducer is a function of the thickness of the element in the direction of vibration; the operating frequency goes down as the thickness of the element increases. Lower operating frequency, from 20 to 25 kHz, may be obtained by loading the element in a metallic sandwich form.

The general shape of a magnetostrictive transducer is primarily influenced by magnetic circuit consideration. The selection of closed end, open end U-shape, or other type core is dependent upon the quality of the resultant magnetic circuit and the efficiency. The transducer is usually constructed of laminated material in order to avoid excessive eddy current losses. The thickness of laminations is selected on the basis of allowable losses at the operating frequency. For example, 10 mil (254 μ m) nickel laminations are adequate at frequencies up to approximately 22 kHz. The length of the lamination in the direction of vibration is controlled by the operating frequency. The usual transducer is in the form of a half-wave vibrator; therefore, the required

length for a given frequency is equal to the velocity of sound in the material divided by twice the frequency.

Transducer Matching. It is necessary to effectively couple into the load some portion of the energy stored in the vibrating transducer element. This in effect is a problem of adjusting the Q of the transducer. The Q as used here is basically the ratio of the energy stored in the element to the energy dissipated (per cycle). The lower the operating Q the greater the energy transferred to the load. As an analogy, a high Q would be desirable in a receiver element since small signal levels would be sensed and stored; however, a low Q would be desirable in a driving element since energy stored in the element should be easily dissipated.

Most often, the free state Q of a transducer is higher than the Q desired for working into a liquid load. Lowering the Q of a transducer may be accomplished in many ways. One method is to load it down so that it will easily dissipate energy. This is done in the sandwich crystal type assemblies. In this approach the liquid driving area approximates the dimensional area of the radiating element. In order to obtain adequate sonic energy dispersion in a large tank it is necessary to employ a number of these elements somewhat closely spaced. The diaphragm of the tank container in this case would be relatively thin. In sandwich elements, the material must be capable of withstanding the compressional load imposed without impairing activity. Another approach in an effort to lower the Q and match the transducer to the liquid load is to obtain a suitable ratio of transducer cross-sectional area versus liquid driving area. In this manner the particle velocity of the transducer element is matched to the particle velocity of the liquid load, allowing the smooth transfer of energy. This may be accomplished by employing matching transducer heads that contact the liquid directly, or by bonding the heads to a thin metallic diaphragm.

The total driving area for each transducer must be extremely rigid at the frequency of operation. This rigidity is necessary in order to obtain uniform velocity across the entire vibrating face. Single frequency operation and smooth energy transfer will thereby result. It is also necessary that the vibrating head be low in mass so that the transducer is not loaded down at its driving end. At 20 kHz, for example, adequate rigidity and low mass are obtained in a horn of approximately 1/4 in. (0.64 cm) vertical fraction thickness. In this manner multiple elements may be properly distributed on the diaphragm, and, under operation, the relatively thick diaphragm becomes an integral part of the transducer. The resultant vibration will be a piston action, with the diaphragm moving in phase with the transducers, enabling almost complete coverage of the liquid.

Efficiency. Transducers are used for the conversion of electrical energy to mechanical energy as well as the reverse of this function. There are two phases of efficiency that must be considered when discussing a transducer in its applied use. The first consideration is the conversion efficiency: that of converting electrical energy into mechanical energy. This efficiency is influenced by the electromechanical coupling coefficient K , which may be derived experimentally by operating the transducer material under power. Most materials have specified coupling coefficients, usually derived from an impedance circle diagram. In general, mechanical efficiency is influenced by the value of the coupling coefficient. The over-all transducer efficiency is the second phase to be considered. Obviously, if a transducer is not attached or coupled to a given load, this load cannot accept any energy; in this case the transducer has a hypothetical zero efficiency when considered as a driver. Therefore the over-all transducer efficiency is the product of the two efficiencies--the efficiency of conversion and the efficiency of energy transfer into the load. For example, if a driving power of 100 W is delivered to a given transducer and 10 W are stored as mechanical power, an efficiency of conversion of 10 percent results. However, if 9 W of this stored energy is delivered to the load, this results in a power transfer efficiency of 90 percent. This example results in an over-all efficiency of only 9 percent.

Driving Power Level

The driving power level of a sonic soldering system should be carefully selected so that maximum efficiency is obtained. The driving level must be high enough to produce adequate cavitation under conditions of heavy part loading. The sonic energy produced within the pot must be dispersed in order to rule out "hot spots" in soldering effectiveness. The power level selected must be safely within the mechanical driving limit of the transducer element or the over-all efficiency or expected life could be lowered.

The driving level of crystal elements is usually limited by the fragility of the material rather than piezoelectric saturation. A further consideration is the internal losses within the material: if driven too high in power the internal losses may cause the temperature of the material to approach the curie temperature. This could result in partial or complete depolarization. Depolarization usually occurs at the center of the piezoelectric material and works its way outward. Adequate design of the entire sonic system, incorporating cooling apparatus, will minimize or eliminate this problem.

Because of higher curie temperatures, higher operating temperatures can also be achieved by using a material such as lead zirconate titanate as compared to barium titanate. Also, the driving level should not cause heat losses that would exceed the safe operating temperature of any bonding agent used. When higher power levels are required, mechanical clamping may be utilized in order to maintain compressional loading throughout the sinusoidal swing.

Fragility does not limit the usable driving power of a magnetostrictive material such as metallic nickel. The limiting factor with this type of material is usually the saturation magnetostrictive strain limit of the material.

The heat generated is not particularly detrimental to operation of the material since it has a relatively high curie temperature (665°F [352°C]), nor does this heat affect the quality of a metallic joint such as produced by brazing. Overpowering would involve considerations of excessive bath temperatures or severe electromechanical design problems. Therefore a suitable driving level of a practical sonic system is one that does not create undesirable heat losses and still accomplishes the results required of the system. In general, a transducer soldering system achieving this end and utilizing only convection or forced air cooling is a practical design.

Natural Degradation

Usually, ceramic piezoelectric transducers will undergo natural degradation and will deteriorate as they age and are put to practical use. The amount of deterioration can adversely affect cleaning parameters after a period of time. As an example of this, let us examine the properties of lead zirconate titanate. The lead zirconate titanate ceramic is subject to all the basic disadvantages of ceramic piezoelectric transducers but has some superior qualities over other piezoelectric transducers such as barium titanate. A leading producer of this ceramic is the Clevite corporation. Clevite's best grade of lead zirconate titanate for ultrasonic transducers is called PZT-4. Clevite publishes official specifications on this material. Their data shows that PZT-4 undergoes deterioration even when not being used. The following data is listed for PZT-4 on the shelf for a period of 50 weeks.

- Decrease in capacitance: 7 percent.
- Decrease in coupling coefficient: 6 percent.
- Change in frequency: 2 percent.
- Change of planar mode (mechanical Q): from 450 to 600.

This percentage of change is probably related to the total efficiency change of piezoelectric transducers from 95 percent to perhaps 70 percent. Some lead zirconate titanate piezoelectric transducer material has a stabilizer added to minimize the effects of natural degradation.

The Generator

There is one vital consideration of a sonic energy solder pot that is often overlooked. The transducer must be driven with electrical power in order to induce the vibrational energy that produces cavitation. This high frequency electrical power must be efficiently and reliably produced by a generator. The generator converts 60-Hz power into high frequency (20 kHz) power that matches the resonance of the transducer.

Generators are available in many types, but vacuum tube and semi-conductor (transistor) types are most applicable to ultrasonic soldering devices. Both types produce the same kind of output to drive a transducer; however, the semi-conductor units are electrically more efficient in converting line current into RF.

Generator outputs are usually one of three wave forms: continuous wave; full wave; and half wave. The latter two are most commonly used. The peak power of a full-wave generator is twice the average power output, while for a half-wave generator it is four times the average. For example, if the average power output is 100 watts with a full-wave generator, the peak power will be 200 watts and the half-wave peak power 400 watts. The selection of the wave form is determined by the type of transducer being driven and the overall electrical and acoustical properties of the entire system.

Generators may be of rotary, electronic, or solid state type. Rotary generators are limited in frequency range and are, therefore, used generally in high power (15-50 kW) applications. Electronic or tube type generators are employed at all frequencies and power levels, and must be recognized as extremely reliable at high power levels. Solid state generators are now in production usage.

SUMMARY

Cavitation is the fundamental source of cleaning action in ultrasonic soldering.

There are three basic steps in the cavitation process: degassing, gaseous cavitation, and vaporous cavitation.

Vaporous cavitation provides the most active force for cleaning.

The lower the frequency the more intense the cavitation event.

An increase in power increases the number of cavitation events.

Cavitation is affected by environmental, physical, and chemical conditions such as surface tension, vapor pressure, hydrostatic pressure, temperature, and viscosity.

While all parts of a sonic system must contribute to the final end, that of performing a soldering job efficiently, the role of the transducer is especially critical. It is the heart of the system; it converts electrical energy into cleaning energy. The transducer must perform this task efficiently and reliably, and the design must be carefully approached. One must consider many characteristics of the transducer material that affect its end use in a sonic system, since a sonic system is not a simple design. The components of the sonic system must withstand severe shock, stress, vibration, and in some cases wide thermal cycling. While under the influence of these environmental conditions, the sonic efficiency must be maintained. The transducer material must have many qualities. Some of the more important are the following: it must be efficient in power conversion; it should be adequately protected if fragile; it must be capable of withstanding thermal cycling; the bonding of the material should be rugged; the material should be easily obtained and of relatively low cost; the stability of the material should be good; the material should be easily fabricated into the design intended; and the material should be capable of the power levels needed to effect good cavitation, and not be permanently affected by the normal internal losses. Reliability is most important.