Measurement of the Ultrasonic Effect in an Ultrasonic Solder Bath

Method for determining relative ultrasonic intensity accurately and repeatably can be used to maintain good process control

BY A. LYSTRUP

ABSTRACT. In ultrasonic soldering ultrasonic effect is transmitted to a solder bath by ultrasonic horns. During operation the horns erode and the transmitted effect becomes less and less. Thus, to obtain good process control it is necessary to be able to measure the ultrasonic effect, i.e., sound level, in the solder bath. This paper describes a recently developed method of measuring this effect. The measurements are carried out with an ultrasonic crystal and the magnitude of the effect is registered on a voltmeter. Just as a piezoelectric crystal is able to send out mechanical vibrations when subjected to an ac voltage, it is able to emit an ac voltage when mechanically vibrated. The measurements show that the ultrasonic effect depends very strongly on the length of the transmitting ultrasonic horn, the chemical composition of the solder, and the distance from the transmitting horn and, further, that the effect is independent of the temperature of the solder bath.

During the work, a method to produce ultrasonic horns with long lifetime was found.

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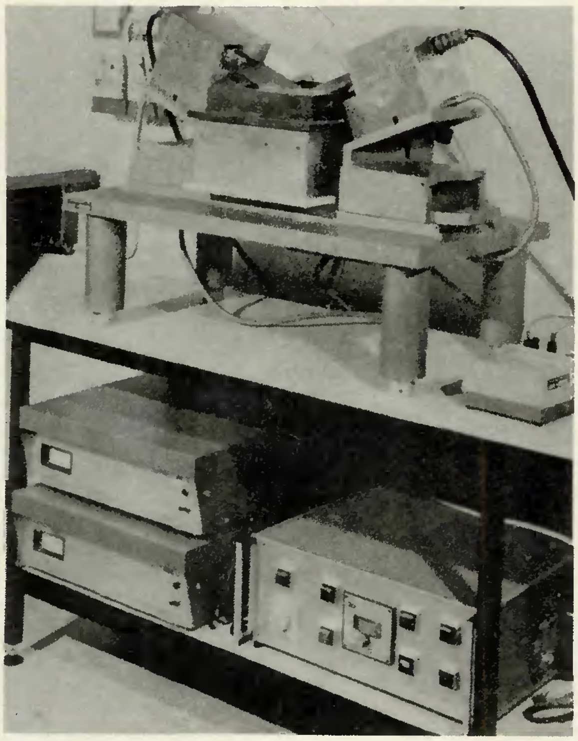

Fig. 1 — The ultrasonic soldering equipment in which the measurements are carried out

Introduction

Ultrasonic soldering is a fluxless joining method in which high frequency mechanical vibrations replace the flux. The mechanical vibrations are transmitted to a liquid solder bath, and the energy of the mechanical vibrations causes cavitation to occur, thus eroding the surfaces of parts immersed in the bath. This removes the oxide layer on the surfaces of the parts and allows the melted solder to wet the clean metal surfaces. The method was developed especially for soldering aluminum parts.

The quality of the soldered joints depends on how completely the oxide layer and other surface contaminants are removed and this, again, depends on the ultrasonic effect in the solder bath. If the ultrasonic effect is too small, unacceptable joints will result. Therefore, one step required in the process is periodic measurement of the ultrasonic effect. This paper describes a recently developed method for measuring this effect and the results which have been obtained to date.

Apparatus

The measurements are carried out with ultrasonic soldering equipment of the type in which two inclined ultrasonic horns are immersed in the solder bath from above (see Fig. 1).

The actual measurements are made using an ultrasonic crystal, and a high frequency ac voltmeter. Just as a piezoelectric crystal sends out mechanical vibrations when excited by an ac voltage, it is also able to emit an ac voltage when subjected to mechanical vibrations.

During soldering, ultrasonic energy is transmitted to the solder bath from both of the ultrasonic horns. When conducting measurements of the ultrasonic effect, one of the transmitting horns and its associated crystal is replaced by a corresponding set, which is only used for measuring the ultrasonic effect. This prevents erosion of the receiving horn and assures reproducible measurements. The ultrasonic crystal of the measuring probe is connected to the ac voltmeter and the equipment is then ready to monitor the output from the other horn. The set up is shown in Figs. 2 and 3, and the components of the apparatus are listed in Table 1.

Procedure

The reproducibility of the ultrasonic measurements has had the first priority in the detailed design of the procedure; applicability for industrial use has had the second priority.

The following four parameters have been investigated to date: (a) the length of the ultrasonic horn, (b) chemical composition of the solder bath, (c) distance from the ultrasonic horn, (d) temperature of the solder bath.

All the measurements have been repeated many times and they are carried out as follows:

1. The equipment is made ready for soldering (i.e., the solder is melted and at the right temperature, the horns are immersed in the solder, but the ultrasonic generator is not yet on).

2. One crystal and horn set is removed and replaced with the measuring set. It is important that the two ultrasonic horns are facing each other exactly, and that the distance between the horns is constant for measurements to be comparable.

3. The ultrasonic horn of the measuring set must be immersed in the melted solder for 5-10 minutes before further operation, to ensure that all the solder around the horn is molten.

If the temperature of the solder bath is 250 C (480 F), 5 minutes is sufficient for the horn to rest in the bath. Ten minutes is necessary if the temperature of the bath is 440 C (825 F).

4. The measuring crystal is connected to the ultrasonic generator and ultrasonic power is applied to both of the crystals for 5 seconds.

During the very first trials, this step was omitted and it was impossible to obtain reproducible results. In fact, the voltage output decreased with each succeeding measurement, even though the equipment had not been used in the meantime. The measuring crystal and the measuring horn were quite new, and they had only been used as a measuring set (the transportation of energy is from the horn to the crystal). If, however, the measuring set was connected to the ultrasonic generator and power applied (transportation of energy from crystal to horn) for a few seconds before each measurement, the output from the other horn was reproducible in each measurement.

5. The measuring crystal is disconnected from the generator and connected to the voltmeter. The two conductor cables from the ultrasonic crystal are plugged into the ampli-

Table 1 — Components of the Apparatus Used for the Measurements

Equipment	Type	Remarks
Solder bath	Zevatron UBZW 4/20	Zevatron GMBH, Germany
Ultrasonic generator	Branson J-22	20 kHz, 300 W, Branson Sonic Power, U.S.A.
Transmitting ultrasonic crystal	Branson	Lead-zirconate-titanate Branson Sonic Power, U.S.A.
Material of the transmitting ultrasonic horn	UHB Sverker 3	2% C, 13% Cr, 1.3% W Hardening: 1020 C (1870 F) Tempering: 520 C (970 F) Uddeholm, Sweden
Receiving ultrasonic crystal	Branson	Lead-zirconate-titanate Branson Sonic Power, U.S.A.
Material of the receiving ultrasonic horn	Branson	Composition unknown Branson Sonic Power, U.S.A.
Voltmeter	Microphone amplifier, 2603	Brüel & Kjaer, Denmark

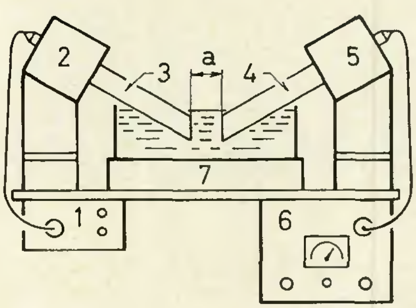

Fig. 2 — Schematic of the measuring equipment. (1) Ultrasonic generator, (2) Transmitting ultrasonic crystal, (3) Transmitting ultrasonic horn, (4) Receiving ultrasonic horn, (5) Receiving ultrasonic crystal, (6) Voltmeter, (7) Solder bath, (a) Distance between the ultrasonic horns

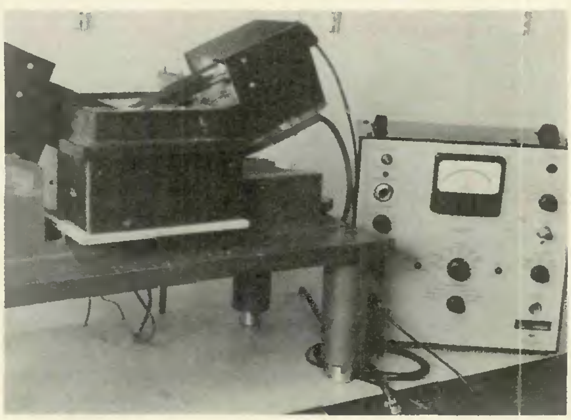

Fig. 3 — Photograph of the equipment showing the measuring set (crystal plus horn) and the voltmeter

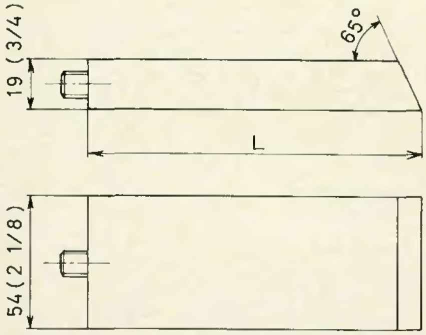

Fig. 4 — Sketch of the ultrasonic horn. L ranges from 142.5 mm (5.61 in.) to 122.5 mm (4.82 in.)

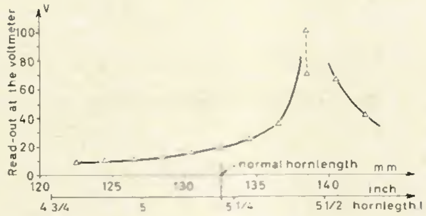

Fig. 5 — The voltage output versus the length of the transmitting ultrasonic horn. Solder bath: 100% Sn. Temperature of the solder bath: 250 C (480 F). Distance between the ultrasonic horns: a = 15 mm (0.59 in.)

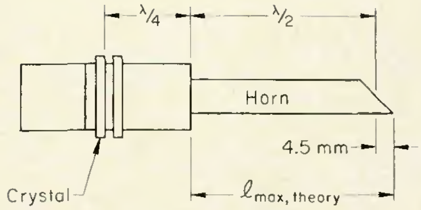

Fig. 6 — Sketch of the crystal-horn assembly. λ = the wavelength. L_{max} (theory) = the theoretical length of the horn at which maximum effect is transmitted

Table 2 — Ultrasonic Effect in Different Solder Baths (a)

Composition, weight %	Temperature C	(F)	Voltmeter reading, volts
95 Zn-5 Al	440	(825)	50
91 Sn-9 Zn	250	(480)	24
100 Sn	250	(480)	19
96.5 Sn-3.5 Ag	250	(480)	18
60 Sn-40 Pb	250	(480)	16

(a) Distance between horns a = 15 mm (0.59 in.). Length of transmitting horn L = 132.5 mm (5.22 in.).

Table 3 — Data of Materials (a)

Material	ρ at room temp., 10^3 kg/m^3	v at room temp., 10^3 m/s	Z = ρ × v 10^6 kg/m^{2}s
Sn	7.3	2.7	19.7
Zn	7.1	3.8	27.0
Ag	10.5	2.7	28.4
Pb	11.3	1.2	13.6
Al	2.7	5.1	13.8
Steel (horn)	7.8	5.2	40.6

(a) ρ = Density. v = Velocity of sound. Z = Acoustic impedance.

fier-input at the voltmeter and the adjustment of the voltmeter is as follows:

Input Switch: Direct (input potentiometer is then out of function)

Frequency Response Switch: Linear 20-40,000 Hz

Meter Switch: RMS, slow

Meter Range: Depends on the actual voltage

Range Multiplier: Depends on the actual voltage.

6. The ultrasonic generator is turned on for 5 seconds to activate the crystal and horn set on which measurement is desired, and output is read on the voltmeter.

Results and Discussion

The Length of the Ultrasonic Horn

The effect of the length of the transmitting ultrasonic horn on voltage output has been measured. The length, L, of the horns has ranged from 142.5 mm (5.61 in.) to 122.5 mm (4.82 in.) (see Fig. 4). All the measurements were made with the same horn. At the beginning the horn length was 142.5 mm (5.61 in.), but it was shortened 2 mm (0.08 in.) by grinding after each series of measurements until the length of the horn reached 122.5 mm (4.82 in.). It was necessary to adjust the ultrasonic generator each time the horn was shortened.

The measurements were made in a 100% Sn solder bath at 250 C (480 F); distance between the transmitting horn and the receiving horn was 15 mm (0.59 in.).

The results are shown in Fig. 5 and it can be seen that the voltage output depends strongly on the length of the horn. The reason for this is that the length of horn, the velocity of sound, and frequency must be well matched to obtain maximum effect. The measurements at each horn length were quite constant, except for those at the 138.5 mm (5.45 in.) horn length. There, the voltmeter read-out ranged from 70 V to 100 V and was very unstable during each measurement, which might be caused by the fact that the 138.5 mm (5.45 in.) is very close to the optimum length, and the following calculations show that there is a good agreement between this experimental result and theory.

The horn length at which the maximum effect is transmitted can be seen from Fig. 5:

L_{max} (research) ~ 138.5 mm (5.45 in.)

Theory says:

$$\lambda = \frac{v}{\nu}$$

where λ is the wavelength
v is the velocity of sound
ν is the frequency

The frequency output of the equipment is ν = 19.59 kHz (measured), and the velocity of sound in steel is v = 5,200 m/s (Ref. 1) (the velocity of sound in a solid in the form of a rod, where the cross-sectional dimensions are small compared with wavelength).

Then

$$\lambda = \frac{5.2 \times 10^6}{19.59 \times 10^3} \text{ mm} = 266 \text{ mm}$$

If maximum effect has to be transmitted, the length of the ultrasonic horn has to be λ/2 (Ref. 2), and because the horn which is used in this investigation has an inclined end the calculation is continued as followed (see also Fig. 6):

$$L_{max}\text{ (theory)} = \lambda/2 + 4.5 \text{ mm} = 133 \text{ mm} + 4.5 \text{ mm};$$

$$L_{max}\text{ (theory)} = 137.5 \text{ mm (5.41 in.)}$$

Composition of the Solder Bath

The ultrasonic effect transmitted to the solder bath depends strongly on the composition of the solder. Measurements were made in five different solders. In each case the distance between the ultrasonic horns was 15 mm (0.59 in.), and the length of the transmitting horn was 132.5 mm (5.22 in.).

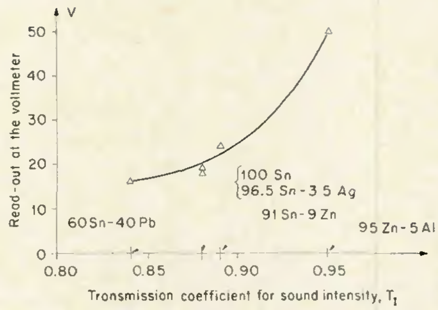

Fig. 7 — The voltage output versus the transmission coefficient for sound intensity. Distance between ultrasonic horns: a = 15 mm (0.59 in.). Length of the transmitting ultrasonic horn: L = 132.5 mm (5.22 in.)

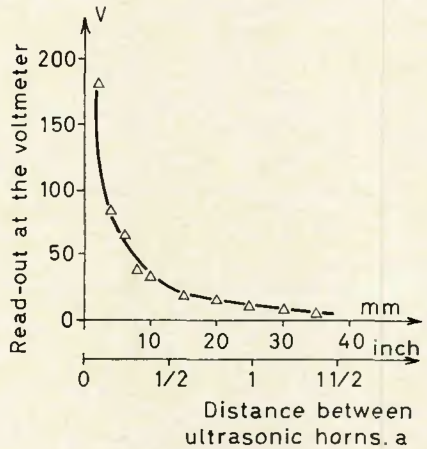

Fig. 8 — The voltage output versus the distance between the ultrasonic horns. Solder bath: 100% Sn. Temperature of the solder bath: 250 C (480 F). Length of the transmitting ultrasonic horn: L = 132.5 mm (5.22 in.)

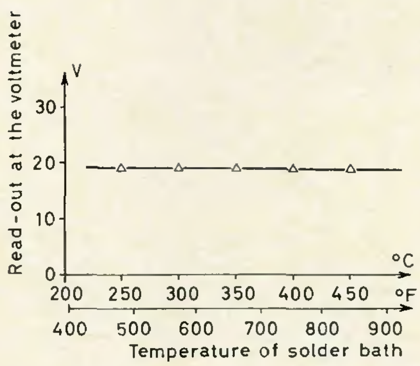

Fig. 9 — The voltage output versus the temperature of the solder bath. Solder bath: 100% Sn. Distance between the ultrasonic horn: a = 15 mm (0.59 in.). Length of the transmitting ultrasonic horn: L = 132.5 mm (5.22 in.)

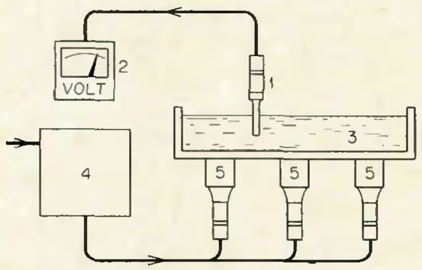

Fig. 10 — Schematic of a recommended design for a measuring probe. (1) Measuring probe, (2) Voltmeter, (3) Solder bath, (4) Ultrasonic generator, (5) Ultrasonic transducers

The composition of the solders and the corresponding voltmeter reading are given in Table 2.

When the ultrasound reaches the end of the horn, a part of it is reflected and another part is transmitted to the solder.

The transmission coefficient, T_I, gives that part of the sound intensity which is transmitted.

$$T_I = \frac{4 \times Z_H \times Z_S}{(Z_H + Z_S)^2}$$

where Z_H and Z_S are the acoustic impedances of the horn and the solder, respectively (Ref. 3).

The acoustic impedance is calculated as:

$Z = \rho . v$
where
ρ is the density
v is the velocity of sound

The calculated acoustic impedances and transmission coefficients for ultrasound transmitted from the horn to each of the five solders are shown in Table 3 and Table 4, respectively. The calculated values must not be taken as absolute because all the data used were for room temperature. All the solders are, of course, solid at room temperature. Additionally, the acoustic impedances of the solders were calculated assuming a simple proportionality (by weight) of acoustic impedances with the metals they contain.

The magnitude of the transmission coefficient is indicative of the fraction of ultrasound transmitted to the solder bath. Figure 7 shows that there is a reasonable qualitative correlation between the transmission coefficients and the ultrasonic effect measured in the different solder bath.

Distance Between Ultrasonic Horns

The voltage output decreases rapidly as the distance between the ultrasonic horns is increased. This is shown in Fig. 8. The measurements were carried out in a 100% Sn solder bath at 250 C (480 F). The length of the transmitting horn was 132.5 mm (5.22 in.).

From the above, it is apparent that it is important to maintain a fixed distance between the horns when applying this measuring technique to control the ultrasonic soldering process.

Temperature of the Solder Bath

The effect of temperature, from 250 C (480 F) to 450 C (840 F), on ultrasound transmission in a 100% Sn solder bath has been measured (see Fig. 9). The measurements show that transmission is independent of the temperature of the solder bath. Therefore, it is not necessary to carefully control the temperature when measuring the ultrasonic effect in the bath. Of course, the measuring horn must stay in the solder long enough to ensure that all of the surrounding solder is molten before the measurement is taken.

Recommended Design of a Measuring Apparatus

The measuring methods which have been described in this paper were especially developed to meet the requirements of the equipment which was available at the time. The same principles of measurement can be used in design of a portable system applicable to measurement of the ultrasonic effect in any ultrasonic soldering equipment. If an ultrasonic crystal is connected to both an ultrasonic horn and a voltmeter, the combination can be used as a measuring probe.

Figure 10 is a schematic of such a setup. Using such equipment, it is possible to record the intensity of the ultrasonic effect at any point in the bath. The shape of the end of the horn must be matched to the type of solder bath which is going to be used and, to obtain maximum sensitivity, the crystal and the horn must be matched to the frequency of the ultrasonic soldering equipment.

Conclusions

This recently developed method for measuring the ultrasonic effect in an

Table 4 — Calculated Data of Solders (a)

Solder weight %	Z_S 10^6 kg/m²s	T_I
95 Zn-5 Al	26.3	0.95
91 Sn-9 Zn	20.4	0.89
100 Sn	19.7	0.88
96.5 Sn-3.5 Ag	20.0	0.88
60 Sn-40 Pb	17.3	0.84

(a) Z_S = Acoustic impedance of solder. T_I = Transmission coefficient.

ultrasonic solder bath is very easy to implement, and the results are extremely reproducible.

The measurements show that the ultrasonic effect depends very strongly on the length of the transmitting ultrasonic horn, the chemical composition of the solder, and the distance between the transmitting and receiving horns. Further, the effect is independent of the temperature of the solder bath.

The maximum effect occurs at a horn length fixed by 138.5 mm (5.45 in.). If the length of the horn is increased or decreased the output effect decreases. The fraction of ultrasound transmitted to the solder bath depends upon the chemical composition of the solder. Thus, the measured ultrasound effect is dependent on the solder composition.

The ultrasonic effect measured in the solder decreases rapidly as distance between the transmitting and receiving horns increases.

During operation of the ultrasonic equipment, the ends of the horns erode and the output decreases. By measuring the effect in the solder bath it is now possible to reject the horns before they produce unacceptable joints, and in general a better process control can be obtained.

References

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Appendix A

Ultrasonic Soldering Horn with Long Lifetime

This appendix describes a method for producing an ultrasonic soldering horn with a lifetime which is three times longer than normal.

In some ultrasonic soldering equipment two inclined horns reach down into the solder bath from above. The length of a new horn (i.e., the horn which is mounted on the equipment when delivered) is 132.5 mm (5.22 in.), but during operation the end of the horn erodes and the output effect decreases. Normally acceptable joints are produced if the horn is not eroded more than 6 mm (0.24 in.). If the horn is longer than 132.5 mm (5.22 in.), it is difficult to start the oscillation of the horn. If, however, a starting impulse is provided by another ultrasonic horn, the vibrations can be initiated at any time even if the horn is 10 mm (0.39 in. longer than normal). In addition, the output effect from the longer horn is much larger than from the shorter one. This means that both the quality of the joints and the lifetime of the horn increase. By choosing the proper length of the horn, one is able to increase the lifetime by at least a factor of three. This has a large influence on the operating costs, because under some circumstances the lifetime of a normal horn is not more than 30 hours.

In practice, the equipment can be run as follows: a normal horn [132.5 mm (5.22 in.)] is mounted at one of the ultrasonic crystals and a 10 mm (0.39 in.) longer horn at the other crystal. The normal horn is used to start the oscillation of the longer one. When the longer horn has been eroded by 10 mm (0.39 in.), the shorter one (which has also been eroded) is rejected and replaced by a new one of 142.5 mm (5.16 in.) length. The virbations of this new long horn can now be started from the other. The procedure can then be repeated as required.