

ULTRASONIC BALL/WEDGE BONDING OF ALUMINIUM WIRES

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The process of ball/wedge bonding and its advantages are described. A capacitor discharge technique for the formation of balls on 25 and 75 μm diameter aluminium wires is discussed. Ultrasonic welding trials were carried out and the bonds subjected to pull tests with good results. Bonds of good strength were made between 25 μm diameter Al-1% Si wire and Al thin films, Pd-Au thick films and Au flashed Kovar.

1. INTRODUCTION

Fine gold or aluminium wires (25 μm diameter) are generally used to make connections between active circuit chips and external circuitry. These wires are welded to the chips and circuitry by the relatively cool thermocompression (hot pressure) and ultrasonic solid phase welding techniques as the devices degrade when subjected to elevated temperatures ($>350^\circ\text{C}$). Ultrasonic welding is currently the more favoured technique as it can be used on both aluminium and gold wires and is generally accomplished without any external heating.

Two ultrasonic wire bonding techniques are currently used: wedge-wedge bonding aluminium wires and ball/wedge bonding gold wires. During wedge bonding of aluminium wires a wedge-shaped tool flattens the wire and forms a weld beneath this region. This has two main disadvantages: the wire can easily be overdeformed which may produce a weak joint, and, before making the second wedge bond, the wire can be led away only along the axis of the first joint. Ultrasonic ball bonding of gold wires has become increasingly popular in the last five years because these limitations are eliminated. A ball is formed on the end of the gold wire and this ball is then welded to the circuit using a capillary tool. Overdeformation of the ball does not reduce the wire cross-section and the welding condition is consequently more tolerant to process variables. The wire can also be led in any direction from the weld which facilitates automation and increases production rate when manually controlled welding is employed. Following the ball bond, a wedge bond

is made using one edge of the capillary. Thus when interconnections are made using this technique, the ball bond is generally made to the solid state device, and the subsequent wedge bond to the external circuitry.

Although ball/wedge bonding has these advantages over wedge/wedge wire bonding, the technique has only been applied to gold wires where the ball is formed by melting the wire either in a hydrogen flame or by capacitor discharge between the wire and a tungsten electrode (460 V, 2 μF). If it could be applied to aluminium wires it would have additional economic and reliability advantages because there would be no degradation of the aluminium chip metallisation. Brittle gold/aluminium intermetallic compounds would not form at the joint in such a monometallic aluminium wire/aluminium chip metallisation system.

The main difficulty in applying the ball bonding technique to aluminium wire has been that of forming the balls. A hydrogen flame is not suitable as the wire oxidises and the tenacious oxide film prevents the wire balling up. Similarly, grossly oxidised balls are obtained when the commercially available electrical discharge technique is used and the application of shielding gases to the work area gives unsuitable electrical discharges which do not cause the wire to melt. Previous workers¹ have also attempted to form balls on aluminium wires by focused laser beam, microplasma torch and radiant heater, as well as by capacitor discharge but no success was achieved.

Because of the potential advantages of an aluminium ball/wedge wire interconnection technique the above methods for forming balls on aluminium

wire were again reviewed and it has been found that the capacitor discharge technique could be used to give good quality balls under certain conditions, and that this technique could be employed for making aluminium wire ball/wedge welded interconnections. This paper describes the techniques employed for forming balls on 25 and 75 μm diameter aluminium wires, the design of equipment which can be incorporated on a standard ultrasonic gold ball/wedge welding machine to enable aluminium ball/wedge bonding and the results of detailed bonding trials to thin film aluminium, thick film palladium-silver and gold flashed Kovar when using 25 μm diameter Al-1% Si wire.

2. BALL FORMING

Various capacitor discharge systems and a special transistor power source with wave shape control, were investigated to establish the effect of electric arc energy control on ball quality. The power sources were attached in turn to an experimental apparatus which simulated the wire feed operation of a bonding machine. The apparatus also had an integral electrode and gas cup assembly which enclosed the end of the Al wire during the ball forming operation. The shielding gases studied were Ar, Ar + O₂, He, Ne, Kr and Xe.

The most consistent balls were formed using a capacitor discharge power source with an Ar gas shield. A condition was established which produced ball diameters in the range of 2.2 to 2.5 x the wire diameter. The ball quality was typical of that shown in Figure 1.

A capacitor discharge ball forming attachment suitable for aluminium wire has been incorporated



FIGURE 1 Good quality ball on 25 μm diameter aluminium wire.

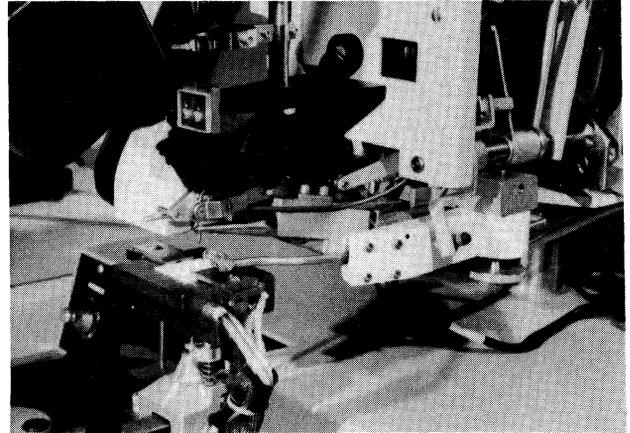


FIGURE 2 Ball forming attachment fitted to Kulicke & Soffa 472 ball bonding machine.

on the Kulicke and Soffa 472 machine, see Figure 2. This replaced the hydrogen torch assembly and involved no substantial modification to the machine.

3. CAPILLARY DEVELOPMENT

Initially three ball/wedge standard bonding capillaries for Au wire bonding were examined to establish their suitability for ultrasonic Al ball/wedge bonding. All three capillaries gave good ball bonds, although the concentricity of the wire with the bond varied according to the capillary face cone angle dimensions. The capillary wedge bonds, however, were poor and had little tolerance to variation of the welding parameters. When capillary wedge welding Au wires, a capillary face angle generally in excess of 8° is used to deform the wire in order to assist wire separation without disrupting the wedge bond. Because Al wire is less malleable than gold such tools tend to sever the wire rather than weld it, see Figure 3. Previous work² has shown that the best wedge/wedge bonds are achieved when ultrasonic welding 25 μm diameter Al wires with a wedge tool having a long foot length and a flat face parallel to the wire. The longer foot length produces a larger bond area which in turn permits higher bond pull strengths at lower wire deformations. The tool face being parallel to the work does not excessively deform the wire when the weld energy is increased because the high pressure produced by the initial point contact of an angled tool face is avoided. These principals were used to design an

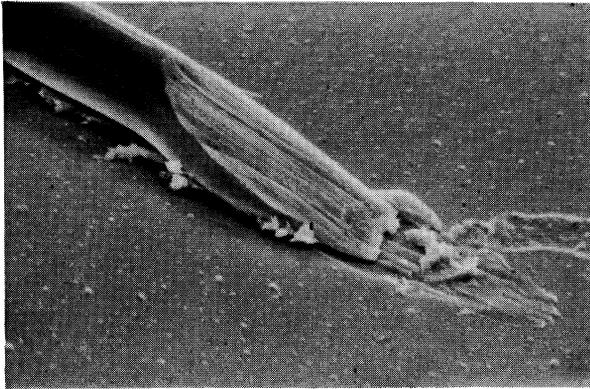
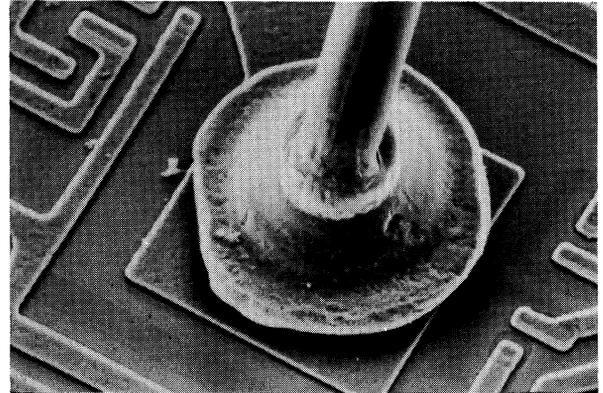
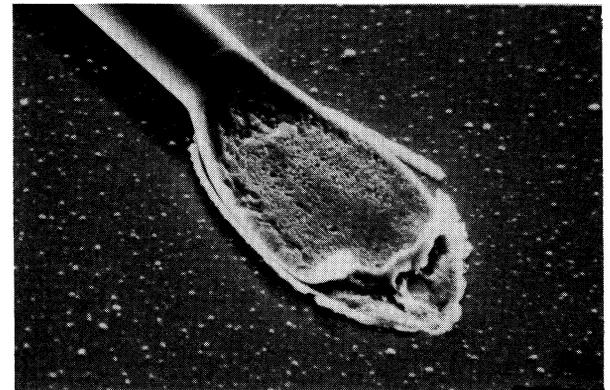


FIGURE 3 A capillary wedge bond between a 25 μm diameter Al-1% Si wire and an Al thin film, made using a capillary designed for bonding Au wire.



(a)



(b)

FIGURE 5 Good quality ball and wedge bonds made between 25 μm diameter Al-1% Si wire and Al thin film substrate.

(a) ball bond
(b) wedge bond

experimental capillary in which a further consideration was the re-alignment of any axially offset balls prior to bonding. This is made difficult when the capillary has too shallow a cone and too large an included cone angle at the mouth of the wire feed hole. Experiments

Dimensions = μm
R = Radius
I.C. = Internal cone
(expressed as half the included angle)

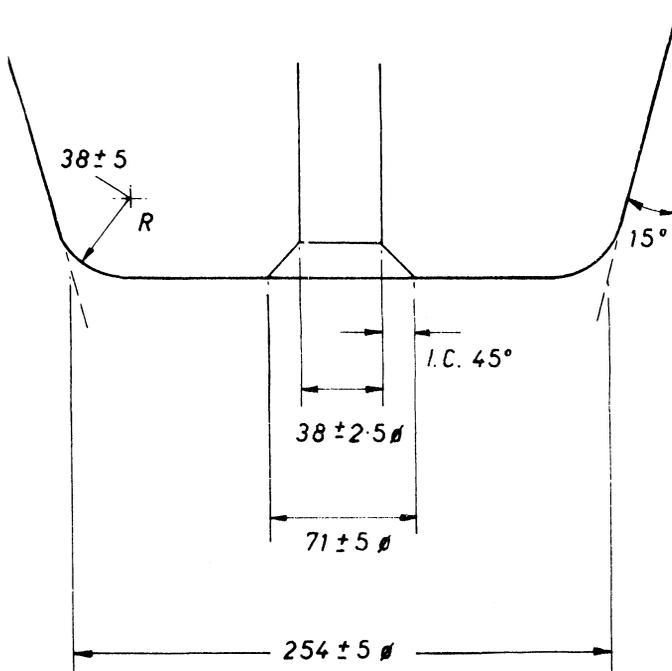


FIGURE 4 Al ball/wedge bonding capillary.

with capillaries having 90° included cone angles showed that if the correct cone depth and diameter was employed good re-alignment of offset balls could be achieved. With this and former wedge tool experience in mind the capillary shown in Figure 4 was designed and manufactured for ultrasonic ball/wedge bonding 25 μm dia Al wires. Good quality Al ball and wedge bonds made with the experimental capillary are shown in Figure 5. Ball re-alignment and the quality of the wedge bonds was considerably improved with the experimental capillary and therefore it was used for the welding trials.

4. WELDING TRIALS

Al-1% Si wire (tensile strength 140 mN) was ultrasonic ball/wedge bonded to Al thin films, Pd-Ag thick films and Au flashed Kovar.

Preliminary work indicated that a bond time of 30 ms was satisfactory for both ball and wedge bonds. A bonding force of 300 mN was used for all the ball bonds, and for the capillary wedge bonds to the Al thin films. The wedge bonds to the Pd-Ag thick films and Au flashed Kovar were made at 400 mN. The ultrasonic vibration amplitude is the parameter most likely to vary in practice and therefore this was studied in more detail. The amplitude was varied in 0.1 μm steps (as measured free standing at end of the transducer horn) over a range which produced welds within established acceptance limits.

The acceptance limits for ball bonds were a minimum shear strength of 200 mN and a maximum bond spread of 4 \times the wire dia. For the wedge bonds the limits were a minimum 30° pull strength of 35 mN (25% of wire tensile strength) and a maximum bond spread of 2.5 \times the wire dia.

4.1 Al Thin Films

For ball bonds made at the above time and force, the optimum vibration amplitude was 0.7 μm with a tolerance of $\approx \begin{smallmatrix} +40 \\ -30 \end{smallmatrix} \%$, see Table I. A histogram, Figure 6, for a sample of 100 bonds made at 0.7 μm amplitude, shows a strength range of 300 to 550 mN. These values, although considered acceptable, do not give a true indication of the bond strength since in almost every instance, especially where the lower strengths were recorded, the shear failure occurred at the Al film/substrate interface.

A number of ball bonds were subjected to a vertical pull test. In every case the wire failed above the ball. The average failure force was 76 mN (range 72 to 80 mN) which is more than 50% of the parent wire tensile strength (130 to 140 mN). The reason for the reduction in strength is that the wire is annealed during the ball forming operation.

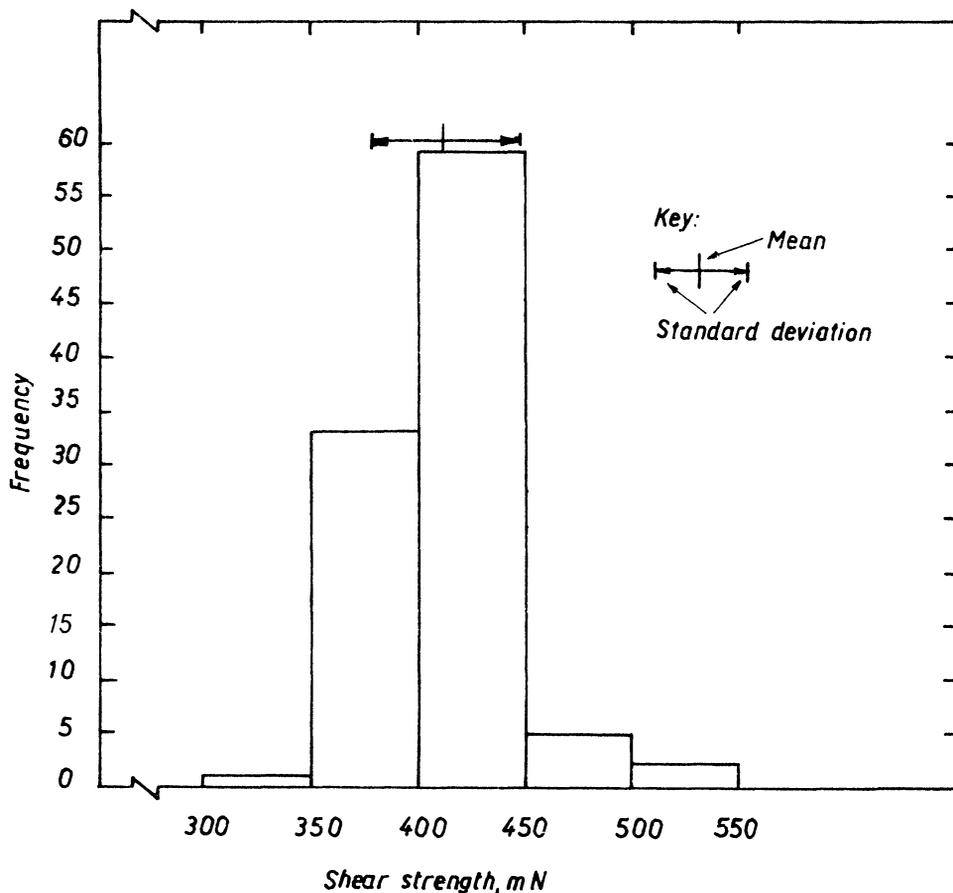
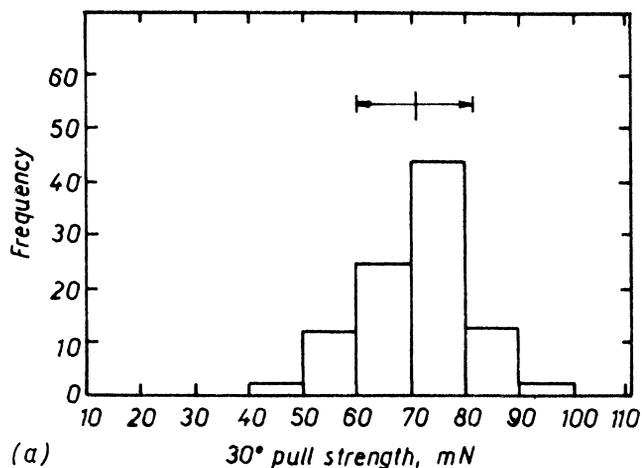
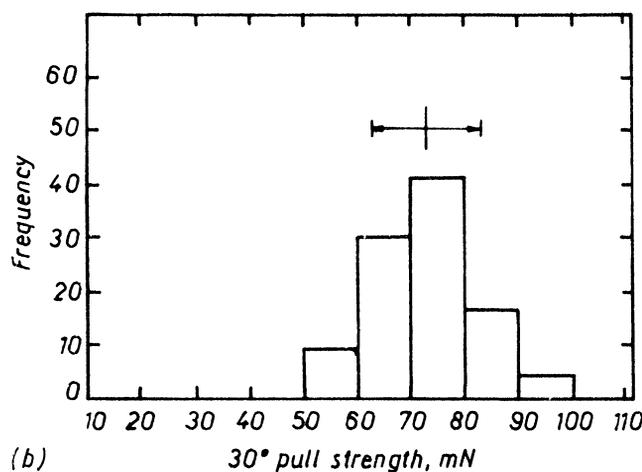


FIGURE 6 The strength distribution of 100 Al-1% Si ball bonds to Al thin film substrate. Optimum vibration amplitude 0.7 μm , weld time 30 ms, weld force 300 mN.



(a)



(b)

FIGURE 7 Strength distributions of 100 Al-1% Si wire wedge bonds to Al thin film substrate. Optimum vibration amplitude 1.2 μm , weld time 30 ms, weld force 300 mN.
(a) parallel
(b) transverse vibrations

TABLE I
Optimum vibration amplitude and tolerance established when ball bonding 25 μm diameter Al-1% Si wires to various films (weld time 30 ms, weld force 300 mN).

Film	Optimum vibration amplitude* μm	Vibration + amplitude range	
		μm	%
Al thin film	0.7	0.5	+40 -30
Pd-Ag thick film	1.1	0.5	+20 -25
Au flashed Kovar	1.2	0.7	+35 -25

*The optimum vibration amplitude was taken as the nearest 0.1 μm magnitude in the middle of the acceptable vibration amplitude range.

* Results based on a minimum bond shear strength of 200 mN and a maximum weld spread of 100 μm .

When making the capillary wedge bonds the vibration amplitude which was most suited to both directions of vibration is 1.2 μm (see Table II) producing an amplitude tolerance of $\approx \pm_{-30}^{+17}\%$ when the vibrations are parallel, $\approx \pm_{-7}^{+10}\%$ when transverse, which therefore gives a tolerance of $\pm 17\%$ when bonding through 360° . The bond strength histograms, Figure 7, for a sample of 100 bonds made at the 1.2 μm amplitude show strengths ranging between 40 and 100 mN for parallel vibrations and 50 to 100 mN for transverse vibrations. In both instances the majority of strengths fall in the 60 to 80 mN range.

4.2 Pd-Ag Thick Films

The optimum vibration amplitude for ball bonds made at the selected bonding time and force was

TABLE II
Optimum vibration amplitude and tolerance established when capillary wedge bonding 25 μm diameter Al-1% Si wires to various films (weld time 30 ms).

Film	Bonding force mN	Optimum vibration amplitude μm	μm		Vibration amplitude range*			
			Parallel	Transverse	Through 360° **	Parallel %	Transverse %	Through 360° **
Al thin film	300	1.2	0.6	0.7	0.4	+17 -30	+40 -17	± 17
Pd-Ag thick film	400	1.2	0.3	0.3	0.3	± 12	± 12	± 12
Au flashed Kovar	400	1.5	0.3	0.4	0.3	+10 -13	+20 -7	+10 -7

* Results based on a minimum bond pull strength of 35 mN and a maximum weld spread of 62.5 μm .

** Results based on a vibration amplitude range suitable for both parallel and transverse ultrasonic vibrations.

1.1 μm , see Table I. Acceptable bonds can be made over an amplitude tolerance range of $\approx +20\%$ to -25% from the optimum. The strength distribution of 100 shear tested bonds made at these optimum conditions extended from 450 to 800 mN and averaged 620 mN. These strengths compared favourably with those previously achieved³ when ultrasonic Au ball bonding to Pd-Ag thick films where the maximum strength obtained was 580 mN and the minimum 420 mN over a range of optimised conditions.

The optimum vibration amplitude for capillary wedge bonds $\approx 1.3 \mu\text{m}$, with a tolerance of $\approx \pm 12\%$ for vibrations in both parallel and transverse vibrations (see Table II) and it is assumed that this will also apply when bonding through 360° . The tolerance to vibration amplitude may well be improved by using a shorter weld time. Previous experience^{3,4} when wedge/wedge bonding Al wires to Pd-Ag thick films has shown that a wider tolerance to vibration amplitude can be achieved using a 5 ms weld time. For both the parallel and transverse vibrations the 1.2 μm amplitude produced a strength range of 50 to 100 mN (average 75 mN) for a sample of 100 bonds. Although the tolerance to ultrasonic vibration amplitude is slightly less ($\pm 12\%$) than that established when making the wedge bonds to Al thin film ($\pm 17\%$) the bulk strength test results were very similar.

4.3 Au Flashed Kovar

The optimum vibration amplitude when making ball bonds was 1.2 μm and the tolerance for acceptable welds, $\approx +35\%$ to -25% (see Table I). A shear test sample of 100 bonds made at the optimum vibration amplitude, gave a strength range of 250 to 550 mN (average 400 mN). These strengths are similar to those achieved on the Al thin films but are much lower than those achieved on the Pd-Ag thick film material. The lower strengths in this instance are not due to failure of the gold plating, but could be due either to the surface finish or alternatively to the use of a non-optimised welding force and time. Nevertheless, in relation to the Al wire tensile strength (≈ 135 mN) the minimum weld shear strength of 250 mN is considered acceptable.

Table II shows that when capillary wedge bonding to Au flashed Kovar the optimum amplitude for the

time force studies was 1.5 μm with a tolerance of $\approx +10\%$ to -13% when the vibrations are parallel, $\approx +20\%$ to -7% when the vibrations were transverse and hence $\approx +10\%$ to -7% when bonding through 360° . For both parallel and transverse vibrations at the 1.5 μm amplitude, the bond strength range for a 100 bond sample was between 40 and 110 mN, (average 75 mN). This strength range is very similar to the ranges achieved during the bulk strength tests of the wedge bonds to both the Al thin film and Pd-Ag thick film substrates.

5. CONCLUSIONS

Equipment employing an electric arc and an inert gas shield has been developed for forming balls on the end of 25 μm diameter Al wires to enable Al ball/wedge bonding. This equipment is easily incorporated onto standard ultrasonic Au wire ball/wedge welding machines. Ball and capillary wedge bonds of good strength were made with 25 μm diameter Al-1% Si wire to Al thin films, Pd-Ag thick films and Au flashed Kovar. The capillary wedge bond is considerably improved by using a flat faced capillary which is parallel to the work.

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