HOT WORK ULTRASONIC BONDING - A METHOD OF FACILITATING METAL FLOW BY RESTORATION PROCESSES

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Summary

A joining process referred to as hot work ultrasonic bonding has been developed. Hot work ultrasonic bonding leads to thin films is accomplished by maintaining the lead in its hot work temperature range during the application of a sufficient quantity of ultrasonic energy. Under these conditions, lead strain hardening associated with conventional ultrasonic bonding does not occur, since the metal undergoes restoration processes of recovery and recrystallization simultaneously with deformation. As a result, solid-state deformation of the lead is enhanced at rates giving it the appearance of "liquid wetting." This permits the formation of the necessary contact area at lower temperatures and vertical forces than thermocompression bonding and at lower power levels than conventional ultrasonic bonding.

A sharp increase in pull strength of copper leads bonded to palladium thin films was shown in the temperature region (150°C to 200°C) where recrystallization developed during the application of ultrasonic energy (hot work "ultrasonic" temperature region). The recrystallized structure was correlated with internal strains induced by conventional ultrasonic bonding.

During hot work ultrasonic bonding, not only does the bulk lead deform readily (by inducing recrystallization), thereby increasing the potential true contact area, but asperity flow at the interface is also expected to readily occur by a similar mechanism. Thus the energy previously absorbed in the form of internal lattice strain has been efficiently utilized to form restored structures which facilitate lead flow.

Introduction

In many areas of integrated circuit packaging, ultrasonic bonding techniques are employed to join a variety of workpieces such as metal leads and silicon integrated circuits to metallized substrates. Ultrasonic bonding[1] is accomplished by a transducer-coupling tool system which converts high-frequency electrical energy into mechanical vibrations and delivers it to the bond region. This vibratory system, a portion of which is tapered, serves as a velocity transformer (or horn). The velocity transformer amplifies the oscillatory (high frequency) motion and delivers it to an attached bonding tool.

To ultrasonic bond metal leads to thin films, the workpieces are held by a clamping force between the tool and supporting anvil. As the tool oscillates in a direction parallel to the thin film surface, a complex mode of stresses are introduced in the lead. As a result, the lead deforms against the metallized surface, forming a bond closely akin to a solid-state friction bond where no detectable interface melting occurs.* During the process, a bulk portion of the lead strain hardens, although the heat generated will tend to reduce this effect. In many cases, where strain hardening effects prevail, unreliable bonds are formed. The extent of strain hardening is also material dependent.

It is the intention of this paper to describe a bonding process referred to as hot work ultrasonic bonding[2,3] where the lead is maintained in its hot work temperature range during the application of ultrasonic energy. In this temperature range, lead strain hardening associated with conventional ultrasonic bonding does not occur since the metal lead undergoes restoration processes of recovery and/or recrystallization simultaneously with deformation. Under these conditions, bulk lead deformation is increased in a manner similar to "super plastic flow." Hot work ultrasonic bonding reduces stresses in the substrate by increasing the contact area as well as by eliminating lead strain hardening during bonding. The process is capable of bonding a wide range of lead materials (composition, thickness). In addition, it is capable of forming the necessary contact area at lower temperatures and vertical forces than thermocompression bonding and at lower power levels than conventional ultrasonic bonding. Finally, a bonder with the capability of ultrasonic, thermocompression, and hot work ultrasonic bonding offers the flexibility often required to optimize conditions for joining new workpieces in the integrated circuit field.

*Melting is expected with lower melting-point materials and/or higher ultrasonic power levels.

Bonding Aluminum Wires to Tantalum Thin Films Deposited on Glass Substrates

In the course of an investigation concerned with ultrasonic bonding of 0.015-inch aluminum wires to tantalum thin films (1,400Å) deposited on glass substrates,[2] relatively low and inconsistent 45° shear-peel strengths were related to glass fractures which occurred in the immediate area of the bond region (Table 1). This was performed with an optimized set of bonding parameters (power, time, and clamping force) employing a commercial 100-watt, 40 kHz ultrasonic welder. The incidence of glass failure was attributed to the initial room temperature flow stress of the lead and its subsequent increase due to strain hardening. For example, during ultrasonic bonding, seizure and compressive deformation of an aluminum wire occurs on the tantalum thin film surface. With the oscillatory displacement of the tool, the aluminum strain hardens, thus requiring an increase in stress to continue the deformation process. This in turn tends to increase the level of stresses transmitted to the glass substrate.

Table I

Forty-Five Degree Shear-Peel Strength of 99.99 Per Cent Aluminum Wires Bonded to Tantalum Thin Films on Glass

Al Wire Size (Inch)	Mean Strength/ Range (Grams)	Bond Temp.* (^{o}C)	Mode of Failure**
0.015 (N=55)	229/(0-500)	25	63.7%--A 36.3%--B
0.035 (N=55)	215/(0-2050	25	100.0%--A
0.035 (N=50)	2519/(650-3020)	400	4.0%--A*** 96.0%--B

*Temperature prior to introducing ultrasonic energy.

**A = glass failure where glass neggets were removed from the substrate; B = wire failure where the bonded portion was left in tact.

***Failure is believed to have been caused by an uncontrolled bond temperature condition ($<400^{o}$C).

Hot-Work Ultrasonic Bonding

The ability to form solid-state bonds of aluminum-to-tantalum thin films is associated with the frictional nature of ultrasonic bonding. In this case, it is believed that vibratory energy effectively disperses the aluminum and tantalum oxides resulting in nascent metal-to-metal bonding. Thus the question of how to utilize the attributes of ultrasonic energy (which form aluminum-to-tantalum bonds) while eliminating its detrimental effects was posed.

It was believed that this could be accomplished by reducing the energy required to ultrasonically deform the lead while increasing its ability to flow. Thus a portion of the 0.015-inch aluminum lead about to be deformed was maintained above its minimum hot work temperature range ($\sim 400^{o}$C) during the application of ultrasonic energy (using the same ultrasonic bonding parameters employed above). Under these conditions, lead deformation greatly increased. This is expected, since, as in the case for simple tensile or compressive stresses, the strain hardening index, n (Equation 1), approaches zero in the hot work temperature region, resulting in a large amount of lead deformation for a given stress.

$$\sigma = \sigma_o \epsilon^n \qquad (1)$$

where:

σ = flow stress

σ_o = yield stress

ϵ = strain

n = strain hardening index

In order to evaluate the hot work ultrasonic and conventional ultrasonic process, a larger aluminum wire (0.035 inch) was employed. This relieved failure modes associated with excessive deformation which occurred when the 0.010-inch wire was hot work ultrasonically bonded. Of course, a reduction in the bonding parameters would also relieve this condition. As shown in Table I, a previously unattainable bond condition for 0.035-inch aluminum wires resulted under hot work ultrasonic temperature conditions where bonds generally failed in the free-length portion of the wire with no evidence of substrate damage. Metallographic cross sections of conventional ultrasonic and hot work ultrasonic bonded aluminum wires showed evidence of strain hardening (internal strain) and restored structures (subgrains and recrystallization), respectively.[2]

Hot Work Ultrasonic Bonding Copper to Palladium Thin Films

To extend the material range of hot work ultrasonic bonding, an investigation of joining copper wires to a multi-layer thin film of palladium-copper-nichrome-tantalum nitride deposited on alumina substrates was pursued.

Method of External Heating

To preheat a copper wire prior to introducing ultrasonic energy, a laboratory system was developed. A U-shaped molybdenum tool was fabricated and attached to a step-horn by a taper-lock fit (Figure 1). The other end was gripped by an electrode. The tool was resistance heated by passing current through the electrode, molybdenum tool, and horn. Though this method of heating lowered the efficiency of ultrasonic energy output by the additional mass of the electrode and tool as well as heating of the horn, the experimental results (to be described) demonstrated the significance of the hot work ultrasonic process. For practical applications, the use of ultrasonic bonders having larger tool masses (such as tuned-reed systems) is expected to simplify methods of heating the tool. For materials whose hot work temperatures are lower, anvil heating may be sufficient.

Pull Strength Versus Ultrasonic Bonding Temperatures

To reduce problems associated with excessive lead deformation during bonding, one end of the copper wires (99.999 per cent) was "balled" by fusion in an inert atmosphere. The wire portion of the "balled" lead was passed through a hole provided at the base of the U-shaped tool. This allowed the tool to compress the ball against the

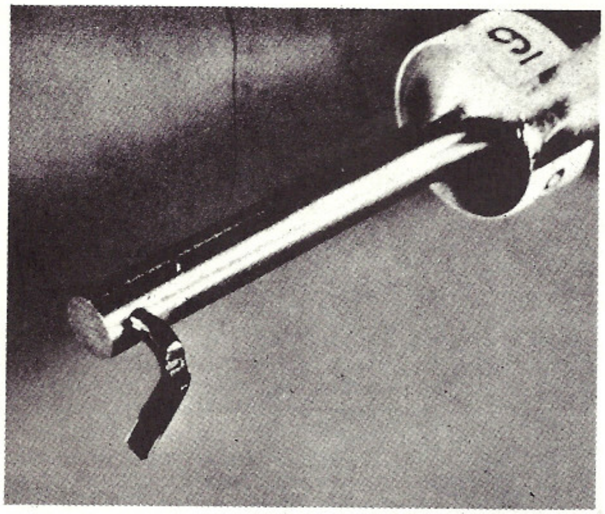

Figure 1

Hot work ultrasonic transmission system composed of a step-horn with an attached U-shaped bonding tool. The base of the U-shaped tool is shown with a groove for coupling "balled" copper leads. With an attached electrode (not shown above), the system is capable of transmitting various combinations of thermal, mechanical, and ultrasonic energy to the bond region.

substrate with the axial length of the wire remaining approximately perpendicular to the substrate during bonding. The copper lead dimensions were: wire diameter = 0.010 inch; ball diameter ≅ 0.020 inch. During the bond cycle, an open forming gas atmosphere was provided to minimize surface oxidation in the bond region. Balled copper wires were bonded over a range of temperatures starting at room temperature with the remaining bond parameters of a 100-watt 40 kHz ultrasonic bonder (ultrasonic power level, bond time, and clamping force) held constant. To form ultrasonic bonds above ambient, the "balled" lead was first clamped to the metallized substrate by the bonding tool. The ball portion of the lead was then preheated for two seconds to attain a desired temperature, after which the ultrasonic energy was introduced for about 0.5 second. Estimated steady-state bond region temperatures were predetermined by placing a "balled" chromel-alumel thermocouple between a copper lead and substrate while simulating a complete bond cycle. The resultant pull strengths (Figure 2) showed a sharp increase between 150°C and 200°C. Above this temperature region, the bonded portion (ball) of the copper lead remained in tact, producing consistent failures in the free-length portion of the lead. Negligible pull strengths (interface failures) occurred to the left of the near vertical portion of the S-curve.

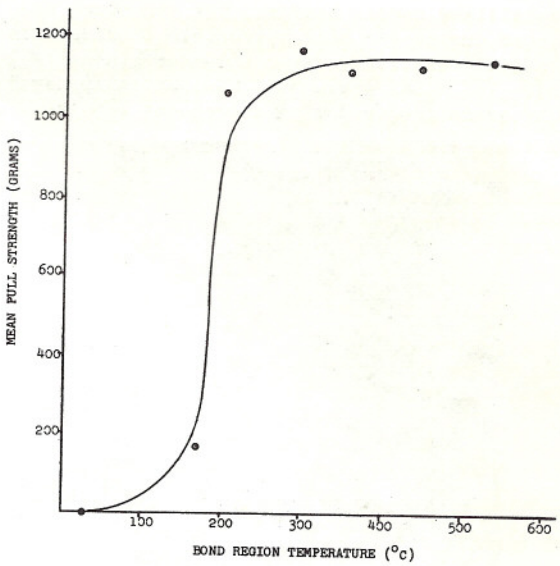

Figure 2

Pull strength of 99.99 per cent copper lead-palladium thin film couples versus bond region temperature (ten samples per point) during the application of ultrasonic energy.

Metallographic Examination of the Bond Structure

Cross sections of bond structures associated with points on the S-shaped strength curve (Figure 2) were prepared for metallographic examination. The general structure of an original "balled" copper wire prior to bonding shows the presence of large columnar-type grains, a common structure found where liquid-to-solid transformations have occurred (Figure 3). A photomicrograph (Figure 4) of a copper "ball" after being conventionally ultrasonically bonded (without external heating) clearly shows deformation markings (strain hardening effects) within individual columnar grains. The bond structure of the lead showing evidence of strain hardening is typical for copper leads that have been ultrasonically bonded without external heating. Pull strengths of bonds made under these conditions were negligible, as indicated on the left side of the S-shaped strength curve (Figure 2). Figure 5 shows the bonded structure made at approximately 173°C which corresponds to the initial strength rise in the S-shaped curve (Figure 2). Figure 5 clearly shows a new structure which is associated with recovery and recrystallization. The newly formed structure was found in the central, upper, and lower regions of the copper "ball." The zone of the new structure closely corresponds to where the strain markings developed in the copper "ball" that was ultrasonically deformed without external heating (Figure 4). The final photomicrograph (Figure 6) corresponds to bonds made to the right side of the S-shaped curve, which clearly shows a fully recrystallized copper matrix. The structure was developed during hot work ultrasonic bonding from the initial relatively large columnar grains (Figure 3). The final grain size was partially developed by grain growth during subsequent cooling.

Figure 3

Cross section of a "balled" copper lead showing a large columnar grain structure. Etchant: Ammonium hydroxide-hydrogen peroxide etch. ~200X.

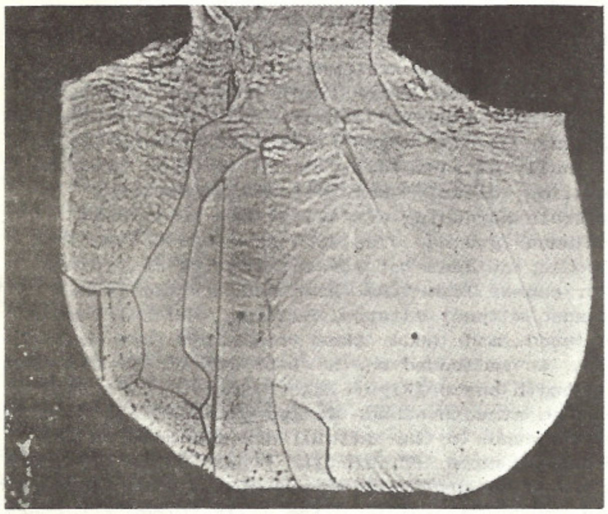

Figure 4

Cross section of a copper "ball" which was ultrasonically deformed against a palladium thin film without external heating showing effects of strain hardening. Thin film substrate is not shown, since bonding was negligible (Figure 2). Etchant: Ammonium hydroxide-hydrogen peroxide etch. ~140X.

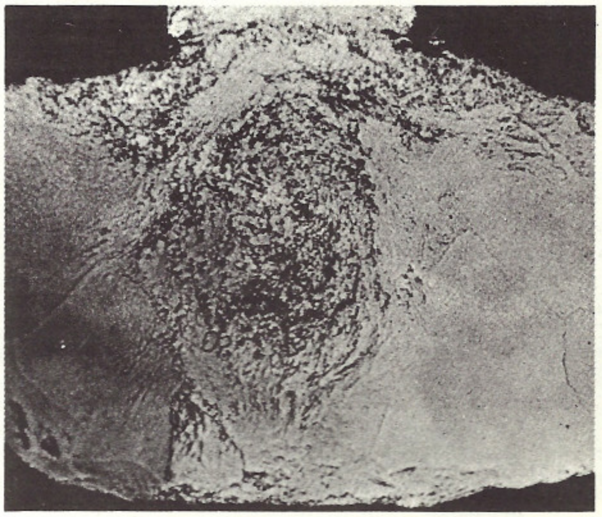

Figure 5

Cross section of a copper "ball" which was ultrasonically deformed against a palladium thin film at about 173°C showing the development of restored structures in regions corresponding to previous strain markings (Figure 4). Pull strength increased as shown in Figure 2. Etchant: Ammonium hydroxide-hydrogen peroxide etch. ~200X.

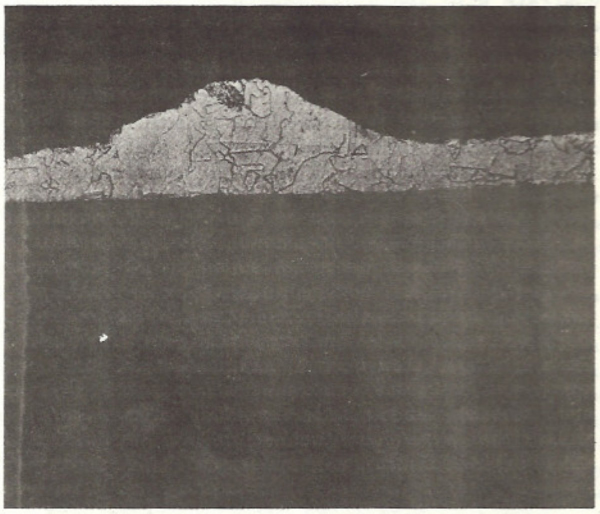

Figure 6

Cross section of a copper "ball" which was hot work ultrasonically deformed against a palladium thin film (shown below) at about 445°C snowing a fully recrystallized structure. Extending wire is not shown since it was imbedded into the mounting material. Pull strengths increased to wire strengths (Figure 2). Etchant: Ammonium hydroxide-hydrogen peroxide etch. ~200X.

The Hot Work Ultrasonic Bond Structure

Relative Lead Flow Characteristics of Thermocompression, Ultrasonic, and Hot Work Ultrasonic Energy Sources

A unique material property observed in this investigation was the dramatic increase in lead deformation caused by the hot work ultrasonic process compared to conventional ultrasonic and thermocompression processes under equivalent vertical loading conditions. For example, during bonding of 0.010-inch "balled" copper wires, the copper ball deformed a negligible amount under the influence of a conventional ultrasonic bonding tool (Figure 4). When the copper "ball" was preheated above its minimum hot working temperature, the extent of deformation was similar until the bonding tool was ultrasonically activated with a quantity of energy (vibratory) equivalent to the conventional ultrasonic bonding cycle. During this latter stage, the copper ball dramatically deformed in the solid state at rates which gave it the appearance of "liquid wetting." Of course, lead deformation by thermocompression or ultrasonic techniques may be increased by raising their respective parameters (force and/or temperature; force and/or ultrasonic power).

Film sequences were taken to compare the extent of metal deformation under the influence of the three energy sources. In this case, 0.020-inch copper wires with about a 0.040-inch "ball" were lap-bonded in each sequence. Single frames prepared from the film sequences clearly demonstrated the relative extent of metal deformation. Figure 7 shows a copper ball being deformed against a palladium surface by the application of heat and pressure from the U-shaped tool. In this case, the copper ball deformed a negligible amount, as shown in Figure 8. With the application of ultrasonic energy under identical loading conditions (Figure 9), the lead again deformed a negligible amount (Figure 10). Finally, a lead was preheated under the same loading and temperature conditions as the thermocompression sequence and then a quantity of vibratory energy equivalent to the conventional ultrasonic sequence was applied (Figure 11). In this case, the lead deformed at rates which gave it the appearance of liquid wetting (Figures 11 and 12). Under these bonding conditions, the thermocompression and ultrasonic bonds failed at the bond interface, while the hot work ultrasonic bonds (Figure 12) failed in the wire leaving the bond in tact.

Hot Work "Ultrasonic" Deformation

Hot working is defined as deformation of metals under conditions of temperature and strain rates such that restoration of internal lattice strains take place simultaneously with deformation. On the other hand, cold working is deformation carried out under conditions where restoration processes are not effective. In hot working, strain hardening and distorted grain structures produced by deformation are very rapidly eliminated by the formation of new strain-free grains as a result of

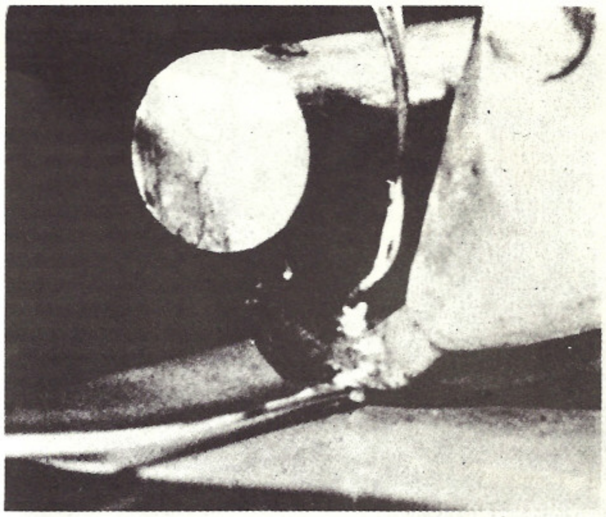

Figure 7

Thermocompression bonding sequence. Thermal and mechanical energy (tool temperature = 450°C, force = 4.1 kgm, time = 3.5 seconds) is being transmitted to the copper ball. Heat is developed by passing current from the electrode (right) through the U-shaped tool to the attached horn. Thermocouple is shown attached to the center of the tool.

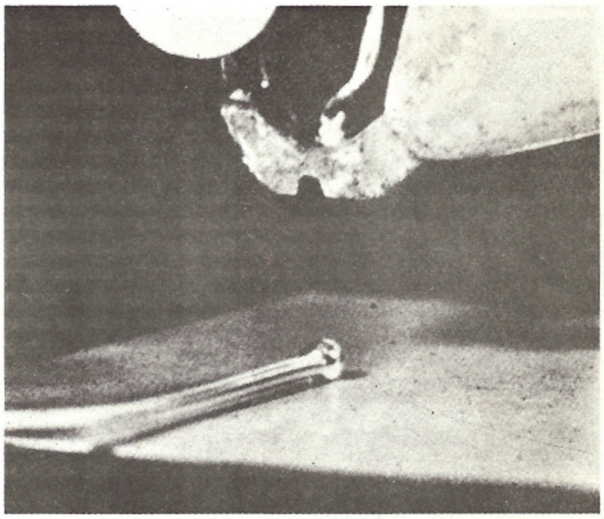

Figure 8

Bonded copper ball is shown below raised bonding tool after the thermocompression bonding sequence (Figure 7). Note the negligible amount of lead deformation.

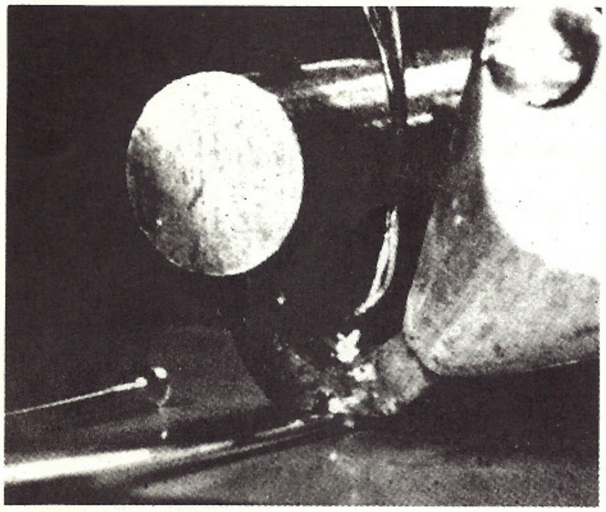

Figure 9

Ultrasonic bonding sequence. Ultrasonic and mechanical energy (ultrasonic power, ~120 watts, force = 4.1 kgm, time = 3.5 seconds) is being transmitted to the copper ball. Ultrasonic energy is transmitted from the horn to the attached U-shaped tip.

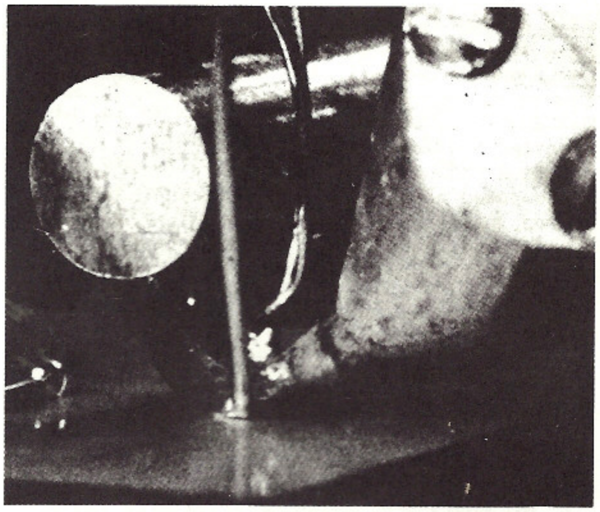

Figure 11

Hot work ultrasonic sequence. Thermal, mechanical, and ultrasonic energy (tool temperature = 450°C, force = 4.1 kgm, preheat time = 3 seconds, ultrasonic power = 120 watts for 0.5 second) is being transmitted to the copper ball. Note the "liquid-like flow" of the ball below the tool. Due to the ease of metal flow, the wire portion of the lead rotated to a perpendicular position during bonding.

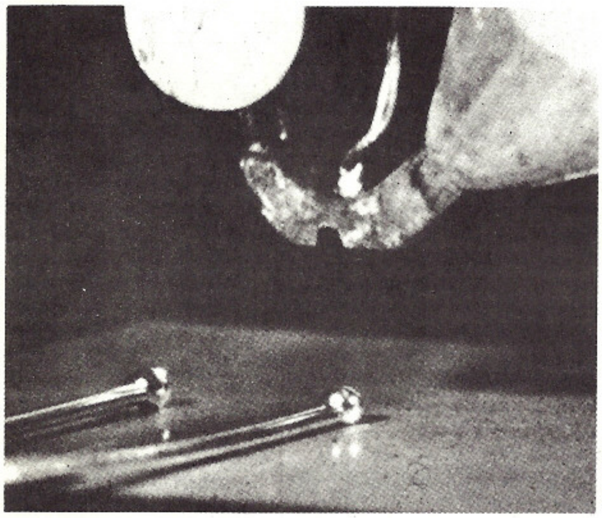

Figure 10

Bonded copper is shown below raised bonding tool after the ultrasonic bonding sequence (Figure 9). Note the negligible amount of lead deformation of the ultrasonic bond (right) and the thermocompression bond (left - Figure 7).

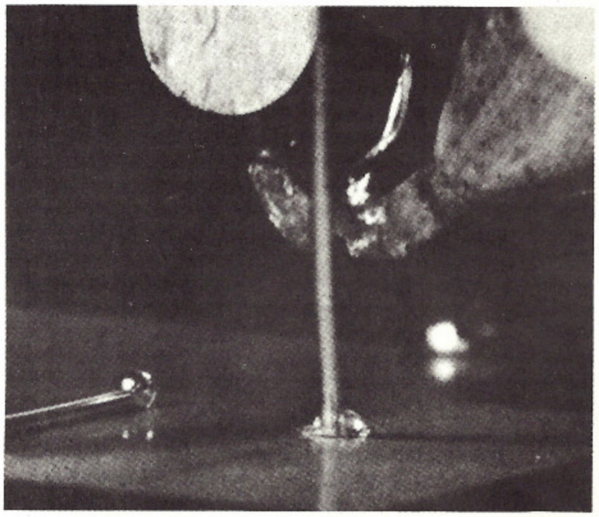

Figure 12

Bonded copper is shown below raised bonding tool after hot work ultrasonic sequence (Figure 11). Note the relatively large difference in lead deformation of the hot work ultrasonic bond (right) compared to the ultrasonic bond (left - Figure 9).

recrystallization. In essence, the energy absorbed during cold working which causes metals to increase in flow stress ($n > 0$, Equation 1) is utilized during hot working to produce structures such as recrystallization. Due to the initial strain-free nature of recrystallized grains, metal deformation is enhanced (where $n = 0$, Equation 1). Secondly, due to the increased grain boundary area of a recrystallized matrix, metal flow is enhanced by grain boundary sliding which is a mechanism associated with high temperature metal flow. This is analogous to the mechanism of flow described for "super plastic materials" where a "stabilized" fine-grain structure readily deforms at about 0.5 of its melting point.

The lower temperature limit for hot working of a metal is the lowest temperature at which the rate of recrystallization is rapid enough to eliminate strain hardening. For a given metal or alloy, the lower hot working temperature will depend upon factors such as the amount of deformation. The greater the amount of deformation, the lower the recrystallization temperature. To further lower the recrystallization temperature of metals, investigators have developed methods of introducing high strain rates in metals. In general, the higher strain rates effectively lower the recrystallization temperatures. This is analogous to isothermal recrystallization studies, where the amount of recrystallization formed by annealing at a constant temperature and time is a function of the initial input of cold work. The greater the amount of cold work (for a given material), the lower the recrystallization temperature.

Now let's examine conventional ultrasonic bonding of wires to metallized substrates. The wire is first positioned between a bonding tool and mating surface under a vertical load. When the bonding tool is activated, it oscillates in a direction parallel to the metallized surface inducing stresses in the lead. As a result, the lead deforms against the mating surface, forming a solid-state friction-type bond. As shown in Figure 4, a portion of the oscillatory motion of the tool may contribute to strain hardening, similar to a simple cold working process. By elevating the lead temperature sufficiently prior to introducing the vibratory motion, the energy previously absorbed in the form of internal strains is very rapidly eliminated by the formation of structures associated with recovery and recrystallization (Figures 5 and 6). Thus the energy previously absorbed in the form of internal strain has been efficiently utilized to form structures which facilitate lead flow. The lower temperature for recovery or recrystallization is expected to be influenced by the amount of ultrasonic power and the vertical clamping force.

A Hot Work Ultrasonic Bond Interface

To form a solid-state bond between a wire and metallized substrate, both a sufficient true metal-to-metal contact area and interfacial diffusion are contributing factors. Now if two metallic surfaces were in perfect atomic registry, atomically flat and free from all types of surface films, in most cases they could be bonded merely by bringing them together. The mechanism of recrystallization occurring at an interface is considered by many investigators to be an ideal condition for forming a reasonable true contact area. For example, when two clean metal surfaces are pressed together, they are held apart by asperities.[4] The effect of higher pressures is to increase the contact area by physically crushing asperities to such a bearing area that they may sustain the applied load. As the metal's flow stress is lowered, an increase in the true contact area results. Bowden and Tabor[4] have expressed this real contact area, A, as a function of the load, F, and mean flow stress, P_m, of the asperities by:

$$A = F/P_m \tag{2}$$

During recrystallization, the mean flow stress of a metal is considerably lowered, and as a result, only a relatively small load is required to form a relatively large contact area.

During hot work ultrasonic bonding, not only does the bulk lead deform readily to increase the potential true contact area by inducing recrystallization, but asperity flow at the interface is also expected to readily occur by a similar mechanism (Figures 5 and 6). In observing the "liquid-like flow" of the lead as it deforms in the solid-state during hot work ultrasonic bonding (Figure 11), the above mechanism appears to be reasonably founded.

Conclusions

A joining process referred to as hot work ultrasonic bonding has been developed. Hot work ultrasonic bonding leads to thin films is accomplished by maintaining the lead in its hot work temperature range during the application of a sufficient quantity of ultrasonic energy. Under these conditions, lead strain hardening associated with conventional ultrasonic bonding does not occur, since the metal undergoes restoration processes of recovery and recrystallization simultaneously with deformation. As a result, solid-state deformation of the lead is enhanced at rates giving it the appearance of "liquid wetting." This permits the formation of the necessary contact area at lower temperatures and vertical forces than thermocompression bonding and at lower power levels than conventional ultrasonic bonding.

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