

# A Footprint Study of Bond Initiation in Gold Wire Crescent Bonding

Norman Zhou, X. Li, and N. J. Noolu

**Abstract**—The morphological features of the crescent bond footprints on the substrate after peeling the wire off were studied to gain an understanding of the effect of process parameters on the crescent bond formation. In the absence of any ultrasonic energy, metallurgical bonding initiated at the peripheral regions of the crescent bond. The bond strength improved at higher substrate temperatures and higher bonding force which promoted higher shear deformation of the substrate. The application of ultrasonic energy drastically improved the growth of micro welds along the bond interface and produced micro weld patterns on the footprint that are characteristic of the level of ultrasonic energy applied. The effect of these process parameters on the mechanisms of crescent bonding are discussed.

**Index Terms**—Bonding force, bonding mechanisms, footprint morphology, gold wire crescent bonding, substrate temperature, ultrasonic energy.

## I. INTRODUCTION

THERMOSONIC wire bonding is the predominant interconnecting technique used for chip-level packaging in the microelectronic industry [1], [2]. Thermosonic wire bonding essentially consists of the application of force, ultrasonic and thermal energy simultaneously to produce a ball bond (first bond of the interconnection) on a chip and a crescent bond (second bond) on a substrate. Although processes are being developed for Cu and Al wires, Au wires are most commonly used for thermosonic wire bonding. These Au wires are commonly bonded to Al pads on the chip on one end and Au plated substrates on the other end. It is widely accepted that wire bonding is a solid-state joining process [3], [4] and examination of the wire bond interface in a transmission electron microscope [5] and wire bonding at liquid nitrogen temperatures [6] substantiate the above argument. It is also proposed that the temperature rise during bonding is probably less than 100 °C [6], which may be low for the bonding to be considered as a thermally activated diffusion process [7]. Based mainly on studies in Al and Au wire wedge bonding and, to a greater extent, on Au wire ball bonding, several models have been proposed to explain the mechanisms of wire bonding. Some have emphasized the importance of large

interfacial deformation to remove surface contaminants by surface extension (i.e., to expose clean surfaces for bonding), regardless of the application of ultrasonic energy [6], [8]–[10]. Typical observations of bonded and nonbonded regions in the periphery and middle regions of a wire bond is cited by the deformation theory to discount fretting mechanisms caused by interfacial sliding. According to the deformation theory, ultrasonic energy merely acts to reduce the force required to deform the wire and substrate [6], [9].

However, based on studies of Au ball bonding using microsensors, Mayer *et al.* [11] indicated that the sliding and scrubbing at the bump/pad interface plays a significant role in the bond formation and ultrasonic softening contributes little to the development of the bond strength. These observations directly contradict the deformation theory. Studies on Au ball bonding using 100-KHz ultrasonic vibrations also showed that the micro welded regions form preferentially in the direction of the ultrasonic vibration [12]. Osterward *et al.* [13] also suggested the existence of relative movement between pad and wedge/wire from a footprint study of Al wedge bonds.

The classical theory of contact mechanics indicates that even at smaller than critical values, the interfacial normal force would still result in an annular area with relative interfacial movement of 0.25–2.5  $\mu\text{m}$  (microslip) [14]. This annular area at the periphery of the faying surfaces surrounds a central “stick” domain with no sliding and spreads radially inwards with increasing tangential forces [15]. When the tangential force is sufficiently high (especially when oscillating), this microslip could result in surface damage due to fretting [14]. This microslip model has been applied to account for the preferential bonding at the edge of an ultrasonic wire bond [13], [16]. In addition, Winchell *et al.* [7] suggested that a wave-form material flow (initiating at the bond periphery and extending toward the centre) with time, is responsible in breaking up of the surface oxides and the formation of the bond.

Although numerous studies were performed on mechanisms of ball and wedge bonding, investigations on crescent bonds are very limited. The integrity of a wire-bonded interconnection is not only dependent on that of a ball bond, but also on that of a crescent bond and the present study focuses on issues of crescent bonding mechanisms. The strength of crescent bonds is generally evaluated by peel testing and the failure is characterized mainly by two modes: wire lift-off (fracturing through the wire/pad interface) occurs when the bond is sufficiently weak, while the wire fractures at the neck of the bond when the bond is sufficiently strong [1], [7], [8]. In the present work, micro welded regions were characterized in Au wire crescent bonding by observing the footprints left on the substrates after peeling off the wires. This facilitated an understanding of the roles of the

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TABLE I  
BONDING PARAMETERS, MAXIMUM BOND WIDTH AND PEEL FORCE OF CRESCENT BONDS USED FOR THE PRESENT STUDY

Trial Number	Substrate Temperature (°C)	Bonding Force (gf)	Ultrasonic Power (W)	Maximum Width (μm)	Peel Force (gf)
1	162	35	0	23	0.25
2	162	120	0	45	1.5
3	262	80	0	38	2.2
4	262	120	0	50	3.7
5	362	55	0	35	8.0
6	23	35	1	47	5.2
7	23	80	1	55	2.7

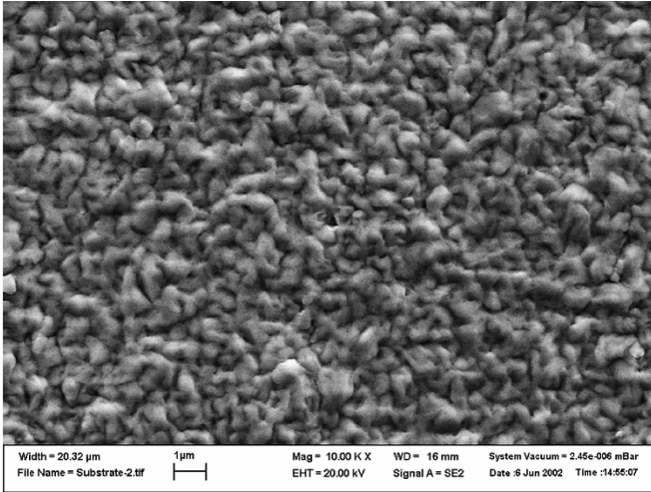


Fig. 1. Secondary electron micrograph of the surface texture of the electroplated gold surface.

bonding force, substrate temperature and ultrasonic vibrations on the initiation and the growth of the micro welded regions.

## II. EXPERIMENTAL METHODS

A Kulicke & Soffa 4524D ball bonder was used to perform the bonding experiments. The bonding operation was performed in semi-automatic mode, in which bond position was controlled manually by a multmouse while other functions were automatically performed by the bonder. The capillaries were supplied by Gaiser Tool Company (part number 1574-18-437GM). The Au wire used for crescent bonding was 25 μm in diameter was supplied by American Fine Wire (Cat. no. AW8). The nominal composition of the wire was 99.99% gold doped with 4~9 ppm Be and 2~5 ppm Ca. The substrates were 0.8-mm-thick Kovar sheets electroplated with a 1.25-μm-thick layer of Au. A 1-μm-thick Ni interlayer was deposited between the Kovar substrate and the Au plating to act as a diffusion barrier. Fig. 1 shows the typical morphology of the surface asperities of the Au plating.

The bonder was powered on for at least 30 min prior to bonding in order to ensure thermal stabilization. After the work stage reached the preset temperature the substrate was clamped to the stage. Bonding was delayed for 6 min after the substrate was placed on the work stage, to allow the substrate to reach the stage temperature. Crescent bonds were produced such that the direction of ultrasonic vibrations was parallel to the axis of the bonding wire. After a set of 10 interconnections (ball and crescent bonds) was made with a particular combination of bonding parameters, the bonded substrate was immediately removed from the work

stage for peel testing. A pair of tweezers was used to break the ball-bond neck before peel testing, and then the tail wire was taped to the lever of a pull tester to measure the breaking force of the crescent bond. Bonding parameters, such as ultrasonic power, bonding force, bond time, and stage temperature, were designed to produce underdeveloped crescent bonds so that wire lift-off would occur. The bond with a peel force that was close to the average value of ten samples under each combination of bonding parameters was selected for detailed study of morphological features of the footprints left on the substrates using scanning electron microscopy (SEM). The metallurgical bonding was characterized by the presence of fractured microwelds on the footprint, i.e., microparticulates of Au wire left on the footprint after peeling the crescent bond apart.

## III. RESULTS

Table I lists typical bonding parameters used for the crescent bonding, and the resultant peel force and maximum footprint width of the bonds. These results along with the morphological features of the crescent bond footprints are presented and analyzed as follows.

### A. Bonding Without Ultrasound

The role of bonding force on the bond initiation was studied by varying the force values at a constant substrate temperature of 162 °C, so as to alter the extent of deformation of the substrate and affect the peel strength of the crescent bonds. The ultrasonic power was disabled to eliminate the effect of ultrasonic vibrations. Fig. 2(a) shows the footprint of a bond made with a bonding force of 36 gf. The maximum bond width was 23 μm and the peel force was almost zero (Table I). The details of the highlighted area of Fig. 2(a) are given in Fig. 2(b). Observations of Fig. 2(b) show that the asperities in the center of the footprint were deformed predominantly due to normal stress. No metallurgical bonding (characterized by fractured microwelds) was observed under these bonding conditions.

Fig. 3(a) shows the footprint of a bond made at the same temperature (162 °C) as the bond shown in Fig. 2(a), but with a higher bonding force of 120 gf (Trial no. 2 in Table I). The maximum width and peel force of the bond was about 45 μm and 1.5 gf, respectively. The increase in the maximum bond width in Fig. 3(a), compared to Fig. 2(a) shows that the higher bonding force results in higher deformation of the wire. Detailed SEM observations of the deformation pattern of the asperities [Fig. 3(b)] indicated that the stresses experienced by the substrate varied from normal stresses at the center (judged from the

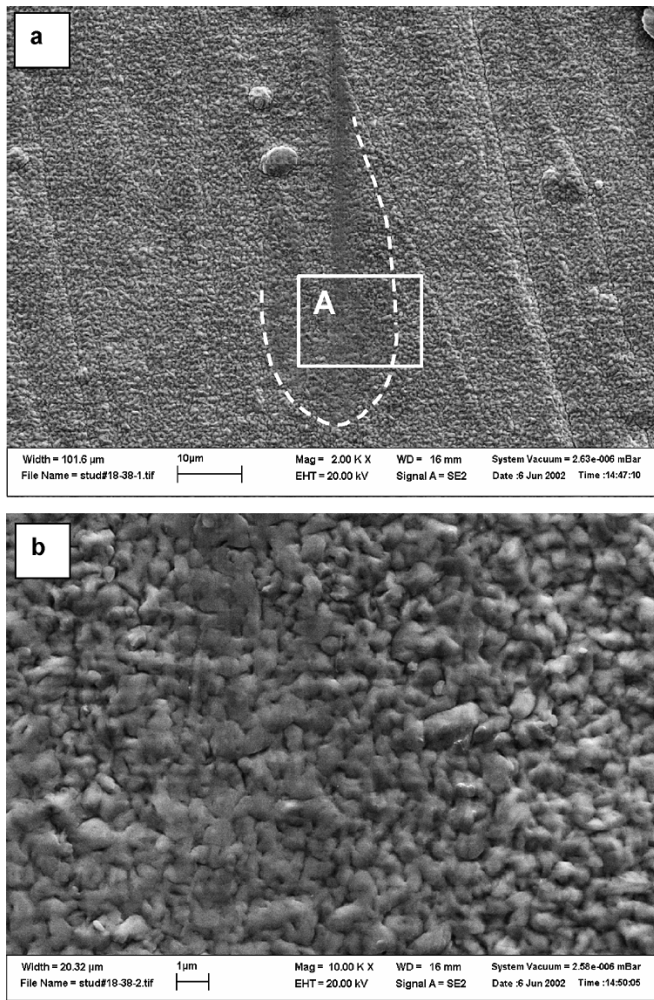


Fig. 2. (a) Footprint of a bond made at 162 °C and 35 gf force without ultrasound: the maximum width was about 23  $\mu\text{m}$  and the peel force was negligible. Dashed line indicates part of the footprint perimeter. (b) Details of the highlighted area A in (a).

undistorted asperity bases) to lateral shear stresses at the edge of the footprint (judged from laterally deformed asperities). The region that is predominantly subjected to normal stresses is termed as “central region” and the region that is predominantly subjected to shear stresses is termed as “outer region.” No microwelds were noticed in this footprint [Fig. 3(b)] although a low peel force (1.5 gf) was registered.

Further studies were conducted by varying substrate temperature so as to obtain higher deformation of the asperities (Table I). The bond made at 80 gf bonding force and 262 °C did neither result in a significant increase in deformation nor in bond strength (Trial no. 3 in Table I). However a bond made with a force of 120 gf at the same substrate temperature (262 °C) resulted in higher maximum bond width and peel force of 50  $\mu\text{m}$  and 3.7 gf, respectively (Trial no. 4). These bonding parameters promoted metallurgical bonding between the Au wire and substrate and the bonding is evident by the presence of fractured micro welds on the footprint in Fig. 4. A further increase of the substrate temperature to 362 °C, at a bonding force of 55 gf, though resulted in a lower maximum bond width of 35  $\mu\text{m}$  increased the peel force to 8 gf (Table I). This increase in peel force is clearly reflected in the higher level of microwelds (Fig. 5). It can also be

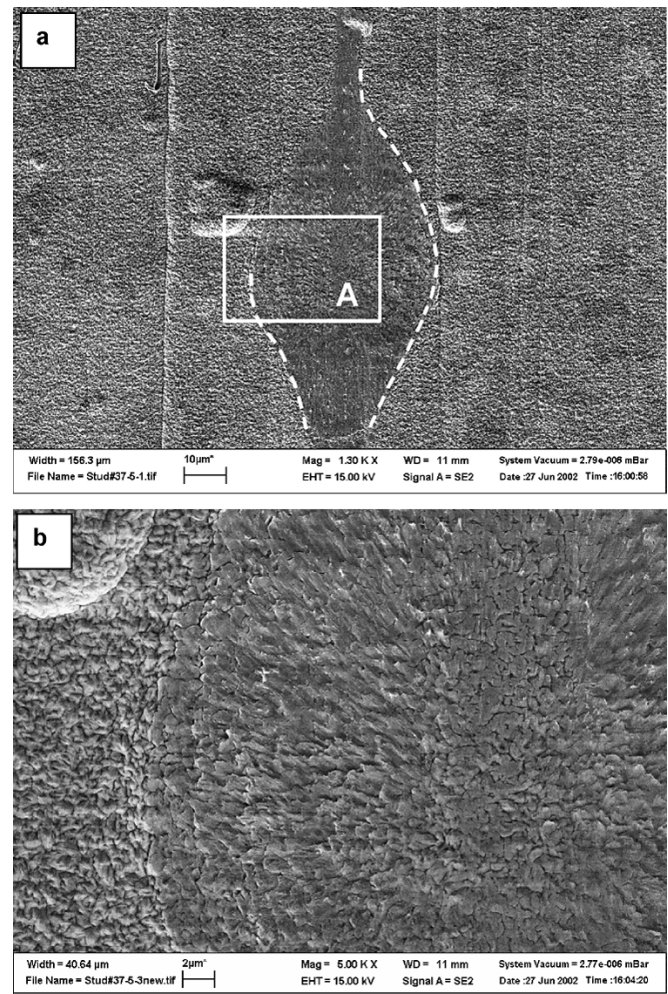


Fig. 3. (a) Footprint of a bond made at 162 °C and 120 gf force without ultrasound: the maximum width and peel force of the bond was about 43  $\mu\text{m}$  and 1.5 gf, respectively. Dashed line indicates part of the footprint perimeter. (b) Details of the enclosed area A in (a).

seen from Fig. 4(a) and Fig. 5(a) that microwelds were mostly concentrated in the outer regions of the crescent bond. A few fractured microwelds were noted in the central region of the footprint [Fig. 5(c)], which was not observed when the substrate temperature was at 262 °C or lower (Fig. 4).

### B. Bonding With Ultrasound

Studies were then performed on crescent bonds with the application of ultrasonic vibrations to investigate the effect of ultrasonic energy on the initiation and the growth of the metallurgical bonding (Table I). Fig. 6(a) shows the footprint of a bond made at 23 °C, an ultrasonic power of and a bonding force of 35 gf (Trial no. 6). Its maximum width was about 47  $\mu\text{m}$  and peel force was about 5.2 gf. The ductile fracture surface as revealed by the microvoid coalescence clearly demonstrated the presence of bonded areas at the end of the long axis of the footprint [Fig. 6(b)]. The extent of metallurgical bonding in this region was higher than that at the lateral edge of the footprint [Fig. 6(c)]. Fractured microwelds were also observed at the central regions of the footprint [Fig. 6(d)], which was not seen in the bonds made at zero ultrasonic power setting and low substrate temperatures.

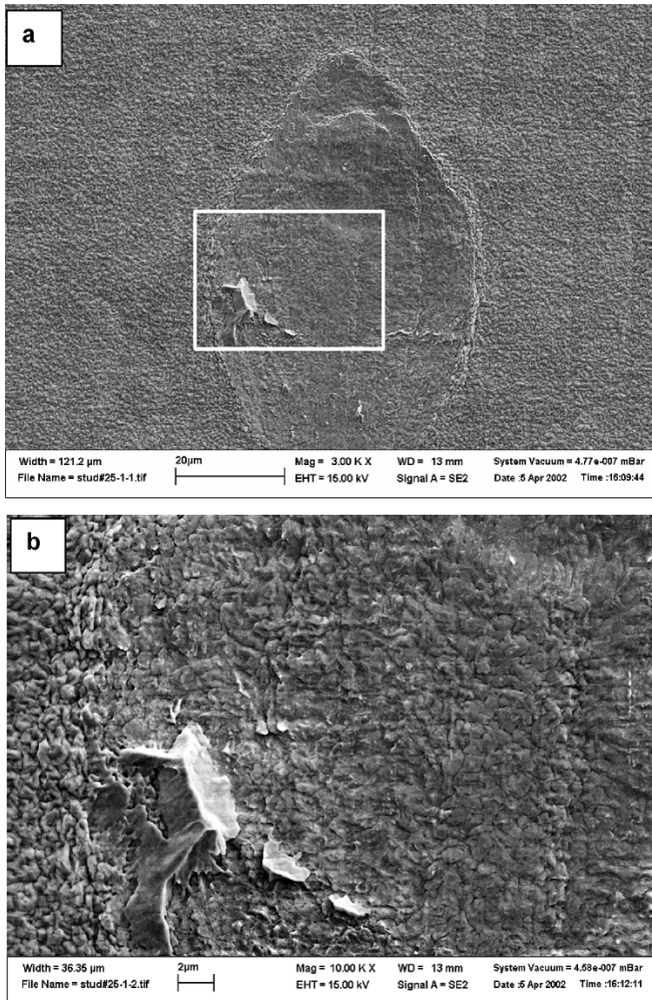


Fig. 4. (a) Footprint of a bond made at 262 °C and 120 gf force without ultrasound: the maximum width and peel force of the bond was about 50  $\mu\text{m}$  and 3.7 gf, respectively. (b) Details of the enclosed area in (a) showing microwelds.

It was also observed that, with the same substrate temperature (23 °C) and ultrasonic power (1 W), an increase of bonding force to 80 gf reduced the peel force to 2.7 gf even though the resultant maximum width increased to 55  $\mu\text{m}$  (Trial no. 7). In this case, the extent of bonding at the end of the long axis of the footprint was much lower, and no bonding occurred at the lateral edges or centre of the footprint. The reduction in the extent of bonding and peel force at higher bonding force suggest that the increase in bonding force impedes the effective transfer of ultrasonic vibrations in forming a metallurgical bond.

#### IV. DISCUSSION

##### A. Effect of Deformation

Solid-state bonding includes a group of joining processes that produce coalescence of the faying surfaces of solids without any melting. In theory, interatomic forces can cause spontaneous metallurgical bonding between two solid surfaces if they are both perfectly clean, atomically flat and brought into intimate contact [3]–[5]. This has been confirmed by a number of experiments under ultrahigh vacuum conditions (e.g., in wafer bonding [17]). However, engineered surface features, typically

have surface contaminants (oxide film, adsorbed layers and entrapped gas) and surface roughness, which prevent faying surfaces from achieving intimate contact. Therefore, overcoming these surface barriers (especially surface films) is an extremely important prerequisite for the initiation of bonding [18]. Pressure welding is one of the extensively studied solid-state joining process, in which pressure is applied to produce plastic deformation of the metals to disrupt/displace surface contaminants and to create intimate contact between underlying fresh metals. While earlier research work focused more on the role of macro bulk deformation, it was later found that the local deformation at the faying surfaces, especially surface extension by shear strain, was more important than the macroscopic deformation [19], [20]. But it is not always possible to separate the relative effects of normal and shear stress in an experiment. In addition, relative tangential movement between the faying surfaces can greatly enhance interfacial bonding by breaking up the surface films [21]. Thermal energy is sometimes applied (as in hot pressure welding) to promote the deformation and hence metallurgical bonding because of reduced yield strengths of metals at elevated temperatures.

Wire bonding without the application of ultrasonic energy (also termed thermocompression bonding), therefore, resembles hot pressure welding for large-scale applications. Unlike pressure welding where two pieces of metal are deformed simultaneously by a pair of tools, the deformation of the wire and Au film in this work, was promoted by the capillary on the top and constrained by the hard-to-deform Kovar core of the substrate at the bottom. The surface extension of the Au film was therefore mainly through the deformation of surface asperities directly caused by wire deformation, and this surface extension peaked at near-peripheral regions [10].

At the moment the wire first makes contact with the substrate surface, the contact area between the wire and substrate would be a single line for crescent bonding. If the bonding force and substrate temperature were high enough, the contact area would increase primarily because the deformed wire surface unfolds onto the substrate surface; this process was modeled numerically by Takahashi and Inoun [10]. However, the unfolding of the wire surface would mainly produce normal stress pressing the asperity peaks downwards, and little lateral shear stress would be experienced by the substrate asperities [Fig. 2(b)]. Further increase in wire deformation (caused by increasing bonding force and/or substrate temperature) would produce interfacial deformation by shear stress in the existing contact area that was created earlier during the unfolding of the wire surface. As a result of progressive interface deformation, the substrate surface asperities in contact with the wire would be sheared outwards away from the contact centre [Fig. 3(b)]. As the extension of existing contact surfaces and the formation of additional wire/substrate interfaces happened simultaneously and continuously, the degrees of lateral shear deformation of substrate surface asperities would vary from the contact center to the perimeter. The observation of micro welds mostly in the outer regions and minimal in the central regions indicates that shear stresses are required to promote metallurgical bonding.

When the substrate temperature is relatively low (162 °C or lower), as observed in Figs. 2 and 3, the shear deformation of the

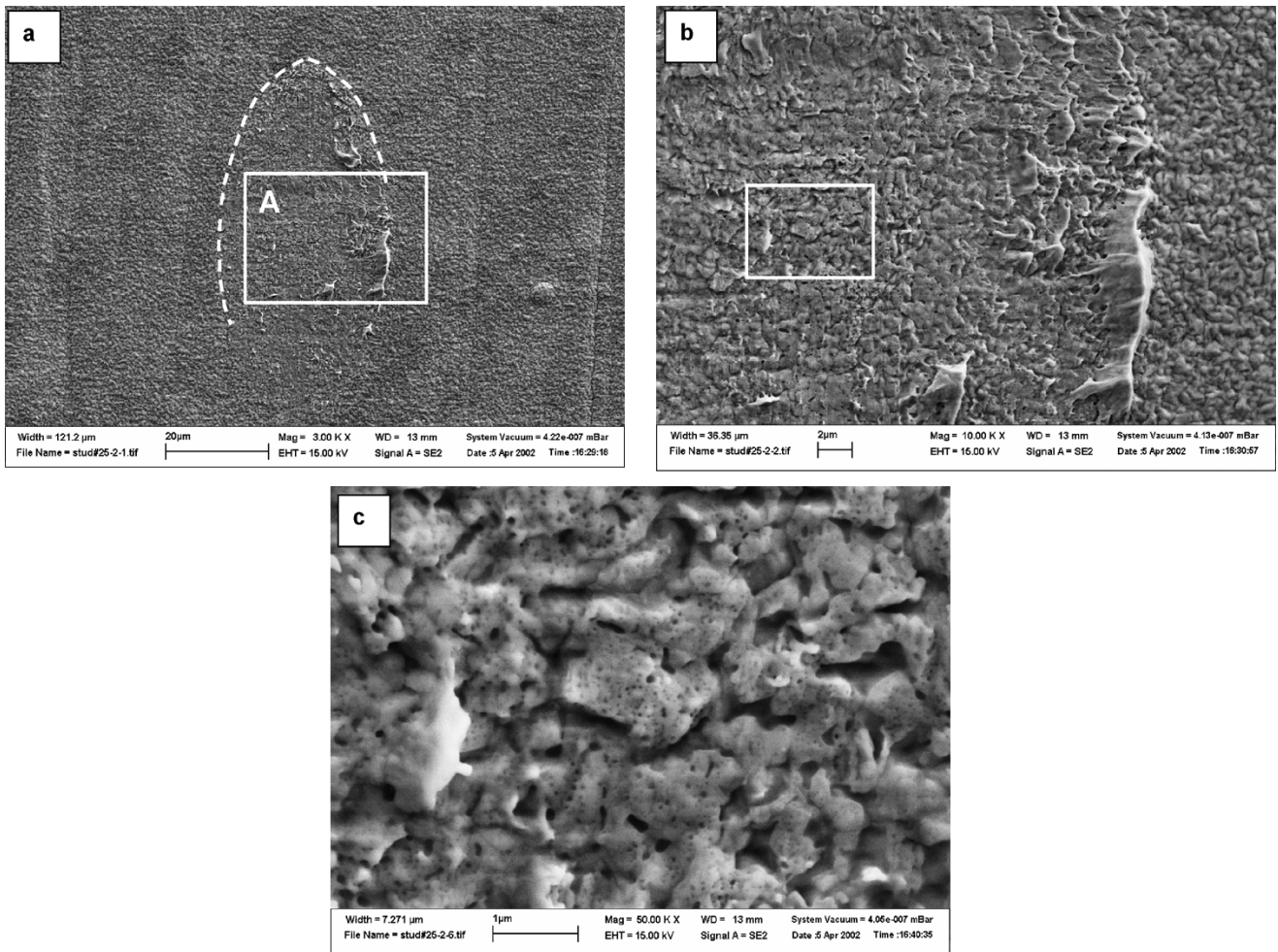


Fig. 5. (a) Footprint of a bond made at 362 °C and 55 gf force without ultrasound: the maximum width and peel force of the bond was about 33  $\mu\text{m}$  and 8.0 gf, respectively. Dashed line indicates part of the footprint perimeter. (b) Details of the highlighted area A in (a) showing microwelds at the lateral periphery of the bond. (c) Detailed of enclosed area in (b) showing microwelds in the central region of the bond.

asperities is not sufficient to initiate metallurgical bonding. The increase of substrate temperature to 262 °C started to produce microwelded regions (Fig. 4) probably due to the compounded effect of thermal desorption and higher substrate deformation. These microwelds were prevalent in the peripheral regions of the bond, where shear stresses were the highest, which is consistent with the observations in hot pressure welding that surface extension by shear stress is much more effective in breaking up surface films and hence initiating metallurgical bonding.

### B. Effect of Temperature

Increasing temperature promoted metallurgical bonding not only by increasing deformation, but also by directly reducing surface contaminants. This is consistent with the observation that, the bonds were stronger at a substrate temperature of 362 °C (Fig. 5) than that at 262 °C (Fig. 4). This improved bonding at higher temperature was also observed in Au wire ball bonding and has been attributed to the reduction of surface organic contamination on the Au surface as a result of thermal desorption [22]. For example, based on an Auger electron spectroscopy (AES) analysis, Jellison [22] reported that 12 h heating in air at 300 °C reduced the level of organic surface contamination of the as-received Au substrate by 90% while

heating at 235 °C did not show significant effect. However, in microelectronic packaging, the bonding temperature is usually limited to 175 °C to avoid thermal damage to organic substrates, packaging materials, laminates and sensitive chips. This is the reason why thermocompression bonding (where only increased bonding force and substrate temperature but no ultrasound are used) is seldom used in microelectronics today, and has been replaced by thermosonic bonding [1].

### C. Effect of Ultrasonic Energy

Comparing Fig. 2 and Fig. 3 with Fig. 6, it is evident that the application of ultrasonic energy promotes metallurgical bonding. At the outset, it could be argued that the ultrasonic energy causes higher macro deformation by which it promotes bonding. However, further observations and comparisons indicate that this may not be the case.

- 1) With the application of ultrasonic energy, metallurgical bonding was mainly at the end of the long axis of the footprint (Fig. 6), while bonding was at the lateral peripheral regions in the absence of ultrasonic energy (Figs. 4 and 5). This indicates that ultrasonic vibration produced a different pattern of bond initiation.

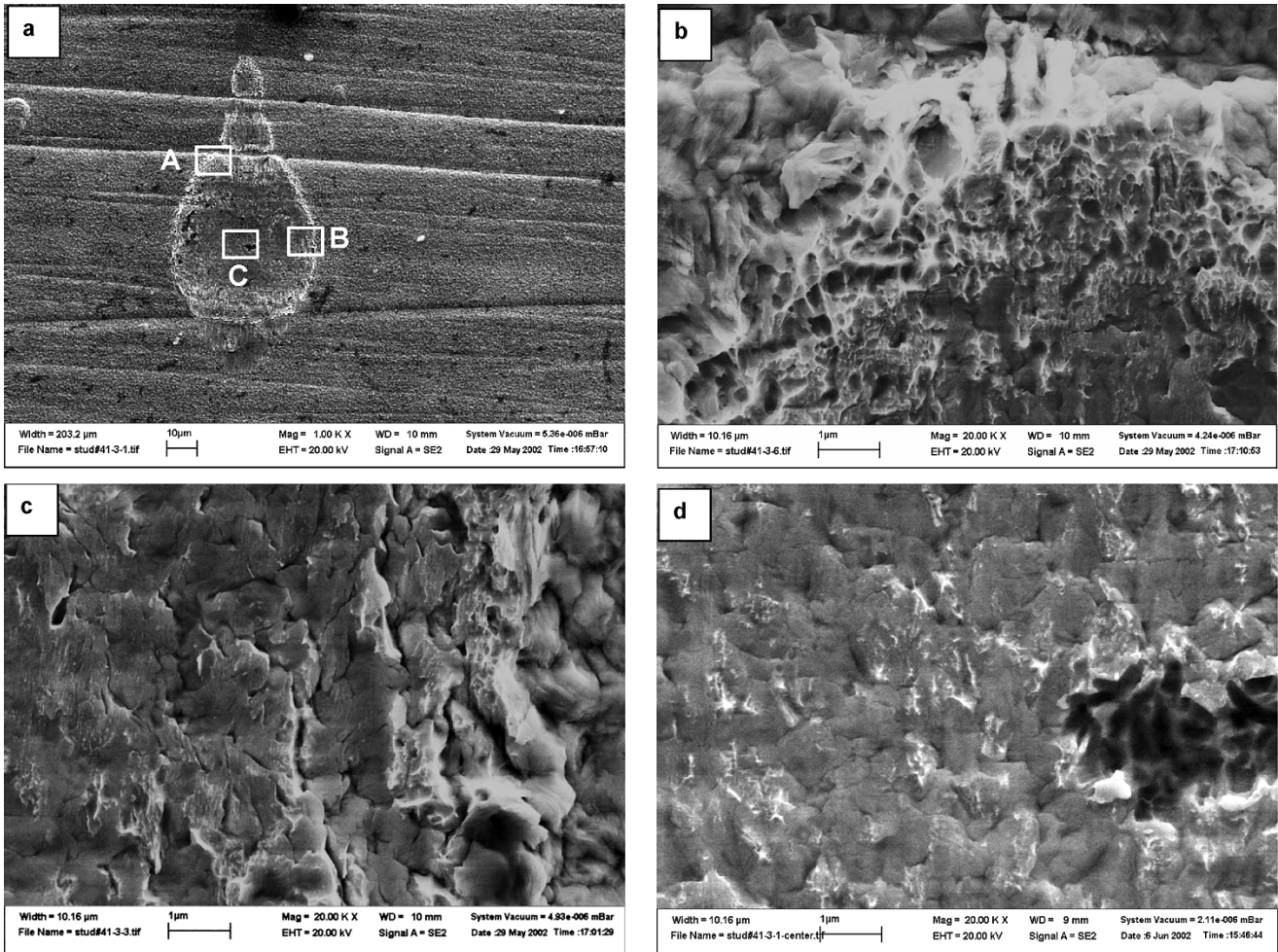


Fig. 6. (a) Footprint of a bond made at 23 °C, force of 35 gf and ultrasonic power of 1 W: the maximum width and peel force of the bond was about 47  $\mu\text{m}$  and 5.2 gf, respectively. (b), (c), and (d) Details of the enclosed areas A, B, and C in (a) showing microwelds.

- 2) Ultrasonic vibration also promoted metallurgical bonding at the footprint center [Fig. 6(d)], where there was little shear deformation or metallurgical bonding observed in the absence of ultrasonic energy (Figs. 2 and 3). This may indicate the occurrence of interfacial sliding [11] since other mechanisms involving shear deformation and microslip would only result in bonding at the peripheral regions. Thermal desorption would not be a factor in this case because of very low substrate temperature.
- 3) The observation in this work that increasing bonding force reduced metallurgical bonding at both the periphery and center is consistent with the observations by Mayer [23] that excessive bonding force would reduce interfacial sliding and hence bond strength by damping the relative movement between the wire and substrate. In other words, the correlation of bond quality and deformation may not be possible [13], which disagrees with the prediction of the deformation theory. A higher bonding force generally requires higher ultrasonic power [23] to achieve adequate bond strengths.

The above discussion points to the conclusion that ultrasonic energy promotes bonding by mechanisms other than deformation-dominated. As suggested by Murdeshwar *et al.* [5] and later by Mayer *et al.* [23], interfacial sliding during ultrasonic

bonding could play a significant role in the dispersal of the surface films and promote bonding. The observations of the initiation and the growth of metallurgical bonded regions are schematically shown in Fig. 7. At low ultrasonic energy, metallurgical bonding initiates mostly at the ends of the long axis of the bond with minimal bonding in the central region. With increase in ultrasonic energy bonded regions grow initially along the periphery of the bond, but move gradually into the center. Higher ultrasonic energy and/or longer bond time not only promotes the growth of bonded regions into the bond but also increases the density of microwelds. Increasing bond time could promote bonding especially when the ultrasonic power is low, presumably because the removal of surface containments (i.e., the surface cleaning) is a time dependent process [7], [11]. Increasing bonding force would have the opposite influence compared with increasing ultrasonic energy as already discussed.

## V. CONCLUSION

A study was performed on the initiation of metallurgical bonding (characterized by the presence of microwelds between the wire and substrate) in Au wire crescent bonding. Bonding parameters, such as ultrasonic power, bonding force, bond time, and substrate temperature, were designed to produce underdeveloped crescent bonds so that wire lift-off occurred in

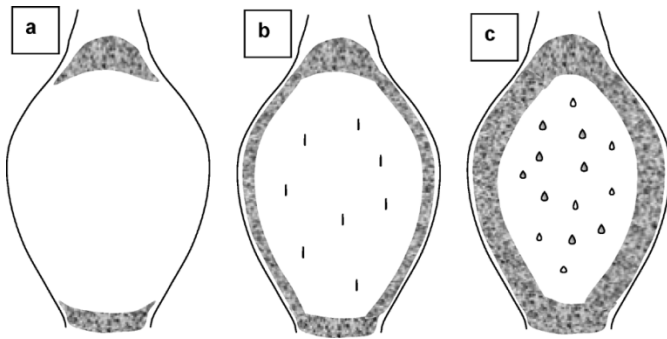


Fig. 7. Schematic showing the initiation and growth of the bonded regions as increasing ultrasonic energy: (a) bonding initiation at the ends of the long axis of the bond, (b) bonding along the periphery of the bond, and (c) growth of the bonded regions toward the center.

peel testing. The morphological features of the wire footprint left on the substrate after peel testing were studied using scanning electron microscopy and compared to the peel strength obtained. The major observations are summarized as follows.

- 1) Metallurgical bonding mainly initiated at the lateral peripheral regions (close to the perimeter) of the wire bond in the absence of any ultrasonic energy. The region of best bonding corresponds to the location of highest shear deformation between wire and substrate at the interface. This shear deformation compounded with the effects of bonding force and substrate temperature causes interfacial extension and probably disrupts surface films and exposes fresh metals for bonding.
- 2) At high substrate temperatures, metallurgical bonding also initiated at the bond central region and may be due to direct reduction of surface contaminants by thermal desorption.
- 3) Ultrasonic vibration played a predominant role in wire bonding, producing different patterns of bond formation compared to the bonds made without ultrasound. This appears to indicate that the application of ultrasound in wire bonding introduced other mechanism(s), such as interfacial sliding, as opposed to pure deformation because of ultrasonic softening.

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