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ANALYSIS AND EXPERIMENTS OF BALL DEFORMATION FOR ULTRA-FINE-PITCH WIRE BONDING

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This paper discusses ultra-fine-pitch bonding on a 50-μm bond-pad-pitch platform using ϕ23-μm gold wire. A technique for the bonding process and the bonding tool design was developed using the finite element method. It was possible to simulate and analyze the variation in the plastic deformation of ball bond when it was subjected to different loading conditions and capillary configurations. The analysis indicated that the critical bonding tool dimensions and bonding process parameters such as free air ball consistency and bonding force played critical roles in reliable bond deformation. A wire diameter of 23 μm with a capillary hole size of 28–30 μm would be robust for a mass production environment. A diameter of 32–33 μm is recommended as the average size of the free air balls for 50-μm bond-pad-pitch bonding using the ϕ23-μm gold wire. Based on the results obtained from the analysis, special bonding tool configurations were designed and fabricated. Actual bonding was performed to further validate the simulation results with experimental bonding responses. Comparison of the simulation results with the experimental data indicated that the actual ball size (38.5 μm) was approximately 3% larger than that (37.4 μm) obtained from the simulation.

1. Introduction

Most devices made in 1996 had low pin-counts, and the bonding-pad pitch for ball bonds was in the 100- to 115-μm range. However, 90-μm pitch was in production in 1996 and 80-μm pitch processes were becoming robust. Such bonds were made with bottleneck capillaries to avoid displacing adjacent bond wires. Bonds with pitches < 70 μm, as well as with finer wire diameters were more subjected to wire-sweep failures during plastic moulding.[1]

Ninety-five per cent of all integrated circuit (IC) packages use peripheral wire bond interconnects as means of providing I/O to the die.[2] The demand for increased computing power and more complex IC devices with increased functions per chip results in higher I/O count packaging. With the shrinkage in IC size and the decrease in pad pitch, the trend is moving from the current fine-pitch mass production to an even lower pad pitch, such as 50 μm or 40 μm.

50-μm bond pad pitch was first introduced in early 1998. Initial volume 50-μm bond-pad-pitch production has materialized at some IC assembly houses. Mass volume production is expected in the near future. Leading edge wire bonding has broken the 50-μm pitch barrier. With the continuous development of the wire, capillary, and mould compound in synergy with wire bonder and auto mould systems, 35-μm ultra-fine pitch for mass production is also feasible in the future. The overall challenges associated with developing a sub-45 μm pitch process are similar to those of a 50-μm process but amplified.[2,3]

Given the tight constraint to produce smaller ball deformation in a repeatable manner, the bonding process and the bonding tool design become more complex. The problems associated with open wire, bond liftoff, surface contamination, etc. have now become more sensitive and more difficult to control.

Meanwhile, the term finite element method (FEM) was first used by Clough in 1960 in a paper on plane elasticity problems. The ideas of finite element analysis (FEA) go back much further to the early 1940s in the applied mathematics literature. The FEM is a numerical analysis technique that solves the governing equations of a complicated system through a discretisation process to obtain approximate solutions to problems posed in every field of engineering. It is a powerful tool for the numerical solution of a wide range of engineering problems, including deformation and stress analysis of aircraft, building, automotive, and bridge structures, filed analysis of heat flux, fluid flow, and so on.[4–7]

The major advantage of the FEM is that it can solve virtually any engineering problem for which a differential equation can be written. The major disadvantage of the FEM is that it is somewhat complex.[8]

Standard solid mechanics based finite element tools are used extensively within the electronic packaging community to calculate stress in solders owing to in-service thermal loads for reliability predictions. Generally, these models assume that the electronic component, joint and board are free from defects, such as stress-induced cracks and voids, which originate during the reflow process.[9] Nonlinear FEA has been conducted to evaluate the sensitivity of underfill properties on reliability of flip chip on board assemblies.[10] The viscoplastic Anand model has also been applied in finite element simulation of stress/strain responses in solder joints for electronics assemblies.[11] The thermal response and the thermal resistance of a chip-face-down plastic ball-grid-array package have been characterized both by numerical finite element simulation and experimental measurement.[12] FEA has also been carried out for evaluation on solder joint reliability of ceramic column grid arrays.[13]

Although the FEM has been utilised to study various problems in electronics packages, little has been done for the ultra-fine-pitch wire bonding.

In this study, a technique for the ultra-fine-pitch wire bonding process and the bonding tool design was developed using the FEA. The main objective was to establish the correlation between ball deformation and various critical capillary dimensions, bonding conditions to achieve the required ball size for a 50-μm bond pad pitch through the FEA. Based on the given bond pad opening, the targeted average ball size was set at 38 μm using a ϕ23-μm gold wire.

Based on the results obtained from the FEA, special bonding tools were designed and fabricated. Actual bonding was performed to further validate the simulation results with experimental bonding responses.

2. Capillary Design Considerations

The development of a new packaging technology for ultra-fine pitch application has made the capillary design as one of the most important critical parameters that influence the final bonding capability results.[14] Over the years, the constant push for smaller bonds has driven the capillary venders to develop new technologies to manufacture smaller capillary dimensions. Mass production of such capillaries demands state-of-the-art ceramic manufacturing know-how.[15]

Although 50-μm bond-pad-pitch bonding has not been utilised in mass production, many companies are aggressively running evaluation and even making prototypes for such applications. The anticipated problem with wire sweep during moulding has forced many companies to revert back to larger wire size ranging from 23 μm to 25 μm.

However, various problems arise on using a larger wire diameter on a smaller bond pad opening. For a wire diameter of 23 μm, the minimum capillary hole size needs to be at least 28 μm. Considering a tolerance of $+2/-0$ μm, the minimum chamfer diameter needs to be at least 34 μm for a reliable stitch bond. Such a chamfer diameter size will make it difficult to produce an average ball size of 38 μm for 50-μm bond-pad-pitch bonding.

Considering that the smallest free air ball size at 1.4 times the wire diameter that the current bonders can attain consistently, the deformed ball size cannot be further reduced.

To address the above-mentioned issues, a unique capillary configuration has been developed to contain the amount of gold squashed out during bonding. Together with high-precision bonding force control on the bonder, such design has proven to be able to control the desired mashed ball and hence reduce the ball size to a smaller dimension.[16,17]

The effect of such capillary design is illustrated in Fig. 1. Usually, small and large diameter wires produce small and large mashed ball diameters respectively. With the specially designed capillary configuration, a small mashed ball diameter can be produced using wire with a large diameter, which is a solution to avoid the anticipated problem with wire sweep.

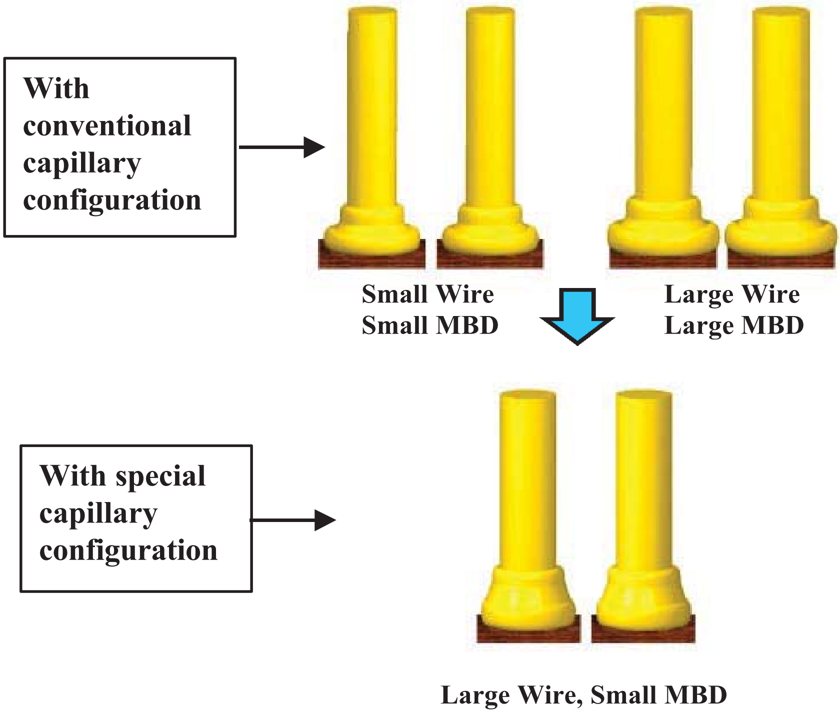

Fig. 1. A special capillary configuration produces small mashed ball diameters (MBDs) with large wires.

A serious problem for ultra-fine-pitch application is the tip breakage occurrence during actual bonding. The introduction of a new ceramic based zirconia composite material with the integration of a slim-line bottleneck design made the capillary strong. The application of the moulded slim-line bottleneck design was made possible by ceramic injection moulding using the new material. The new material has exhibited significantly higher bending strength value (2400 MPa) compared with that (850 MPa) of the standard high-density material. The 4°, 8° and 11° face angles performed better compared to 0° in terms of actual bonding results.[14]

3. Considerations for Simulation and Experiments

Unlike bonding on non-fine pitch devices, which can accommodate a wide range of ball size variation due to the large pad opening, bonding on ultra-fine-pitch devices requires the ball size to be controlled within a much tighter tolerance. The reduction in the bond pad pitch requires the capillary tip dimensions to be reduced significantly to prevent the capillary from any interference with the adjacent wires during bonding. Given such tight bonding process requirements, optimal machine performance and capillary designs are necessary to achieve a reliable bond process control.

In ultra-fine-pitch bonding, the most difficult task is to obtain small ball deformation consistency and reliable stitch formation. For a typical 50-μm bond-pad pitch, the bond-pad opening is in the range of 40 μm to 44 μm. Considering the ball placement accuracy that current bonders can attain, the eventual ball size needs to be controlled within an average of 38 μm to 40 μm.

Although it is known that the combination of various critical bonding parameters and capillary dimensions has significant effects on the ball deformation, it is difficult to establish the individual effects of these parameters on the ball deformation. Simulation using the FEM with actual bonding experiments can help to overcome the difficulties and shorten the development time.

The plastic deformation of a gold ball was simulated by using a software package "MARC". The considerations include:

- Wire and capillary. For the simulation and actual bonding, a ϕ23-μm gold wire and a ceramic based zirconia composite capillary were used.

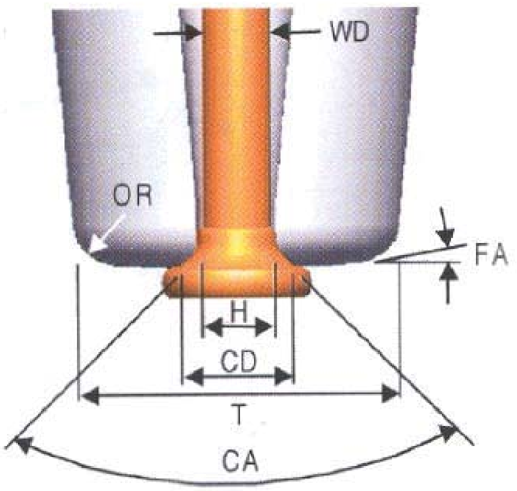

Fig. 2. Critical capillary dimensions: hole diameter (H), chamfer diameter (CD), chamfer angle (CA), face angle (FA), outside radius (OR), and tip diameter (T).[18]

- Critical machine setting, which can affect the ball deformation. These parameters include free air ball diameter, bonding force and time, bonding temperature, search speed (constant velocity from the search height), etc.
- The ultrasonic displacement waveform obtained from a laser vibrometer with the actual bonding parameters.
- Bond pad. For the chip metallisation, it was considered to be an aluminium layer.
- Critical capillary dimensions, which can affect the ball. These dimensions include hole diameter, chamfer diameter, chamfer angle, face angle, outside radius, and tip diameter, as shown in Fig. 2.

Capillary dimensions directly affect the ball bond formation. Hole diameter is typically around 1.3 to 1.5 times the wire diameter. Chamfer diameter aids in the determination of targeted mashed ball diameter. Chamfer angle provides a certain amount of flatness in the formation of mashed ball diameter. Typical chamfer angle is 90°. Capillary dimensions that directly affect the stitch bond formation are tip diameter, outer radius, face angle, chamfer diameter, etc. The sintered capillary has a well-defined surface finish with its specified dimensions injection moulded to its net shape using ceramic injection moulding technology.[18]

4. Results and Discussion

Examples of the analysis of the ball deformation are shown in Fig. 3. The analysis revealed that the critical bonding tool dimensions and bonding process parameters such as free air ball consistency and bonding force played critical roles in reliable ball deformation. The chamfer angle and the chamfer diameter of the capillary have significant impacts on the ball deformation. The combined effect of the chamfer angle and the chamfer diameter can result in a smaller ball size by containing the amount of gold inside the capillary during impact and eventually restricting the gold squashed out during the bonding process.

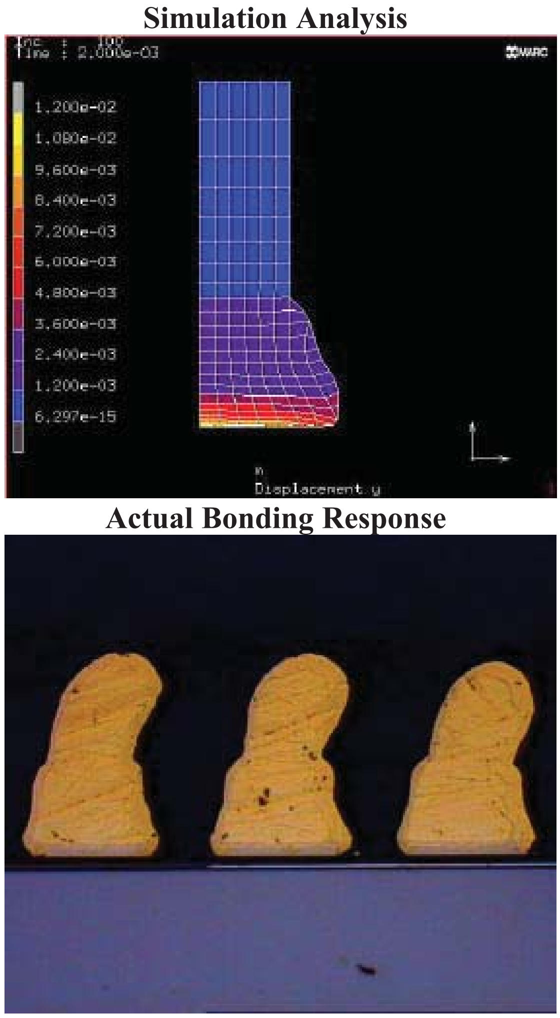

Fig. 3. Examples of the simulation and actual bonding results.

Although the hole size of the capillary can influence the final ball size, this is normally taken care of by using the smallest possible hole size for a particular wire diameter. In this case, it was decided that a wire diameter of $\phi 23$ μm with a capillary hole size of 28–30 μm would be robust for a mass production environment.

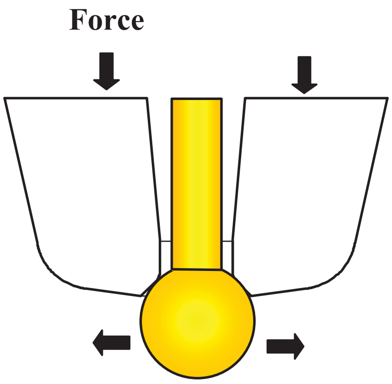

Fig. 4. A large free air ball can result in excessive gold squashed out during bonding.

For ultra-fine-pitch bonding, the free air ball diameter plays a critical role in the deformed ball size, ball height, and the bond quality. Too large a free air ball can result in excessive gold squashed out during bonding instead of containing the ball inside the capillary as shown in Fig. 4. In addition, a thicker ball height can affect the ultrasonic energy transfer from the capillary to the bond surface resulting in less intermetallic diffusion. A diameter of 32–33 μm is recommended as the average size of the free air balls for 50-μm bond-pad-pitch bonding using ϕ23-μm gold wire.

Besides those factors mentioned, machine parameters such as bonding force and search speed can influence the final geometry of the ball size. As shown in Figs. 5 and 6, a lower bonding force results in a smaller ball size, which is a critical requirement for ultra-fine-pitch bonding, but produces a thicker ball height. The ideal situation would be to have as low a bonding force as possible to ensure that the ball is not over deformed.

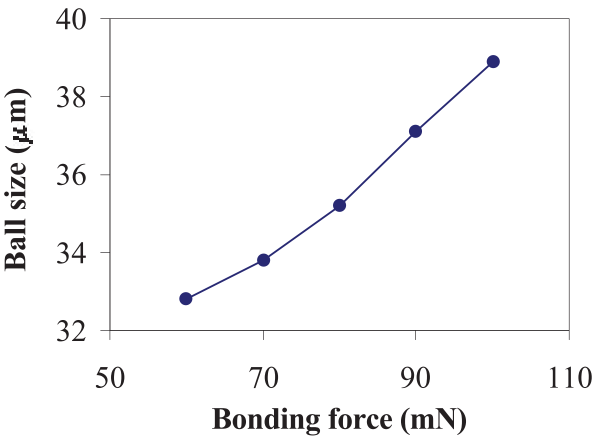

Fig. 5. The relationship between ball size and bonding force obtained by the simulation. A lower bonding force results in a smaller ball size.

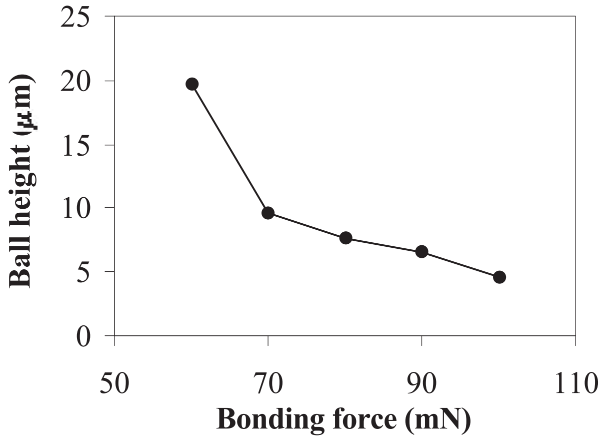

Fig. 6. The relationship between ball height and bonding force obtained by the simulation. A lower bonding force produces a thicker ball height.

During the formation of the ball bond, the bonding force actually deformed the free air ball to a ball size approximately 7% smaller than the required ball size. The final ball size was achieved through the combination of bond force and power. In fact, various ultra-fine-pitch DOEs (design of experiments) have been conducted and the results have also indicated that bond force has a more influential role in the formation of the eventual ball size while the ultrasonic energy helps to form the intermetallic layer.[19]

The effects of the various capillary dimensions and free air ball variation on the ball deformation

Table 1. Relationships of capillary dimensions, free air ball, and ball deformation.

	Ball Size	Ball Height
Hole diameter	●●	●
Chamfer angle	●●●	●●●
Chamfer diameter	●●	●
Free air ball diameter	●●●	●●●
Bonding force	●●●	●●●

●●● Strong relationship
●● Moderate relationship
● Slight or possible relationship

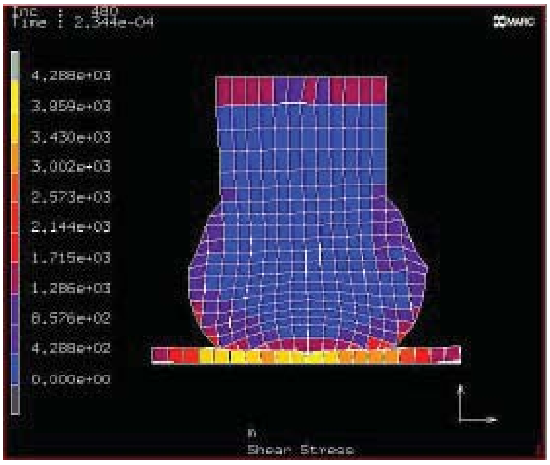

Fig. 7. Stress distribution with the new capillary design.

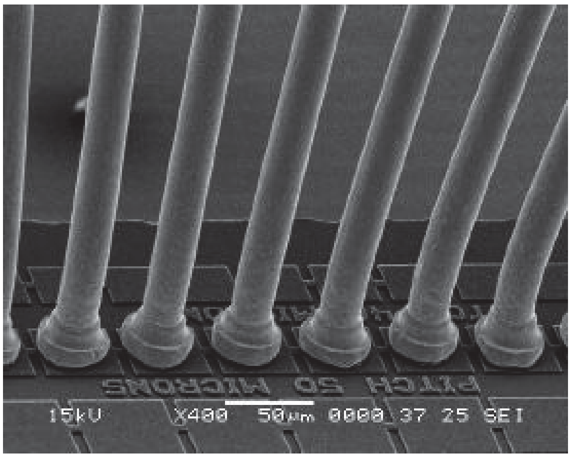

Fig. 8. An example of actual bonding responses of ultra-fine-pitch bonding on a 50-μm bond-pad-pitch platform using ϕ23-μm gold wire.

for ultra-fine-pitch bonding using the new capillary design can be summarised as shown in Table 1.

Stress analysis was also conducted as shown in Fig. 7 to evaluate the stress level on the metallisation between a standard capillary design and the new design. No significant difference was observed through the simulation. This observation was further verified with the cratering test with no sign of craters or oxide cracks during the visual inspection.

Experimental verification on the analysis results was carried out on an ESEC 3008 wire bonder, software version 53.0 using a QFP (quad flat pack) 208 copper lead frame with silver coating and using a ϕ23-μm wire size. Figure 8 shows an example of actual bonding responses.

Table 2. Comparison of simulation and actual bonding responses.

	Simulation	Actual Bonding
Device	QFP 208	QFP 208
Capillary Type	DFXE-28XX	DFXE-28XX
Wire Diameter, μm	23	23
Average Ball Size, μm	37.4	38.5
Average Ball Height, μm	8.0	8.5

Comparison of the simulation results with the experimental data indicated that the actual ball size (38.5 μm) was approximately 3% larger than that (37.4 μm) obtained from the simulation, as shown in Table 2. This deviation could be due to the free air ball deviation, bonding force variation, tolerances of the capillary and the frequency of the transducer, which were not taken into consideration during the simulation.

An important aspect in ultra-fine-pitch bonding is the surface quality of the metallization. Since only little deformation is allowed, there is a limited possibility to rub away contamination or to break through layers of oxidation and contamination.[20] This also needs to be taken into consideration in the future's research.

5. Concluding Remarks

Although wire bonding has been a well-established technology for many years, the bonding tool design and the devices become more complex especially when bonding at the ultra-fine-pitch range. The simulation analysis for design concepts can be used to optimise the capillary design configuration, which helps to shorten the development time. By this analysis, behavior of various bonding factors can also be analyzed and optimized. The eventual target is to provide a standard template to assist engineers to understand potential bonding related problems.

Future research is to understand the effects of pad metallisation, intermetallic diffusion, transducer type, capillary tolerances, etc. which have not yet been taken into consideration in this study.

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