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Choosing capillaries for fine pitch bonding

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Optimized wire-bonder capillary designs improve wire bond quality and provide stronger bonds, particularly for applications where the bonds are for <100µm pad pitches or where conditions dictate wire bonding at reduced temperatures. Software analysis has made possible new capillary designs that improve robustness and increase the process capability of high-frequency bonding by providing a larger process window.

With smaller wire bonds a critical factor in process development comes the need to maintain and improve the strength of the smaller welded cross-section of each bond. To maintain an optimum process, each decrease in wire bond size also requires the selection and qualification of a new bonding capillary, with design features sized appropriately for the new application.

For example, fine pitch packages — <100µm pad pitch — present unique wire bonding challenges [1]. Consider wire bond loops in a ball grid array (BGA) package (Fig. 1): as the loop profile approaches the second bond, it must be high enough to provide clearance and avoid shorting to the power or ground bus bar. Fine-pitch quad flat packs (QFPs) require very long, low loops, and achieving strong second bonds is more difficult because of the narrow lead width.

Combining these complex loop shapes with smaller, finer-pitch wire bonds requires the use of smaller-diameter wire [2] and bottle-necked capillaries with smaller tip diameters. These material and tool modifications are required to eliminate the possibility of interference between the capillary, as it is bonding, and adjacent wires that already have been bonded. Smaller wire bonds have smaller cross-sectional areas with correspondingly lower strengths, however, and this can cause important reliability concerns.

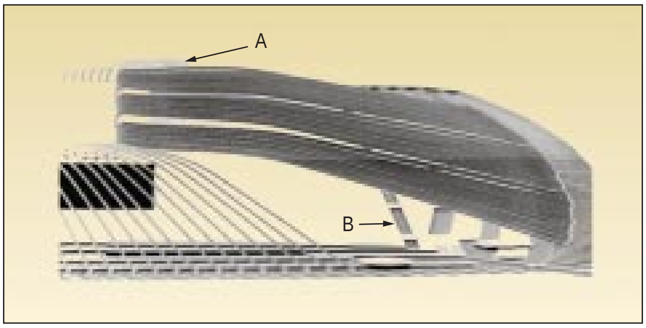

Figure 1. Worked loops in a BGA showing a) flat length parallel to the die surface, and b) standoff above power and ground bus bars.

In addition, new BGA laminate packages require bonding at lower temperatures, below the glass transition temperature (Tg), to avoid laminate plasticity. Lower bonding temperature generally has a negative effect on the strength and

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reliability of the second bond, because the principal bonding mechanism is diffusion controlled, and the diffusion rate is always lower at lower temperature.

Capillary geometry effects

For a bottle-necked capillary with tip dimensions appropriate for a 70µm-pitch bonding process, hole and chamfer diameters vary depending on the process requirement. Use of such designs, with tip diameter reduced to less than half the standard capillary diameter, has been common practice for several years.

Issues associated with interference between the capillary and adjacent ball bonds have been resolved by 3D modeling techniques and extensive experimentation. Because BGA packages require lower bonding temperature, however, new issues have emerged.

Conventional bottle-necked capillaries have been unable to provide a robust bonding process at lower bonding temperatures (125–150°C). New capillary designs — with their moment of inertia optimized for use with higher frequencies, and bond heads equipped with adaptive high-frequency ultrasonic generator systems — provide stronger, more uniform bond strength in both *x* and *y* bonding directions and at the lower bonding temperatures required by BGA packages.

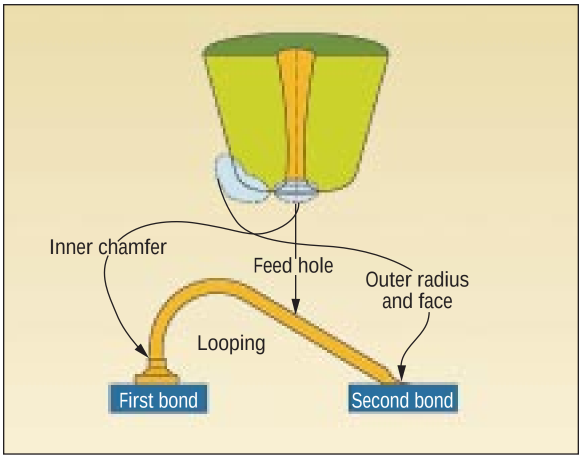
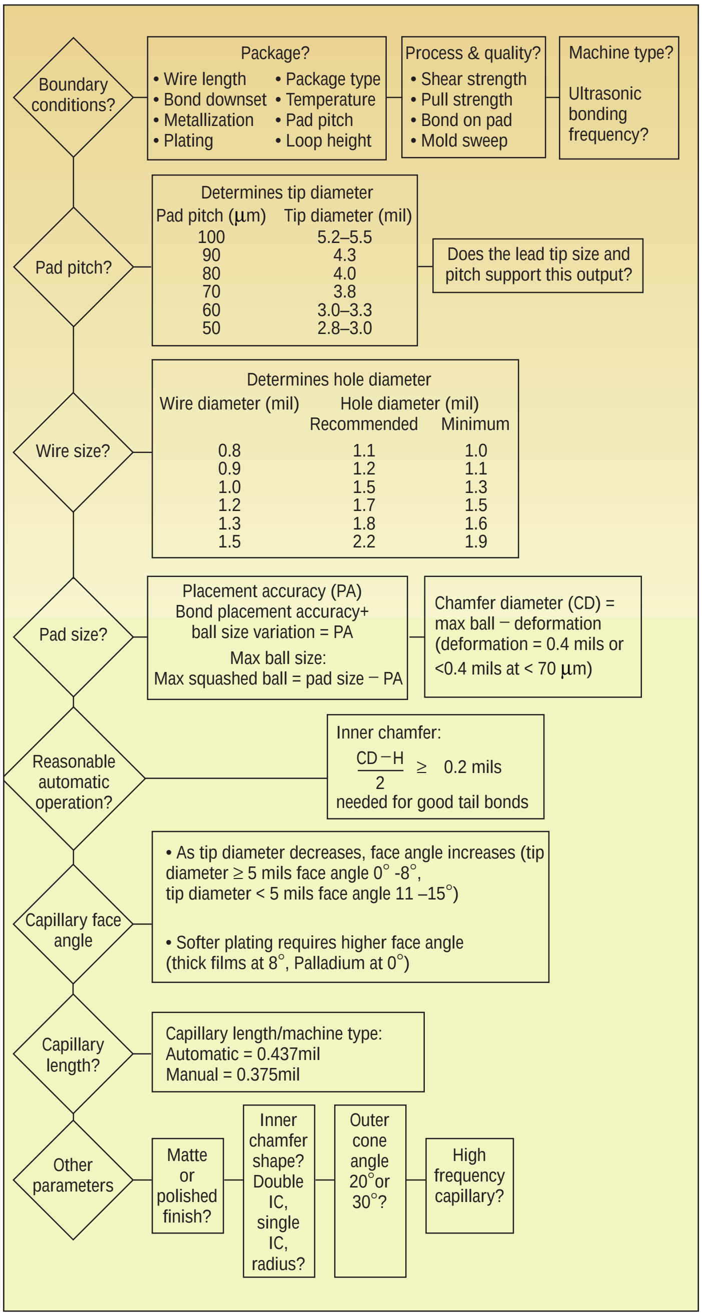


Figure 2. Capillary features and their effects on the bonding process.



Determines tip diameter

Pad pitch (µm)	Tip diameter (mil)
100	5.2–5.5
90	4.3
80	4.0
70	3.8
60	3.0–3.3
50	2.8–3.0

Determines hole diameter

Wire diameter (mil)	Hole diameter (mil)	
	Recommended	Minimum
0.8	1.1	1.0
0.9	1.2	1.1
1.0	1.5	1.3
1.2	1.7	1.5
1.3	1.8	1.6
1.5	2.2	1.9

Figure 3. Capillary selection flow chart.

A capillary has many significant features and properties that affect the bonding process (Fig. 2):

- Its tip shape and geometry give the bond its size and shape.
- The mechanical properties of the capillary affect the transfer of energy from the bonder's ultrasonic transducer into the weld interface, developing a high-strength intermetallic bond.
- The stiffness of a capillary plays an important role in preventing undesirable bending modes that affect energy transfer during bonding.
- The surface of the capillary provides the boundary conditions and friction affecting deformation.

Feature	Effects
Feed hole	Wire centering Looping
Inner chamfer	Ball bond centering Ball bond strength Bond size Looping Tail bond strength
Face angle & outer radius	Second bond strength Looping
Tip diameter	Second bond strength Pitch

In general, these features can be grouped into two categories: those determined by the constraints of the package, and those determined by application-specific bond quality requirements.

As discussed previously, computer-aided tools have been developed to model the possible interference between the capillary and adjacent bonds in fine-pitch applications [3]. These software tools use solid modeling techniques to determine whether interference will occur between the capillary and an adjacent ball or wire on a package. The model re-

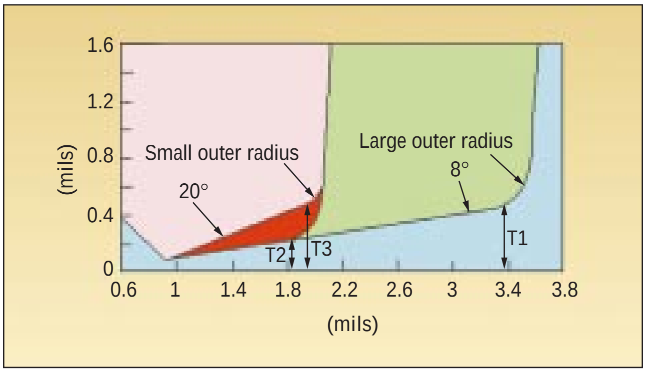


Figure 4. Comparing 4-mil vs. 7-mil capillary tips and 8° vs. 20° face angles.

quires input of wire and package dimensions and determines suitable capillary and ball dimensions. The results allow a process engineer to select capillary dimensions, including tip diameter, hole diameter, chamfer diameter, and bottleneck height, that are required by the package constraints.

Rules of thumb

Using Capdesign software, a 3D modeling tool developed by K&S Micro-Swiss for packages with similar pad pitch and bond pad size, often results in clear trends. These trends can be expressed as “rules of thumb” and are applicable for choosing the tip, hole and chamfer diameter dimensions without requiring additional use of the software.

Figure 3 shows a flow chart for selecting capillary dimensions based on these rules of thumb. It shows that:

- Boundary conditions can affect the process — for example, package type (BGA vs. QFP) may have a strong effect on the bond temperature or loop shape requirements. These issues must play a role in initial design considerations.
- Bond pad pitch determines tip dimension.
- Common wire sizes determine capillary hole diameter.
- For a given placement accuracy (PA) — bonder accuracy plus ball size variation—there is a maximum squashed-ball size that will fit on a bond pad. In addition, maximum ball size is used to calculate capillary chamfer diameter (CD) for high shear strength ball bonds.
- The relationship between CD and the hole diameter (H) provides a measure of inner chamfer and a check of reasonable automatic bonding.
- Capillary face angle is application specific and often requires evaluation of several samples to determine the optimum design. However some rules and generalizations do apply.
- Different wire bonders require different capillary lengths. Using the incorrect capillary length is a setup problem that may result in the capillary not being perpendicular to the work surface during bonding. At best, perpendicularity problems result in highly variable bonds. At worst, they cause defects.

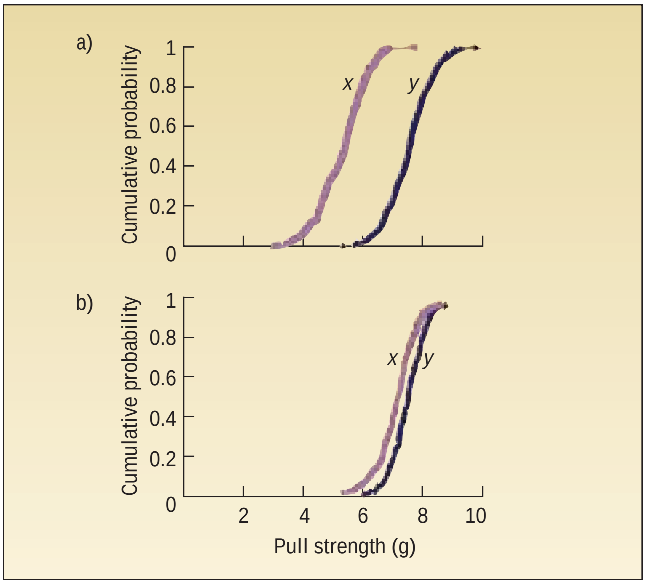


Figure 5. Wire bond pull strengths from a) a standard capillary, and b) a high-frequency capillary.

In addition to these rules of thumb, there is a host of other conditions to consider (see bottom row in Fig. 3).

Figure 4 shows a quarter-section view through several possible capillary tip configurations. For a standard capillary, producing a full-strength second bond with thickness T1, the tip diameter and face angle might be 7mil and 8°. From Fig. 4, one can infer that a small 4mil tip diameter capillary with the same face angle would produce a bond that is half the thickness of the standard capillary (i.e., point T2 in Fig. 4). This bond would produce lower pull strength values than the thicker bond because its cross-section is smaller. In general, when capillary tip diameters are reduced, the face angle of the capillary is increased to maintain higher pull strength values (i.e., point T3 in Fig. 4).

In addition, as the tip diameter is reduced, the outer radius — the radius between the capillary face and the cone angle — is also reduced. Reducing the outer radius increases the length of the face, maximizing bond length for higher pull strength.

Bonding at reduced temperatures

Bonding at reduced temperatures presents additional challenges to wire bond integrity. Acceptable first ball-bond shear strength values can normally be achieved by increasing ultrasonic energy. The strength of the second bond, however, is often adversely affected, because the dominant mechanism forming the second bond is diffusion, and the rate of diffusion is reduced at lower temperatures.

When we analyze the second bond pull strength for a QFP bonded at 180°C, there is a significant difference in pull strength between the *x* and *y* bonding directions (Fig. 5a). In this package, the *y*-direction leads are aligned with the ultrasonic displacement, and the *x*-direction leads are perpendicular to the displacement. When we used a new high-frequency capillary design at 180°C, however, pull strengths were stronger and more equivalent (Fig. 5b).

The new design mentioned above has a different configuration above the bottle-necked area. This capillary is stiffer, to reduce displacement associated with capillary rocking and bending modes caused by ultrasonic vibration. In addition, it is easier to insert and remove from the transducer clamp. The overall result is improvement in the consistency of the second bond, changing the pull strength population from a bimodal to a normal distribution. Commercialized in 1997, this

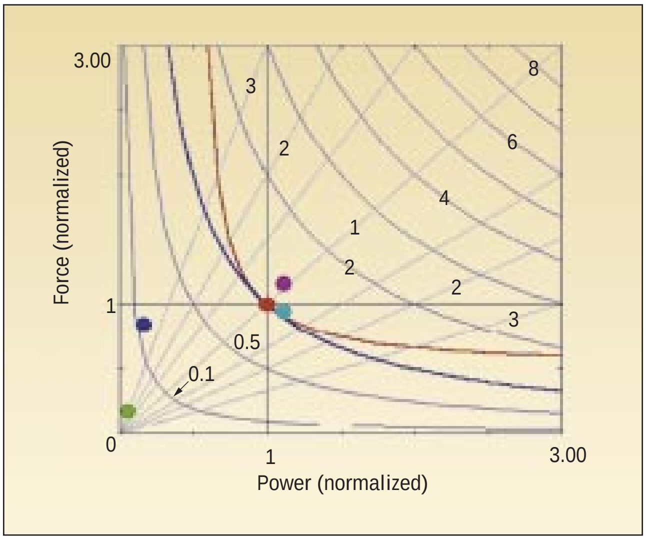


Figure 6. Response surface comparisons of five different capillaries (represented by the dots). The “best” is the dot furthest out on the x and y axes. In arbitrary units, the curved lines define the same process window area and the straight lines radiating from the lower left are process window aspect ratios. (Source: derived from Process Window Analyzer software)

design is being used by several manufacturers for fine-pitch (<90µm) applications.

Second, then first

In packaging, there is a significant interaction between the second wedge bond and the first ball bond. A bad second bond can result in a badly shaped or sized ball being formed prior to the next first bond. The result will be a bad first bond on the next wire following the bad second bond. Because of this interaction, the best practice is to conduct second bond optimization experiments first, using the following caveats:

- The “tail bond” (i.e., where the wire breaks away from the completed second bond) controls the length of the short piece of wire extending from the capillary that will form the next ball. Separation of the tail bond should occur in a specific region. Fractures that occur by peeling the tail bond into the second bond weld area represent reliability risks.
- When testing second bonds, the pull test hook should be placed near the second bond. Placing it as close to the bond as possible changes the resolution of forces so that the dominant load is at the second bond; maximizing the results in this manner allows true optimization.
- Optimized second bonds provide assurance that subsequent ball bonds are not affected. However, separately designed experiments should be performed to optimize the ball bond. When conducting ball bond experiments, the responses measured should be ball shear strength and ball diameter. When these results are optimized, the average shear strength / area should be at least 5.5g / mil^2 [3].

Further optimization

Recently, K&S Micro-Swiss introduced new software — Process Window Analyzer — that normalizes and compares response surfaces of different capillaries (Fig. 6). This software makes it possible to determine which response surface has the largest and most robust working area. Comparisons can be used to identify a capillary with the largest working region (i.e., region with second bond pull strength greater than 5g). In addition, preference can be given to a capillary that requires lower bond parameters for equivalent performance. The five points shown on Fig. 6 are a comparison of five capillaries. The software shows graphically the capillary that provided the largest process window (set of process conditions with pull strength ≥5.5g).

Looping

It is desirable for a wire bonder’s programmable control parameters to serve as the dominant factors controlling loop shape. Boundary conditions, such as capillary friction, should have a minor effect on the process. Low drag capillaries, with an inner radius instead of the standard double inner chamfer, are available to minimize capillary friction. The capillary inner geometry, however, plays a secondary role in the formation of the wire loop.

The wire bonder plays the primary role in loop formation. New generation wire bonders have large libraries of standard loop shapes and capabilities. This enables them to process the latest packaging designs. Standard loop shapes include multiple low, worked, and BGA. Wires as long as 7.6mm and loop heights as low as 100µm are within their capabilities. In addition options such as CSP looping, more sophisticated BGA loop profiles, spider, and J-wire looping algorithms are available.

Conclusion

Optimized capillary designs improve wire bond quality and provide stronger bonds, even when the bonds are small and are produced at reduced temperatures. Working in concert with the wire bonder’s capabilities, new capillary designs improve the robustness and increase the process capability of high-frequency bonding by providing a larger process window. ■

Acknowledgments

Capdesign and Process Window Analyzer are trademarks of K&S Micro-Swiss.

References

1. L. Christie, et al., “Bonding BGA Packages Requires Integrated Solutions,” *Semiconductor International,* pp. 311–318, July 1988.
2. I. Hadar, “Experimental Investigation of Wire Diameter Effect on Fine Pitch Ball Bonding,” *Proceedings of Semicon Test, Assembly & Packaging,* Singapore, April 1996.
3. K. Dittmer, S. Kumar, F. Wulff, “Influence of Bonding Conditions on Degradation of Small Ball Bonds due to Intermetallic Phase (IP) Growth,” *Proceedings HDP/MCM Denver,* pp. 403–408, April 6–9, 1999.

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