As originally published in the IPC Printed Circuit Expo, APEX & Designer Summit Proceedings.

Fighting the Undesirable Effects of Thermal Cycling

Gabe Cherian
Cherian LLC
P.O. Box 1335, Sun Valley, Idaho 83353 USA

Abstract
Most electronic assemblies comprise a number of chips, packages and similar components that are attached to Printed Circuit Boards (PCBs) or similar substrates, usually using solder joints. Also most frequently, the components and the substrates are made of materials that have different Thermal Coefficients of Expansion. If such assemblies get exposed to harsh environments, such as severe thermal cycling, or to frequent power cycling, then they run the risk of having their solder joints stressed, and in some cases, the stresses can reach a level where some joints would fail. This is especially true, when the components are relatively large in size, like half an inch square or larger, and when the temperature variations are fairly large. It is well known that if the solder joints are tall, like columns, stretching between the components and the substrate, like the Solder Column(s) with Copper Tape, then the induced stresses in the joints are reduced and the assemblies can more readily survive such harsh conditions. This paper discloses some additional novel features, which enhance the performance of such column-like joints, which make such joints even better than traditional columns, and enhance the reliability and extend the operating life of such electronic assemblies. The columns in this case have an elongated cross section, and are oriented in a way that presents the lowest resistance to flexing in the direction of the thermal deformation of the assembled components. The concepts have been applied also to leaded components, by orienting their leads. The paper describes a number of such design concepts and embodiments. Some of them are already patented, while others are still patent pending.

Keywords:
Assemblies, Assemblies life, Chips, Column, Column-like joints, Cross section, Cycling, Deformation, Direction of the thermal deformation, Electronic assemblies, Elongated cross section, Enhanced reliability, Extend the operating life, Failure, Flexing, Harsh conditions, Harsh environment, Joints, Joints failure, Leaded packages, Leadless packages, Life, Lowest resistance to flexing, Operating life, Oriented, Packages, PCBs, Power cycling, Printed Circuit Boards, Reduced stresses, Reliability, Slender, Solder, Solder joints, Solder stresses, Solder joints stresses, Stresses, Substrates, Survive the harsh conditions, Survive, Tall, Tall column-like solder joints; Temperature variations; Thermal Coefficients of Expansion, Thermal cycling, Thermal deformation.

Non-Commercialism
In compliance to the Non-Commercialism Policy of IPC, I would like to limit my use of any terms that could be construed as Commercials for my products or other related products. For this reason, I will use Substitute Terms or Phrases, which are more generic for the following terms:

- **CCMD** will be referred to as Solder Column(s) with Copper Tape. These solder columns have a copper tape wrapped around their solder core, to ascertain that the solder does not ball up when heated to its melting temperature and so that the column would retain its columnar shape. Please see Fig. 7. Note: This product is not owned by me. I was instrumental in developing it while working at Raychem Corporation, but it is own now by Six Sigma, Winslow Automation, San Jose, CA. However, to follow the IPC requirements, I will refrain from repeating this word and will use the substitute phrase in its place whenever appropriate.
- **No-Wick™** are my Trademarks for my Column(s) mentioned in this paper here. I will refer to them in this paper as the Non-Wicking Connecting Column(s). These columns are designed so that the solder will adhere only to the tips of the columns and will not be allowed to wick along the stem of the columns between the tips.
- **POL™** is my Trademark for my Package(s) with Oriented Leads mentioned in this paper here. I will refer to them in this paper as Package(s) with Oriented Leads. These are packages, whose leads are shaped so that these leads would present a low resistance to bending in the direction of the expected thermal deformations. The purpose of orienting the leads this way is to reduce the risk of micro-cracking the plastic housing and of moisture migrating to the chip. Otherwise the chip might fail prematurely.
- **OSJ™** is my Trademark for my Oriented Solder Joint(s) or Oriented Starved Joint(s) mentioned in this paper here. I will refer to them in this paper as Oriented Solder Joint(s) or Oriented Starved Joint(s). These are solder joints provided on a device, like a BGA or a chip, which would be intended to be attached to another device, like a substrate. The joints are supposed to have an elongated cross-section and the joints are oriented in a way so that they would present a low resistance to bending in the direction of the expected thermal deformations. In some cases, the solder joints have a generally uniform cross section along most of their height and they could be referred to simply

as Oriented Solder Joint(s), and in other cases, the solder joints would generally look like they have an hour-glass shape more or less, in which case they could also be referred to as Oriented Starved Joint(s).

- **DAM-COLUMNS™**, for Non-Wicking Connecting Column(s) with a dam to restrict the flow of solder and to prevent it from wicking on to the stem of the columns. See Fig. 15.
- **BOND-COLUMNS™.** I will refer to such columns as the Non-Wicking Bonded Columns. See Fig. 20.

Executive Summary

I will assume that the attendees are familiar with the Thermal Cycling testing of assemblies comprising BGAs, Chips, etc, mounted on PCBs or substrates in general, as described by the appropriate MIL Specs or other similar standards. I will briefly touch on the effects of thermal cycling on such assemblies, then the effects of thermal cycling on the joints between the components, then, again briefly, talk about the Solder Column(s) with Copper Tape and their benefits. This would lead us to a brief review of the Non-Wicking Connecting Column(s). Then I will cover the main features of the Package(s) with Oriented Leads. All these reviews will give us the basic background, which will lead us to the Oriented Solder Joint(s) or Oriented Starved Joint(s), which will be the main topic for this presentation. Finally, I will conclude by answering questions from the audience.

Introduction

Around 1982-84, I developed for Raychem Corporation, Menlo Park, CA, what was called “CCMD”, short for “Chip Carrier Mounting Device” and later became known as the “Solder Columns”, which were used to attach Leadless Ceramic Chip Carriers (LCCCs) to Printed Circuit Boards (PCBs). During the rest of this paper and presentation, I will use the term “Solder Column(s) with Copper Tape” as a replacement for the abbreviation CCMD. The purpose the Solder Columns with Copper Tape was to provide “flex joints” between the LCCC and the PCB, with the hope that this would reduce the stresses on the solder joints and consequently would result in longer operating life for such assemblies and improve the reliability of systems having such assemblies. The results were very satisfying. Our first major order for the product was for $4.8 Million from ITT, who was the major contractor to build the SINCGARS radio for the ARMY. ITT determined that the Solder Columns with Copper Tape helped in passing the Thermal Cycling MIL Spec.

The Solder Columns with Copper Tape were marketed by Raychem for a few years, and then that part of the business was sold to Winslow Automation, aka Six Sigma. I understand that the Solder Columns with Copper Tape and some variations thereof are still being used nowadays, according to Raymond Kuang, Actel Corporation, main author of References 15 and 16, listed at the end of this paper.

However, the Solder Columns with Copper Tape were built for devices that have a pitch of 1.27 mm (0.050 inch), the prevalent pitch at that time. In the meantime, the electronics industry has miniaturized almost everything, including the pitch. The pitch nowadays is down to 0.50 mm (0.020 inch) or smaller. Unfortunately, the way the Solder Column(s) with Copper Tape are constructed does not allow it to be easily “miniaturized” the same way. So, a few years ago, I decided to address this “new” problem.

First, I came up with what I call the Non-Wicking Connecting Column(s) mounting system. I received US Patent No. 6,884,707, issued 4/26/2005, Title: INTERCONNECTIONS [1], for it. I presented a paper on it at IPC Printed Circuit EXPO, Long Beach, CA, March 2003 [14].

Also in the meantime, I came up with what I call “Packages with Oriented Leads”, which I presented in a paper at IPC ECWC10 Conference, IPC Printed Circuits Expo®, SMEMA Council APEX® and Designers Summit 05, Anaheim, CA, February 2005 [15]. I received US Patent No. 7,196,402, issued 3/27/2007, Title: Interconnections [2], for these Package(s) with Oriented Leads.

Then I came up with what I call “Oriented Solder Joints” or “Oriented Starved Joints”, to provide additional capabilities. I received US Patent No. 7,433,201, issued 10/7/2008, Title: Oriented connections for leadless and leaded packages [3], for these the Oriented Solder Joint(s) or Oriented Starved Joint(s). I will concentrate my presentation here on these, the Oriented Solder Joint(s) or Oriented Starved Joint(s).

Thermal Cycling

Thermal Cycling tests are used to test electronic assemblies as a prediction of their reliability. The purpose of the test is to determine how long an electronic assembly can survive in an environment, where the temperature would fluctuate between cold and hold temperature limits, defined by the various specifications or standards. But the real purpose is to establish the reliability of such assemblies and to predict how long, how many years of service, can they provide to their end users.

If two electronic assemblies are tested side by side, under the same thermal cycling conditions, and one assembly survives more cycles than the other, then that surviving assembly would be considered more "reliable". And if it survives a certain number of cycles as required by a specific specification, then it would be considered "acceptable". Of course, it is understood that the "sample" that would be tested, would be a "representative" sample of a batch of similar assemblies, and it is assumed or understood that the units in that batch or any unit built in a similar fashion would perform "statistically" in a similar way.

Effect of Thermal Cycling on the device under test.
In order to get a feel for the effect of thermal cycling on the device under test (DUT), it would be helpful to analyze the components in the DUT, the materials they are made of, and the characteristics of those materials, and the behavior of those materials when they undergo temperature variations. The key characteristic is the "Thermal Coefficient of Expansion" (TCE), sometimes called "Coefficient of Thermal Expansion" (CTE). **Figs. 1 and 3 illustrate such behavior**.

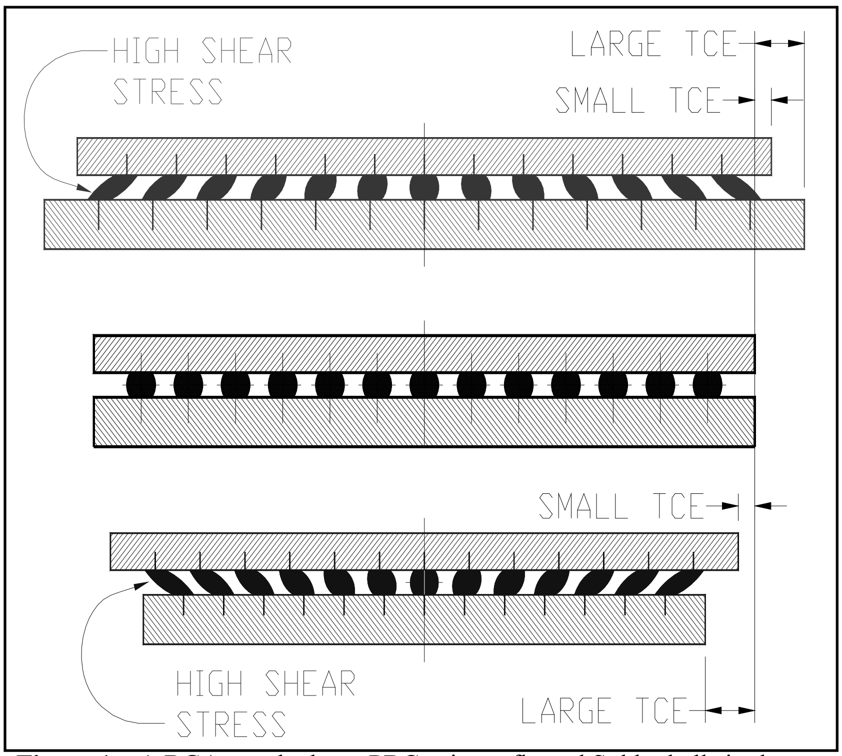


Figure 1 – A BGA attached to a PBC using reflowed Solder balls is shown.

If an assembly comprises two components having different TCEs, then it is said that there is a "TCE mismatch". This is when the problems start. Unfortunately, it is very difficult, if not impossible, to have ALL the components in an assembly to have the same TCE. So, we have to accept the fact that TCE mismatch does exist and try to find ways to live with it. My goal in this paper is to show some new ways to do that.
When an assembly has two components with different TCEs, then one component will expand and contract/shrink at a different rate than the other component. The effect of this TCE mismatch would show as a difference in the dimensions of the components. This in turn would create some internal stresses in the components and in the joints between these components. If the temperature excursions are large, and if the starting dimensions of the components are large, then the difference in the dimensions of the joined components would be so large, that the induced stresses in the components as well as in the joints can be large as well and can reach stress levels, which can be detrimental to the integrity of the assemblies.

For small size components and for small temperature variations, the difference in the dimensions of the components is small, almost negligible. But when the size of the components reaches certain large sizes, and/or when the temperature variations are large and reach some high values, then the difference in the dimensions of the components can be relatively very large.

Now we should ask ourselves the following question. What does all this mean and how important or relevant is all that to our problem. It is important in certain cases. For example, in the case of a BGA attached to a Printed Circuit Board (PCB) by reflowing the solder balls of the BGA to the PCB pads, the solder joints have to "absorb" the difference in the dimensions of the BGA and the PCB during these thermal fluctuations. See Fig. 1. Fig. 1 shows a BGA attached to a PBC using reflowed solder balls. At rest and at normal temperatures, the components of the assembly would look as shown in the center figure. If the TCE of the BGA is smaller than the TCE of the PCB, and the assembly is exposed to thermal cycling, the components will behave as shown in the upper and the lower figures. At high temperatures, the PCB will expand more than the BGA and the solder joints will be stressed "under shear" as shown in the upper figure. The reverse will occur at low temperatures, where the PCB will contract (shrink) more than the BGA and the solder joints will be stressed, again "under shear", but in the reverse direction, as shown in the lower figure.

So, the next question would be "how do the solder joints behave under these conditions?" Basically, as follows: most of the solder joints in such cases are relatively short and stubby. They look like truncated spheres, providing a space between the BGA and the PCB equal to a fraction of the original diameter of the solder sphere before reflow. With such a configuration, and when the components have changed dimensions due to the thermal fluctuations, the solder joints get stressed, mostly under shear stress. The resulting shear stress will be higher at the joints farthest away from the center of the assembly. So, the corner joints on a square or rectangular BGA or any similar Package would be the ones undergoing the highest stresses. This is why most of the failures can be seen in the solder joints closest to the corners. When the assemblies are repeatedly exposed to similar thermal fluctuations, the induced stresses are also repeated, for every thermal cycle. This is referred to as repetitive stresses, or fluctuating stresses, or cyclic stresses.

In material science, such repeated stresses are fairly critical and have been studied at length. In one group of materials, such as steel and ferrous metals in general, there is what is called an "endurance limit". At high stress levels, the material, or rather the component under stress, can survive only a certain limited number of such stress cycles. By reducing the stress level down to a certain scientifically known amount, then it is said that the component can survive an unlimited number of such cycles and this stress level is called the endurance stress limit. However, another group of materials, such as solder or aluminum, does not behave the same way. The materials in this group have a characteristic known as "flow" or "creep". Their endurance curve does not level off to a stable endurance stress limit, but it keeps on dropping down continuously. This is illustrated in Fig. 2. So, it is said that each repetitive stress level has a finite number of cycles before the material fails.

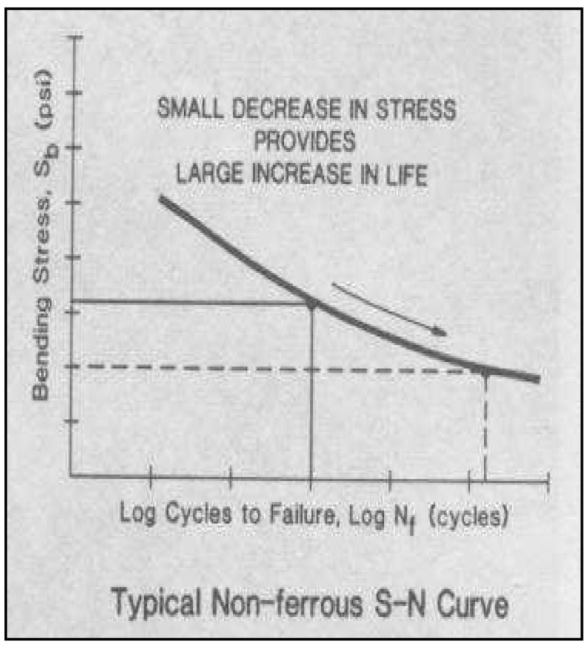


Figure 2 – The curve shows a typical S-N curve for non-ferrous metals, like most of the solders used to assemble electronic components.

The figure shows two illustrative points on the curve. The point at the left shows, along the horizontal axis, the number of repetitive cycles leading to failure, if a solder joint is exposed to a repetitive stress at the high level shown along the vertical axis corresponding to this point on the curve. If the stresses in joint are reduced to the level shown by the second point, the point at the right on the curve, then the joint would survive a larger number of repetitive cycles before it fails. Conclusion: If we want a solder joint to survive a higher number of repetitive cycles, we should find ways to reduce the stress level on that joint.

So based on that, once we know the characteristic endurance curve, or rather the S-N curve, of the solder material that we are using, and once we can calculate the level of the repetitive stresses induced in the solder joint, then we can theoretically predict the number of such stress cycles, which that specific joint can survive before it fails. However, it is not so easy to calculate all these stresses, and there are so many other variables and effects acting on the joints and on the assembly in general, that it is always easier to go through some empirical tests, such as the Thermal Cycling tests, to arrive at some reasonable prediction of the expected life of such assemblies.

However, our fate is not locked and we do have certain room to maneuver if we want to extend the life of similar assemblies.

UNDERFILLs

One method to fight the effect of thermal cycling is to apply a material between the BGA and the PCB. Such a material is referred to in the industry as “UNDERFILL”. This material acts as a bonding agent or “glue”, holding the two components together as a piece of plywood, a two-layer plywood in this case. See Fig. 3. In effect, this converts the characteristics of the “assembly” to behave more like a foil of bimetal, as represented in this Fig. 3. If the assembly is exposed to fluctuating temperatures, and if the assembly is not “restricted” in its deformations, then at high temperatures the assembly would “warp” and curl upwards as shown in the figure, and the opposite will happen at low temperatures, where the assembly will “warp” and curl downwards as shown as in the lower curve in the figure. This is assuming that the bottom layer of the assembly/bimetal has a larger TCE than that of the upper layer, like in the case of the BGA and PCB shown in Fig. 1.

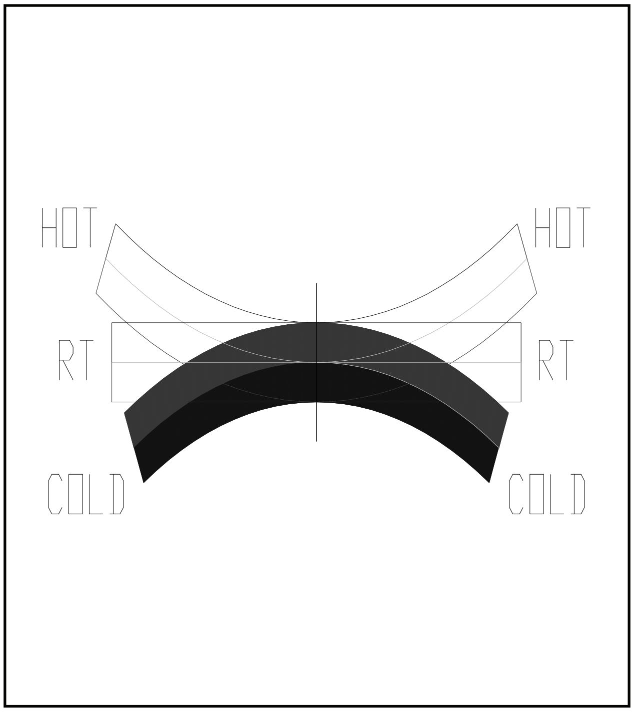


Fig. 3 – One method used to reduce the stresses in the solder joints is to apply a bonding agent between the BGA and the PCB. In effect, this converts the characteristics of the “assembly” to behave more like a foil of bimetal, as represented in this figure.

Dr. Ken Gilleo, Cookson Electronics, in his paper “Underfill Update: NUF, MUF, WUF, and Other Stuff” has discussed “the "underfill effect" – (which provides) enhanced performance by interposing adhesive between chip and substrate”, and talked about “the mechanical coupling mechanism of underfills”. The Underfill mechanically couples the two main components’ bodies, i.e. the body of the BGA and the body of the Substrate, so as to transfer and distribute the stresses, from the solder joints, to the bodies of the two components. Underfill can help in many cases, especially when the devices or packages are relatively small in size and when the temperature fluctuations are not excessive. But, theoretically, it could “warp” the assembly, in certain cases as stated above.

Dr. Gilleo enumerated, in his paper, see Ref 19, the potential problems with the many types of Underfill, including the following, and I will paraphrase here:

(CUFs) “Capillary underfill”: Problem: A 5 minute cure at 165 ºC, which creates "production bottleneck."

(NUF) "No flow underfill”: Problem: higher than optimum TCE: 70 to 85 ppm/ ºC. This is three times higher than the solder joint TCE of about 25ppm/ ºC. Underfill cracking and delamination.

(MUF) “Molded underfill”: Used to make FCIPs in BGA format. Individual packages, strips and even full arrays (flood molding) work well. Allows over molding so that the FC can be totally encapsulated in a single step, if desired. Predictions are that MUFs will be the choice among packaging foundries, because of their focus on high productivity, and the ready availability of molding presses."

(WUF) "Wafer-level underfill": "Build the flux and underfill right into the chip". Thermoplastic reworkable die attach adhesives are applied to the back of wafers, hardened and the wafer is then sawn. The chips are ready to bond. So why not flip the adhesive to the front and call it wafer-level underfill (WUF)? Encouraging results, but, considerable work remaining, the program was shelved. Group funded by the US government is pursuing the effort.

Solder Balls vs. Solder Columns

One other way to combat this undesirable effect of thermal cycling is shown in **Fig. 4**. The figure gives us a clue as to how to reduce the stresses in a solder joint. In this figure, we see two ways of attaching a BGA or a similar package or device to a PCB or any substrate in general. The figure on the left hand side shows the conventional method, where the solder joint is short and stubby, and where the major stresses acting on the joint are "shear stresses". This is what we talked about earlier above. The shear stress, represented by the term Ss, can be represented by the formula under the figure. We can see that the only parameters that affect the level of the stress are F and A. The term F is the force resulting from the thermal deformation between the two joined components, occurring at the joint due to the temperature fluctuation. Actually, it is due to the difference between the deformations of the two individual components that are joined together. The term A is the area of the solder joint. Both these two parameters are difficult, if not impossible, to change.

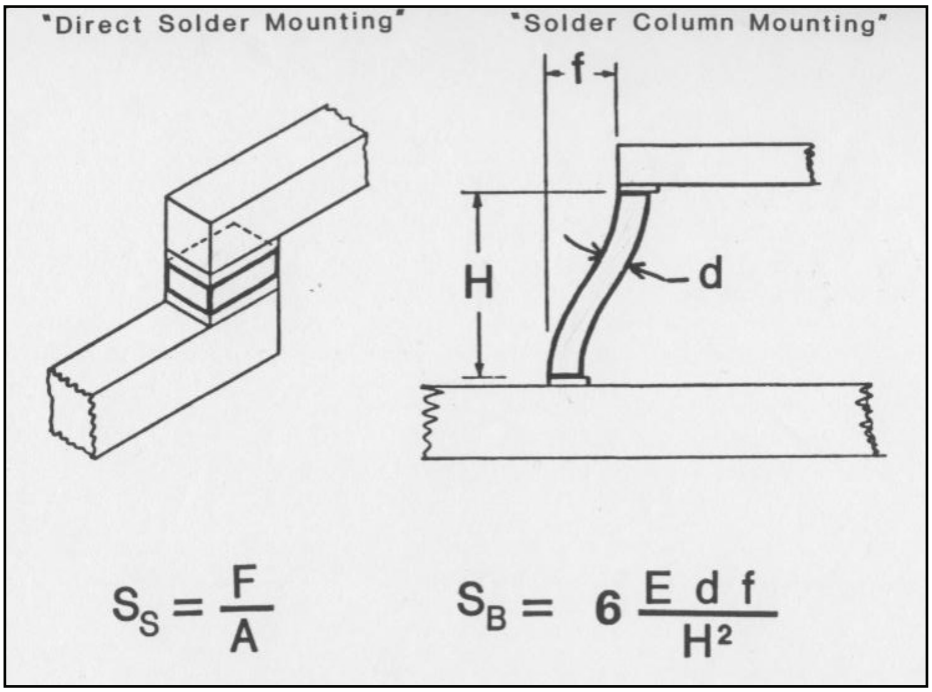


Figure 4 – The figure above gives us a clue as to how to reduce the stresses in a solder joint.

But on the right hand side, we see that the joint is formed as a tall slender column. Now here the stresses in the joining column are totally different. Here the column acts as a beam under bending. The prevailing stresses would be "bending" stresses. The formula at the bottom of the figure gives the relation between the various factors affecting the stresses induced in the column. By studying the formula, we can see that there are certain factors that we have more control on and by varying the values of these factors, we can "reduce" the stresses induced in the joining column. The formula under the figure shows us that the terms "d" and "H" can be used to manipulate the level of bending stress in the column. By reducing the diameter "d" of the column, we can reduce the stresses linearly. And by increasing the height "H" of the column, we can reduce the stresses geometrically, or to the square of the change.

And by reducing these stresses, we would expect that the joint would survive more such thermal cycles, and consequently the "life" of the joint and of the assembly would be longer/enhanced.

Many years ago, IBM came up with their "solder columns". They were mostly "cast" on the packages, if I remember correctly. It was a good convincing move that showed that "columns" do reduce the stresses on the joints, and consequently, extend the operating life of assemblies using such columns.

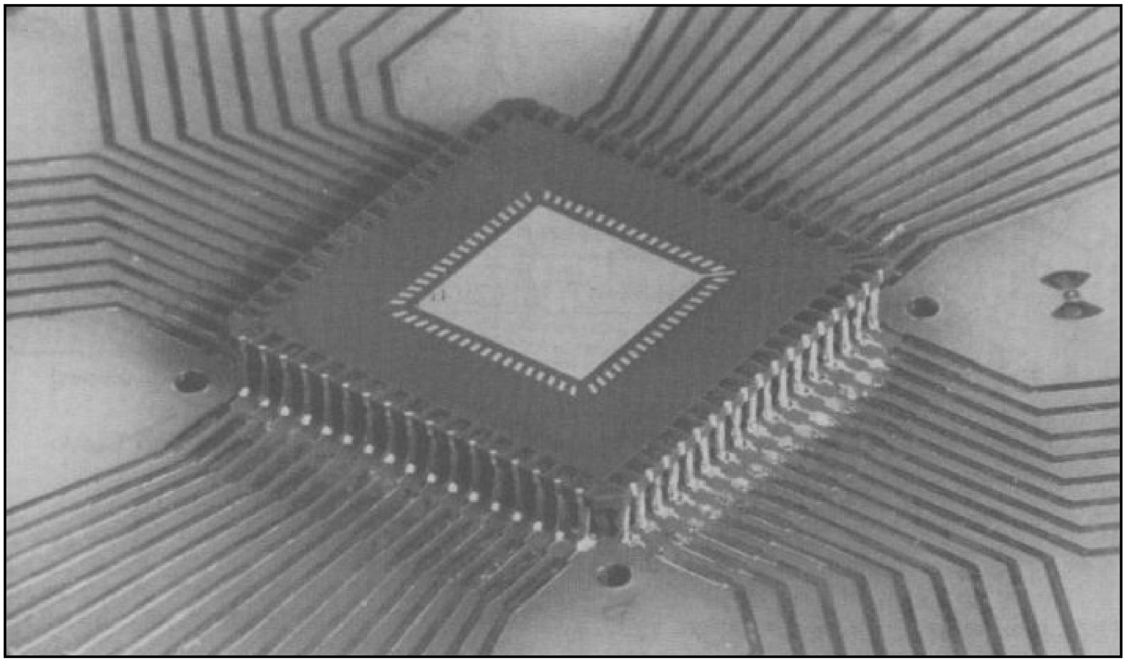


Figure 5 – A Leadless Ceramic Chip Carrier (LCCC) is mounted onto a Printed Circuit Board (PCB) using the Chip Carrier Mounting Device (Solder Column(s) with Copper Tape) or what became known as the “Solder Columns”.

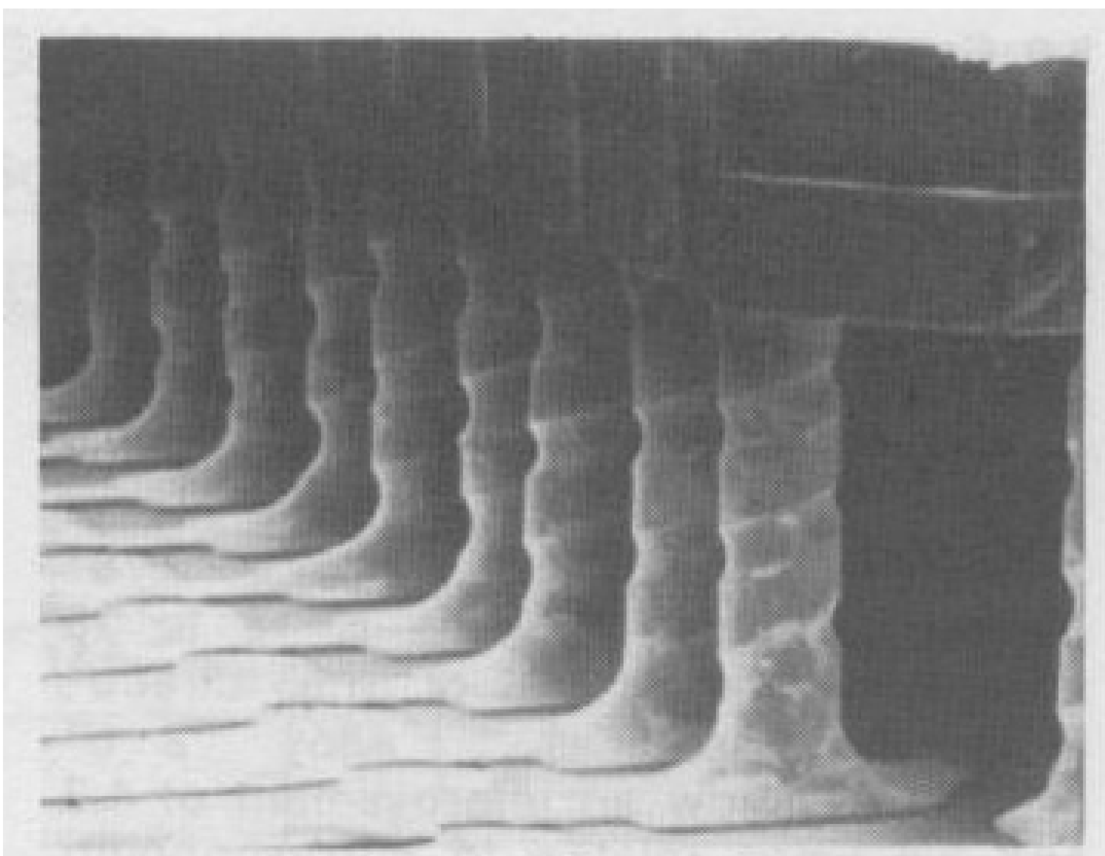


Figure 6 – An enlarged view of one side of the assembly shown in the previous figure. The “Solder Columns” are clearly visible.

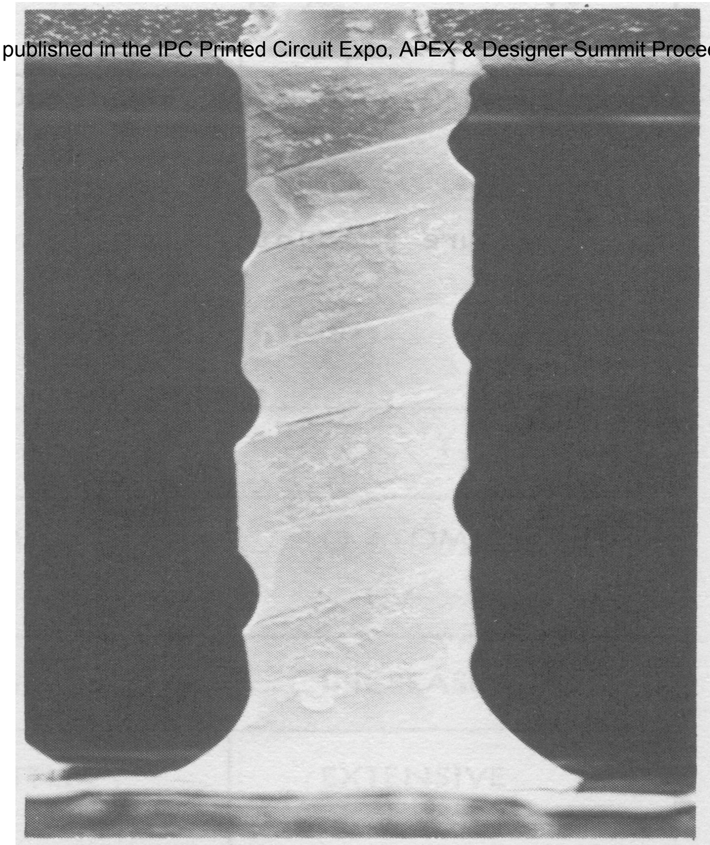


Figure 7 – Enlarged view of the "Solder Column". We can see the copper tape wrapped around the solder core.

Chip Carrier Mounting Device or Solder Column(s) with Copper Tape

Based on the above analysis, we, at Raychem, came up with the Solder Column(s) with Copper Tape. See **Figs. 5 through 7**, which show an example of an assembly using the Solder Column(s) with Copper Tape, to attach a Leadless Ceramic Chip Carrier (LCCC) to a PCB. We made such assemblies and tested them, side by side, with other assemblies made the conventional way, i.e. made using short stubby solder joints. The results were very satisfying. **See Fig. 8**. The conventional assemblies survived between 87 and 142 cycles. The assemblies made using Solder Column(s) with Copper Tape survived from 931 to 1,216 cycles. Other tests, using Solder Column(s) with Copper Tape of various heights, see **Fig. 9**, proved that by increasing the height of the columns, we can increase the number of cycles that the assemblies can pass through and survive. This was expected, based on the formula explained earlier above.

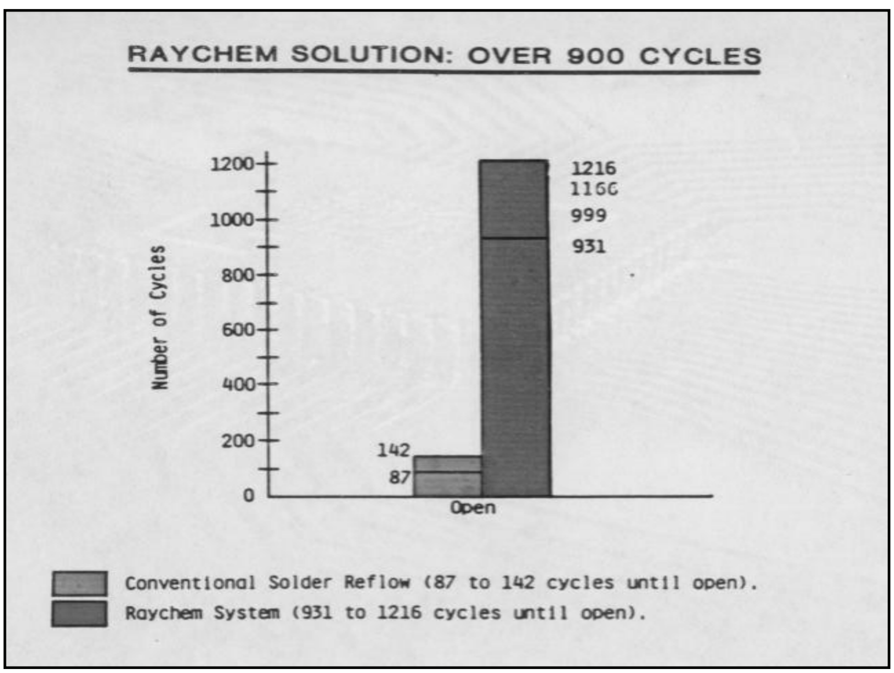


Figure 8 – Test results showed that the conventional assemblies survived a small number of thermal cycles, while the assemblies using Solder Column(s) with Copper Tape lasted almost ten times (10x) as many.

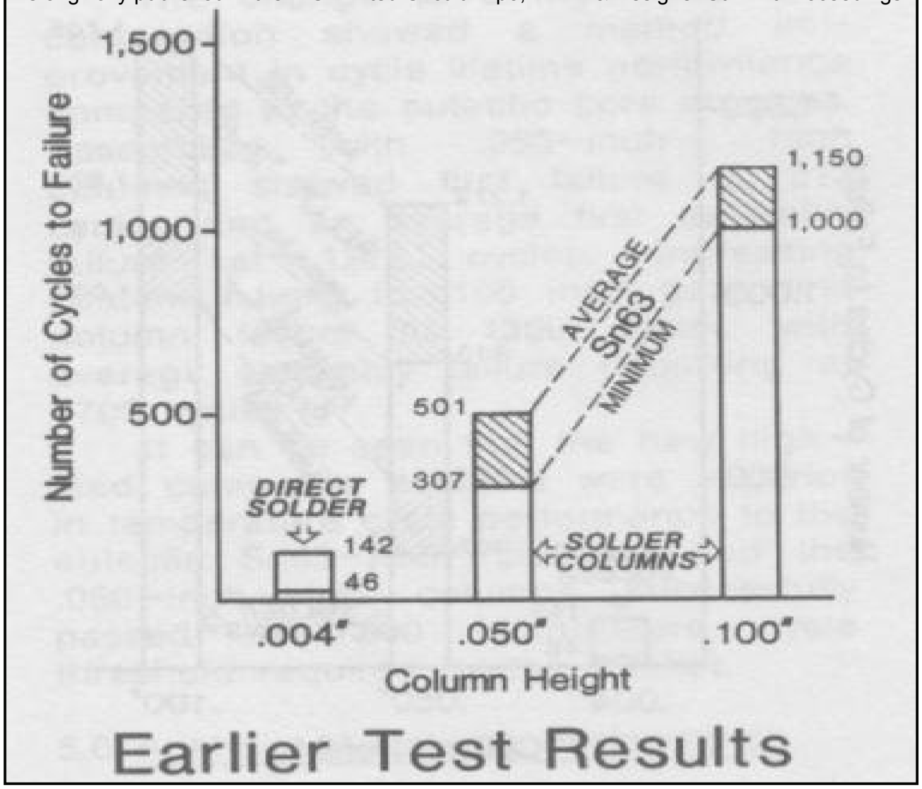


Figure 9 - Other tests showed that taller columns can survive more cycles than their shorter counterparts.

So the conclusion was this. We can increase the number of thermal cycles that a BGA/PCB assembly can survive, first by replacing the short stubby solder joints by tall slender columns, and second by reducing the diameter of the columns and/or by increasing the height of the columns.

Disclaimer

The Solder Column(s) with Copper Tape have been manufactured and sold on the market for many years. There should be plenty of history that can confirm their performance and value. However, the other new products, which I will cover in the rest of this presentation, have not been implemented yet. They are just "designs" and "concepts" for products that can be prototyped, tested, and once proven to be successful, then they can be produced and sold on the market. I am still trying to find the right outfits to collaborate with me on this effort.

Non-Wicking Connecting Column(s), US Patent Nr. 6,884,707.

Solder Column(s) with Copper Tape were built to accommodate a pitch of 1.27 mm (0.050 inch), the prevalent pitch at that time. Unfortunately, the way Solder Column(s) with Copper Tape are constructed does not allow it to be easily "miniaturized", to address the present popular smaller pitch of 0.50 mm (0.020 inch). So, the Non-Wicking Connecting Column(s) came into being to take care of that.

US Patent Nr. 6,884,707, issued 4/26/2005, Title: INTERCONNECTIONS, covers this new Non-Wicking Connecting Column(s). **Figs. 10 through 23** show some examples of the Non-Wicking Connecting Column(s). I have presented a paper on these Non-Wicking Connecting Column(s) at IPC Printed Circuit EXPO, Long Beach, CA, March 2003 [14].

Please read the captions under the figures for explanations.

The whole idea and purpose of the Non-Wicking Connecting Column(s) is to provide tall slender columns between the BGA and the PCB, or between a chip and a substrate, to accomplish the same goals as those with the Solder Column(s) with Copper Tape, but where these columns can be arranged closer to each other, to at least accommodate the smaller pitch. Actually, the concept allows us theoretically to work with much smaller pitches. I believe we can work with a pitch as small as 0.25 mm (0.010 inch). We need to prototype this first, to prove it.

Non-Wicking Connecting Column(s) with Underfill

Of course, we can combine the Non-Wicking Connecting Column(s) with Underfill. Any of the underfills mentioned above by Dr. Gilleo can be used, in any which combination that suits the application and the assembly manufacturer.

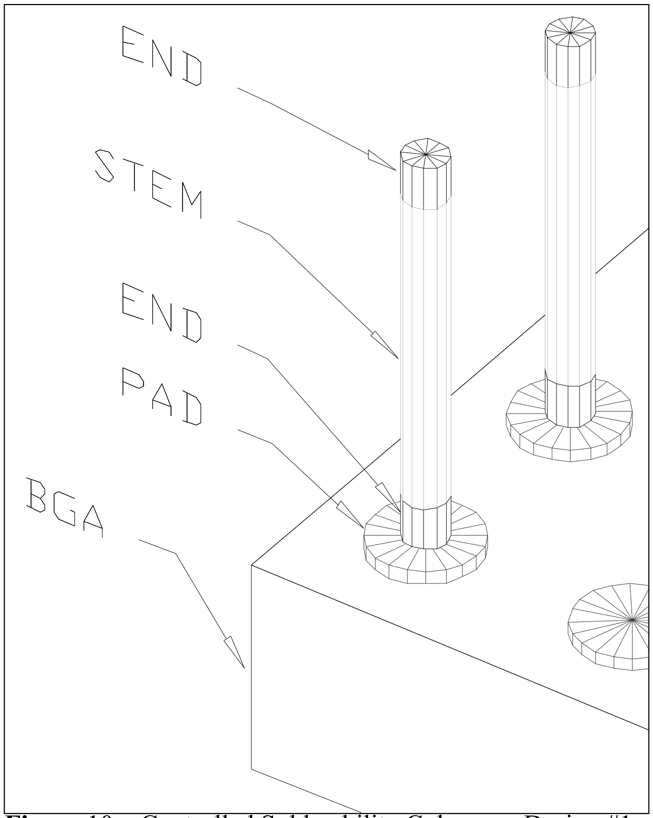


Figure 10 – Controlled Solderability Columns - Design #1: Copper Wire With Solder Resist along the stem, hence No solder will wick along the stem, hence the term Non-Wicking Connecting Column(s).

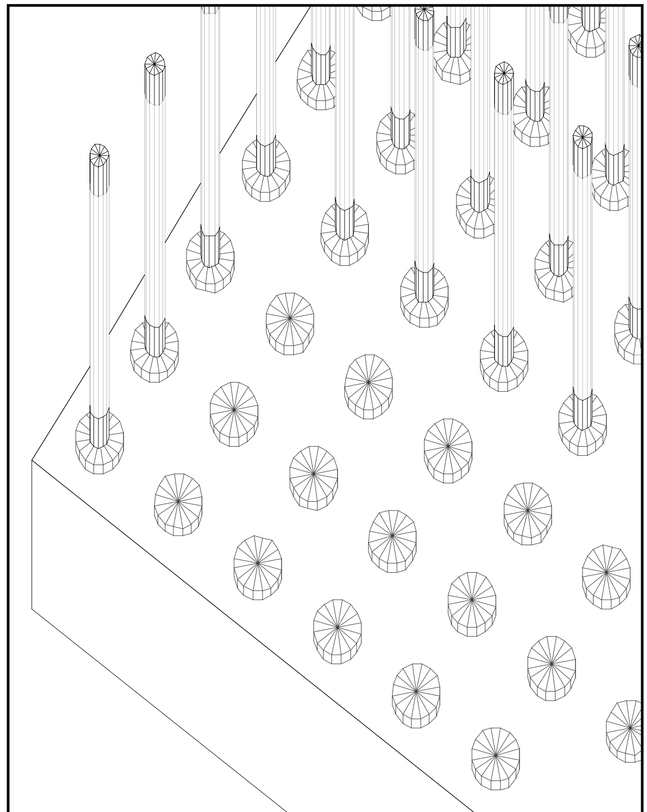


Figure 11 – BGA or Chip with Non-Wicking Connecting Column(s).

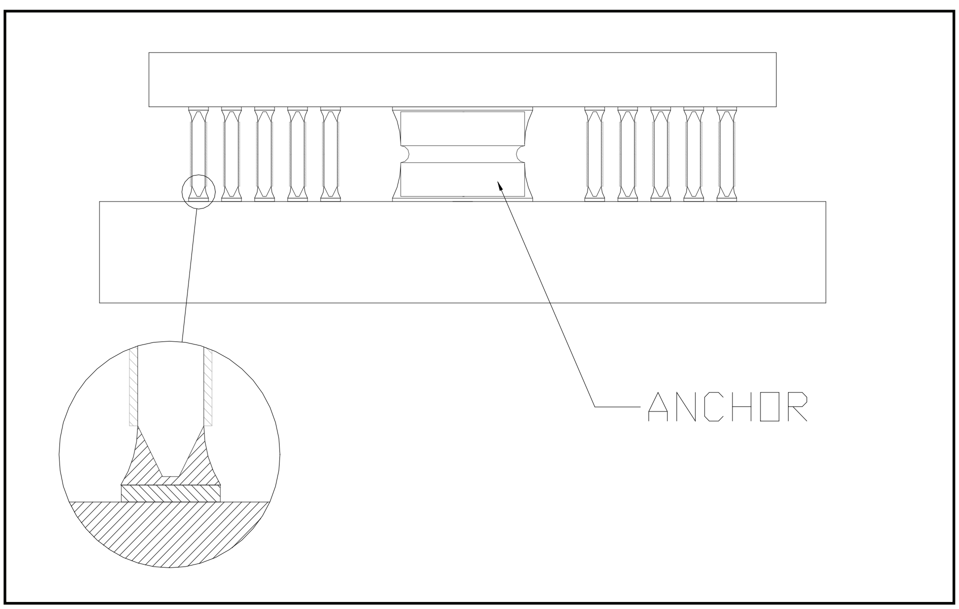


Figure 12 – Column Tips can be conical. The anchor at the center of the assembly can counteract any harsh shock or vibrations.

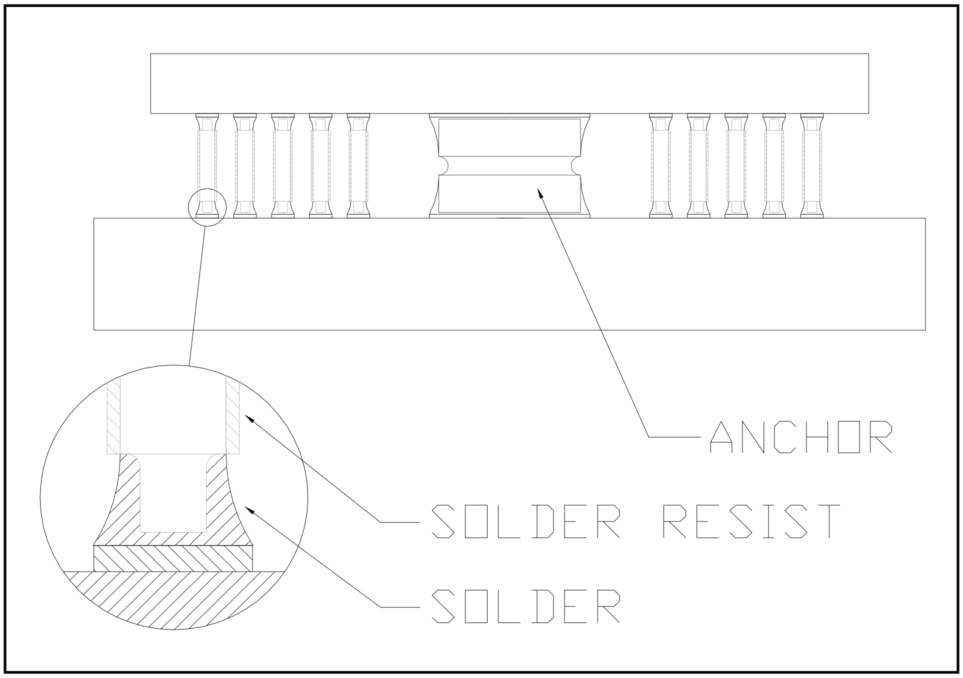


Figure 13 – Column Tips can also be cylindrical. Again, the anchor can add more mechanical strength to the assembly.

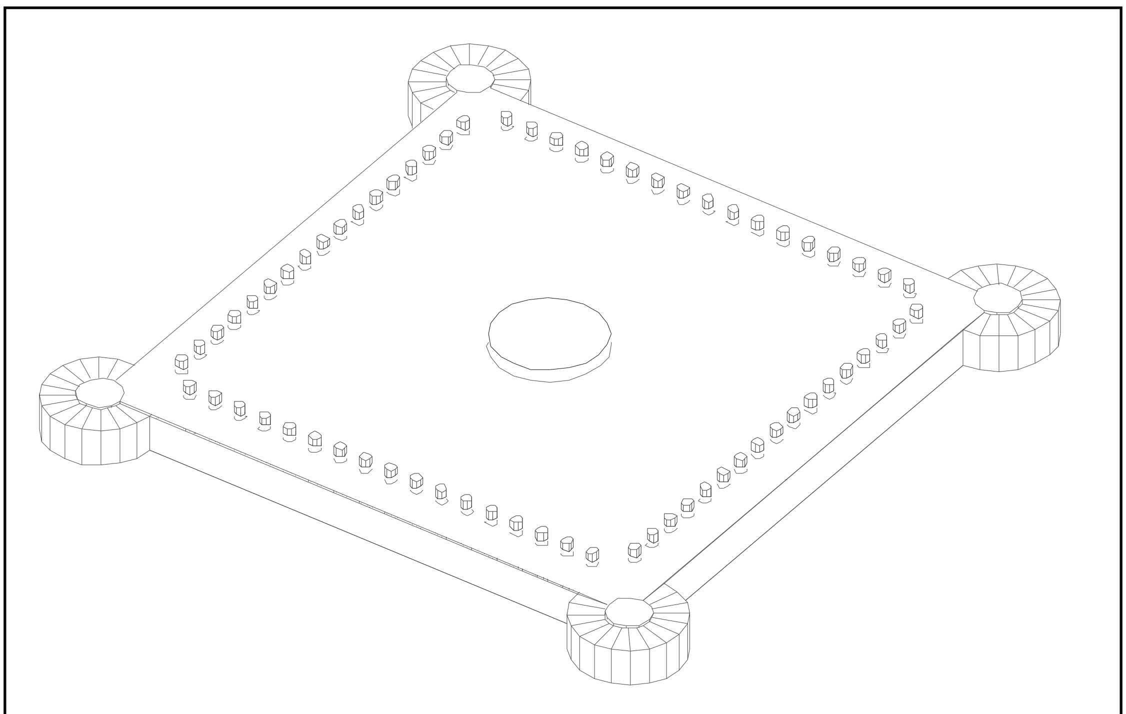


Figure 14 – Non-Wicking Connecting Column(s) in a Carrier Wafer. The anchor can be incorporated in the Carrier as well. The Carrier can be made of a removable or dissolvable material.

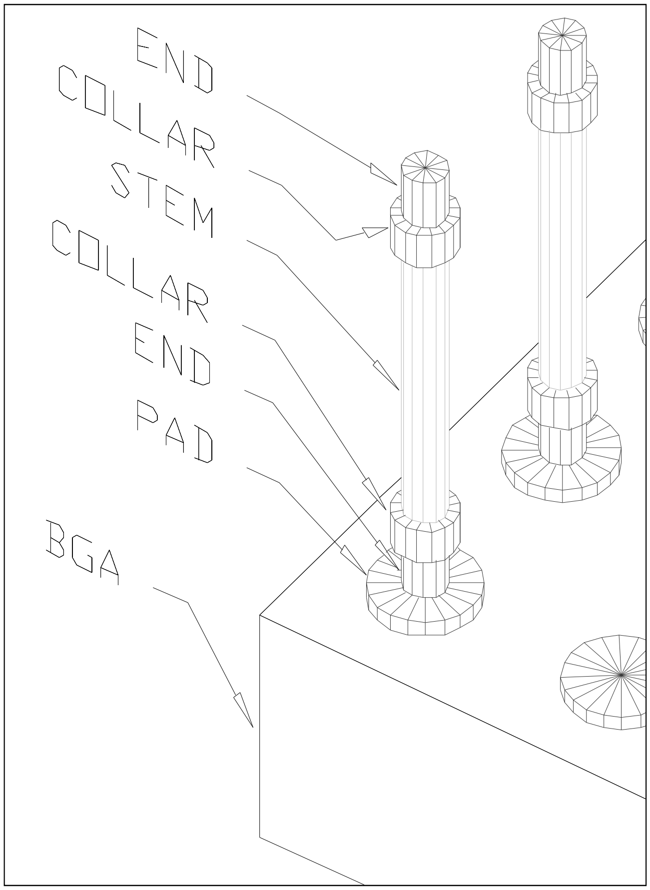


Figure 15 – Controlled Solderability Columns. Design #2: Columns with Solder Dams.

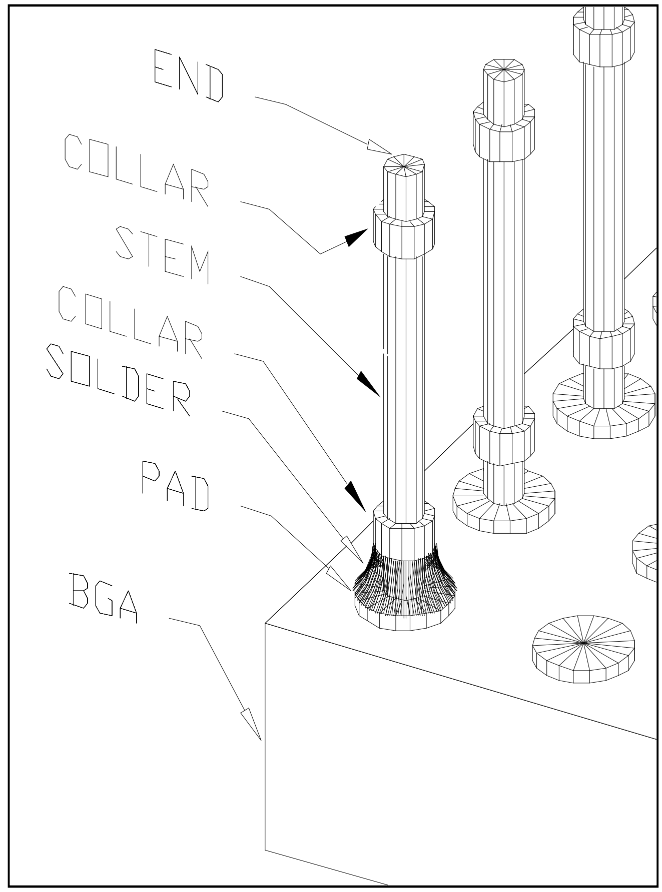


Figure 16 – Controlled Solderability Columns. Design #2: Columns with Solder Dams shown with a Solder Joint at the bottom of one column.

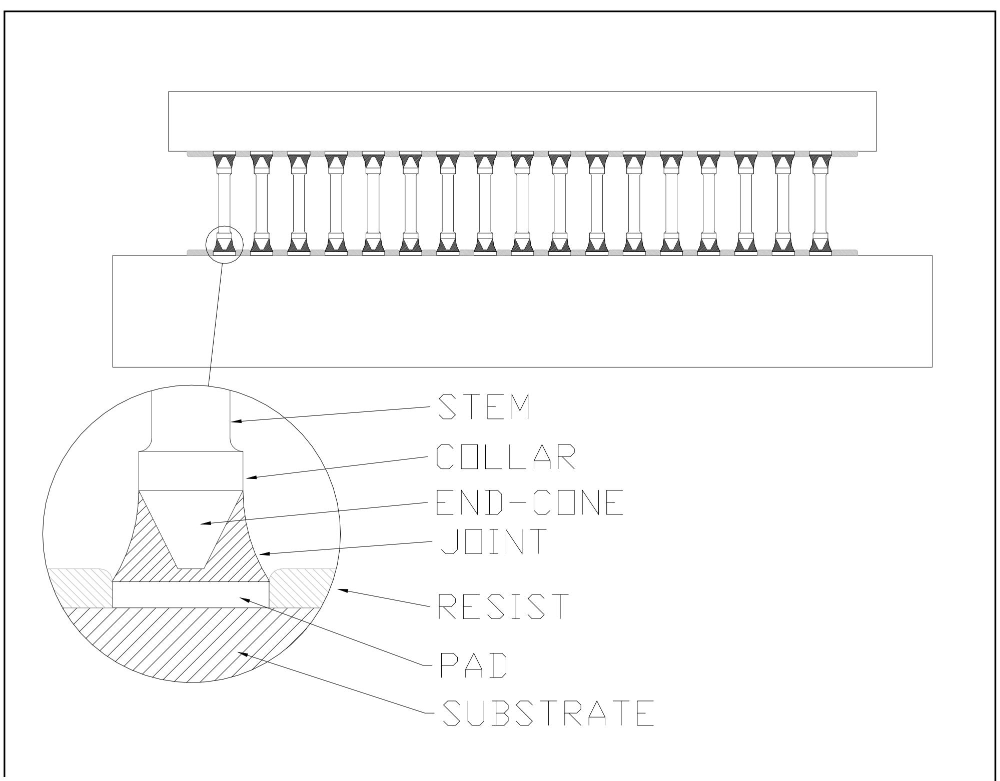


Figure 17 – Non-Wicking Connecting Column(s) with a dam. Here too, tips can be conical.

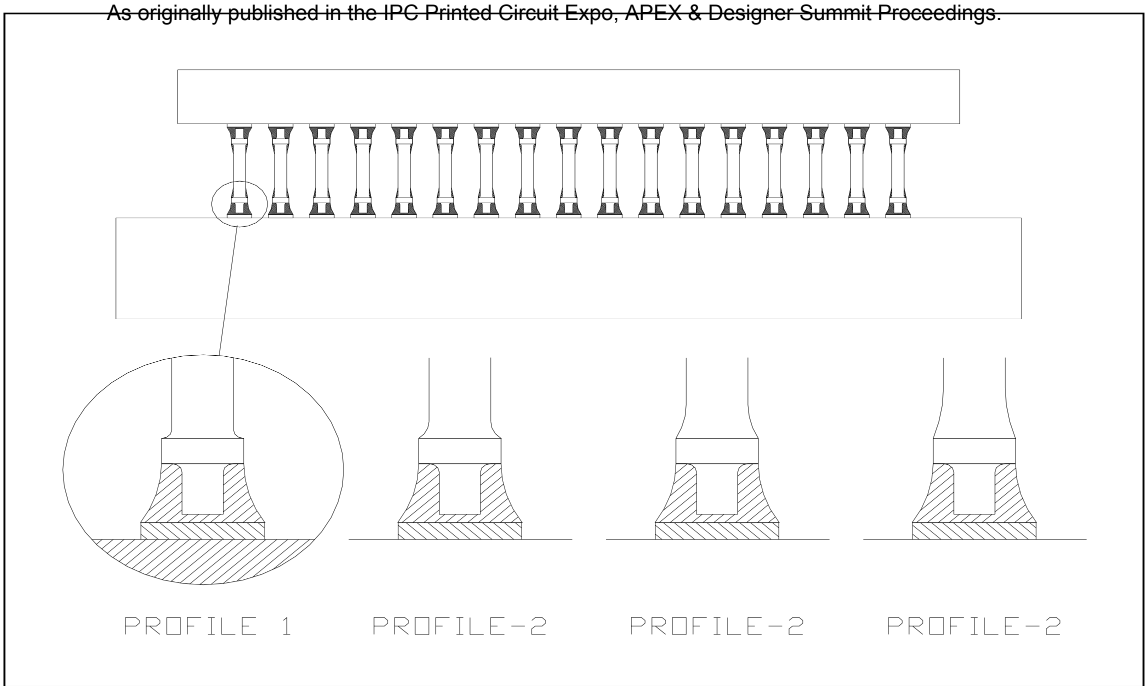
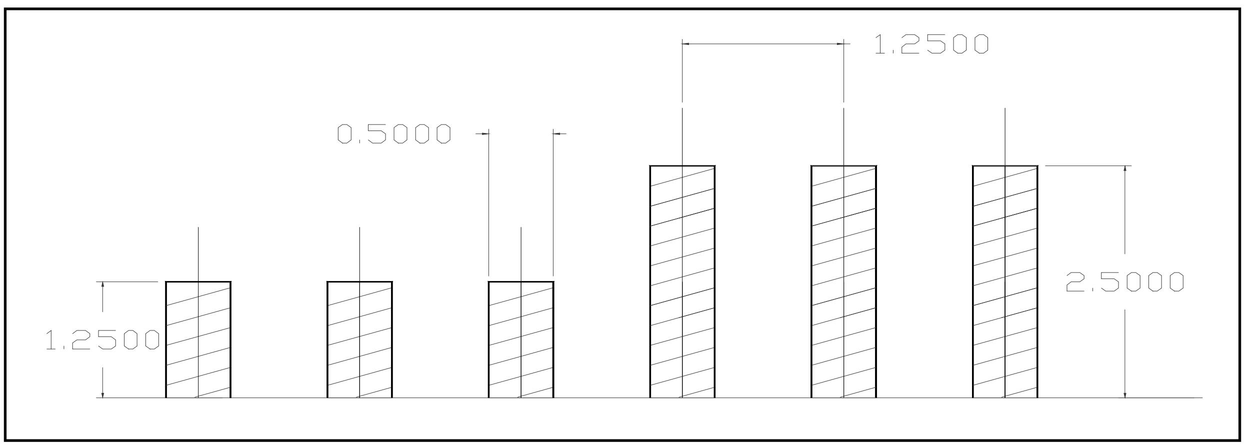


Figure 18 – Non-Wicking Connecting Column(s) with a dam. Here too, tips can be cylindrical, as well.



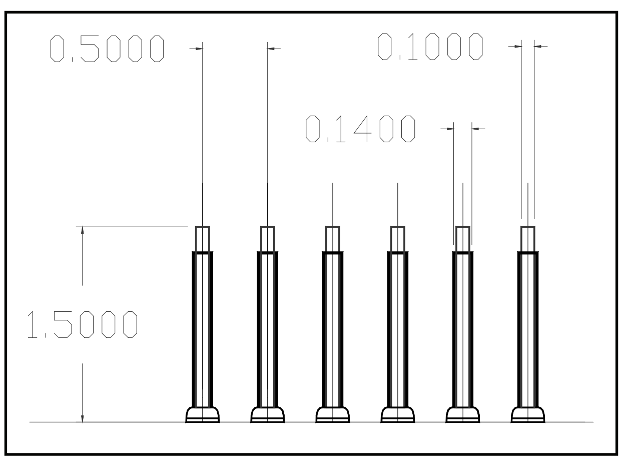


Figure 19 – Comparing the old and the new. The diameter of the Solder Column(s) with Copper Tape is practically equal in size to the Pitch of Non-Wicking Connecting Column(s), i.e. the distance between the columns centers. Another way to compare them is to say that the linear density of the Non-Wicking Connecting Column(s) is equal to 2.25 times that of Solder Column(s) with Copper Tape. Or in different words, five spaces of Non-Wicking Connecting Column(s) can fit in the space of two spaces of Solder Column(s) with Copper Tape.

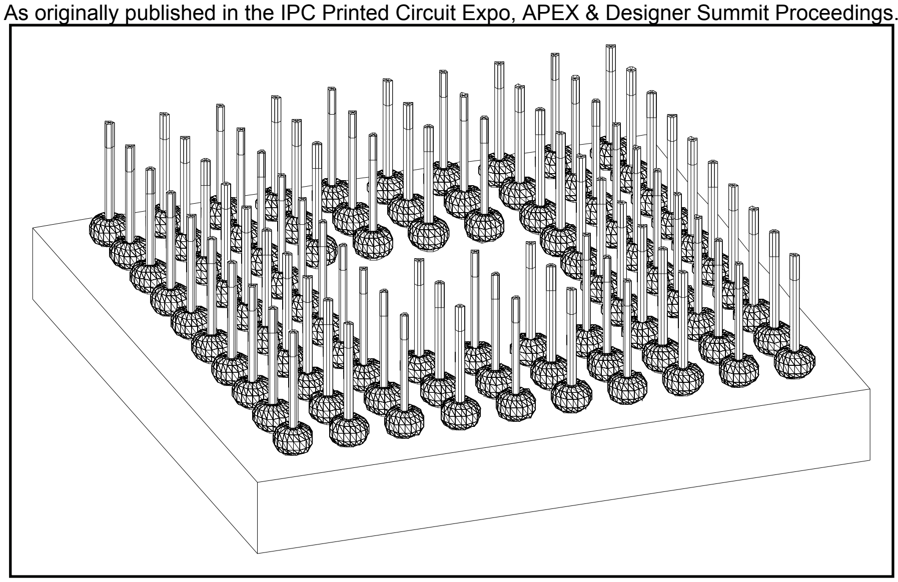


Figure 20 – Another application method: Columns by "Wire Bonding" referred to as the Non-Wicking Bonded Columns. The illustration shows a BGA or Chip, with Non-Wicking Bonded Columns.

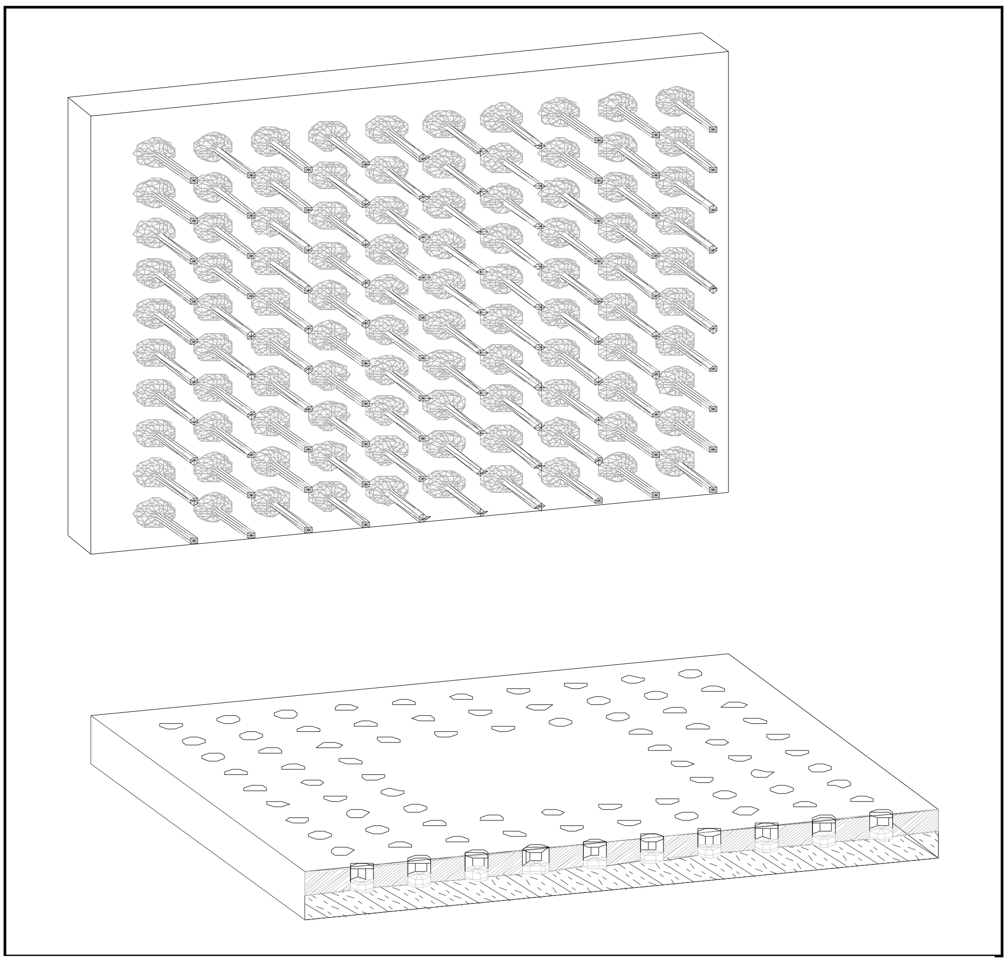


Figure 21 – A BGA or Chip, with Non-Wicking Bonded Columns is being readied to be assembled to a substrate. Substrate could be provided with "Solder Wells".

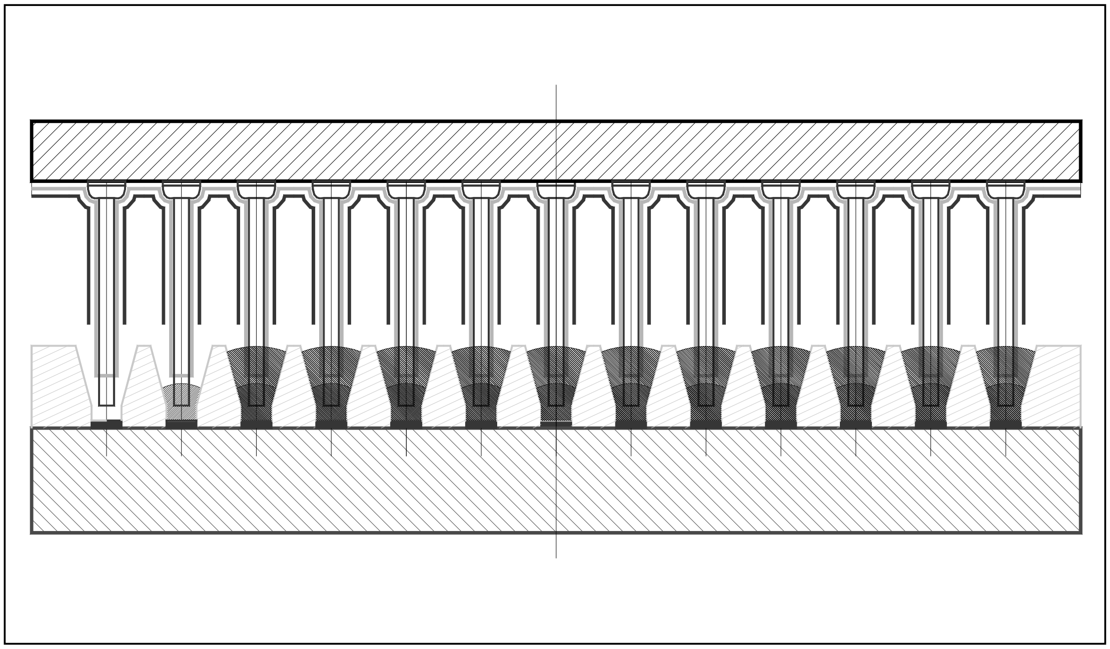


Figure 22 – Non-Wicking Bonded Columns would be inserted in Solder Wells, as shown, to avoid bridging.

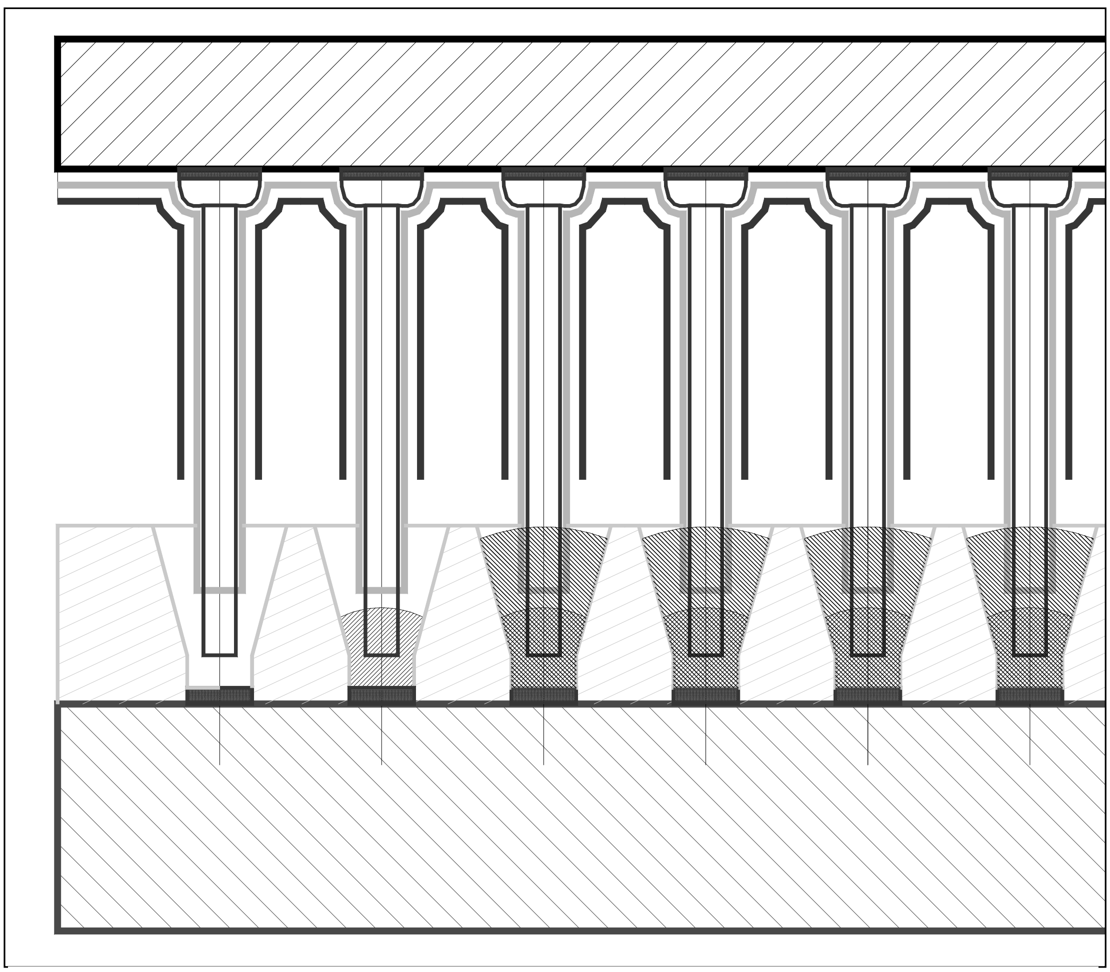


Figure 23 – A close-up look at the Non-Wicking Bonded Columns inserted in the shown Solder Wells, to avoid bridging.

Packages with Oriented Leads, US Patent Nr. 7,196,402.

US Patent Nr. 7,196,402, issued 3/27/2007, Title: Interconnections, describes these Packages with Oriented Leads. The whole idea and purpose here is two folds. It is to build on the success of the Solder Column(s) with Copper Tape and the Non-Wicking Connecting Column(s), plus to add a new innovation and advantage. First, we utilize the inherent standard long leads of such plastic packages, which provide flexibility, similar to the long leads/columns in the case of the Solder Column(s) with Copper Tape and the Non-Wicking Connecting Column(s). But second, which is new here, is to make these columns with an elongated cross-section, which usually is the case anyway, AND to orient that cross-section, so that these columns/leads would present the least resistance to bending in the direction of the expected thermal deformation.

And the purpose of reducing the stresses is to prevent the occurrence of micro-cracks in the plastic housing of the package, at the base of the leads. Because if such micro cracks do occur, then moisture can penetrate inside the housing and can migrate along the leadframe all the way to where the chip is mounted. This could make the chip age prematurely and consequently, fail prematurely.

I have presented a paper on these Packages with Oriented Leads at IPC ECWC10 Conference, IPC Printed Circuits Expo®, SMEMA Council APEX® and Designers Summit 05, Anaheim, CA, February 2005 [15]. See also References 20 and 21, listed at the bottom of this paper.

See Figs. 24 through 33, which give some examples of the Packages with Oriented Leads. Again, please read the captions under the figures for explanations.

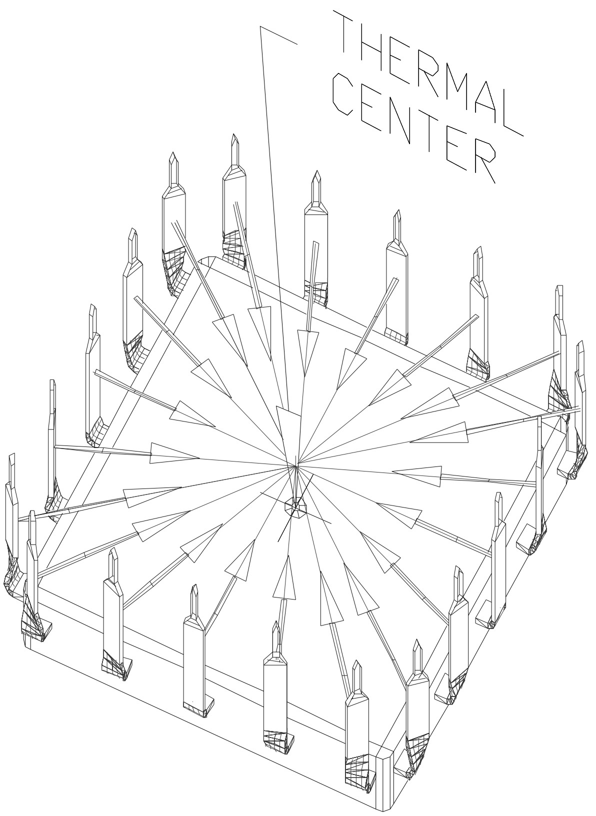


Figure 24 – A Package with Oriented Leads showing how the leads are shaped to have their “elongated” cross-sections “oriented” to present the least resistance against bending, in the direction of the expected “thermal deformation”. Here, the leads have been “twisted” near their bases to obtain the desired lead orientations. This reduces the risk of micro-cracking the plastic housing and of moisture migrating to the chip. Otherwise the chip might fail prematurely.

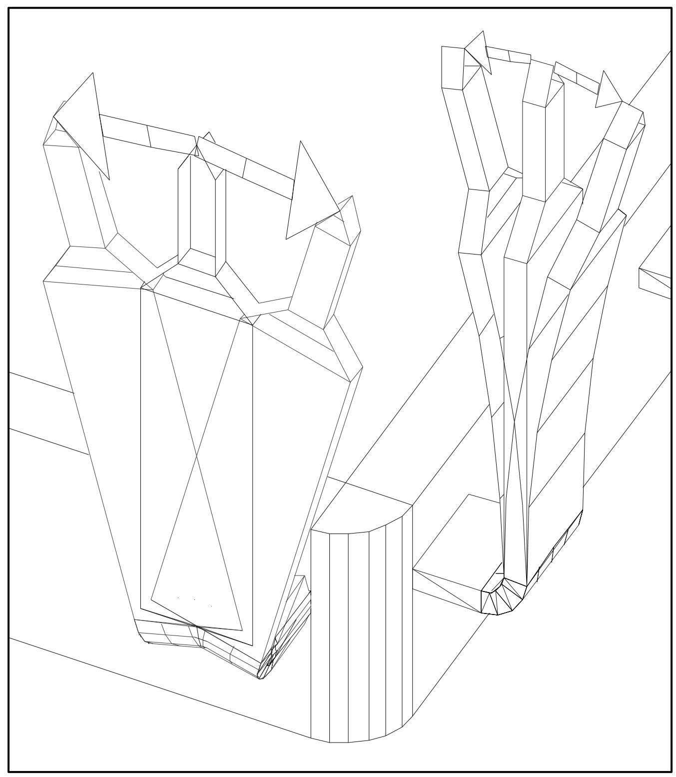


Figure 25 –The figure tries to illustrate the difference in the bending resistance of the leads. If we try to bend the lead “across flats”, as with the lead at the right hand side of the figure, we can feel that the lead is fairly flexible. By contrast, if we try to bend the lead “across edge”, as with the lead at the left hand side of the figure, we will notice that the lead behaves as a very stiff lead or very stiff spring. That is if we want to have the same amount of deflection in both cases. The result is that trying to get the same amount of deflection at the left lead, will induce very high stresses at the base of the lead and may create micro-cracks in the plastic housing of the package, allowing moisture to migrate to the chip and shorten its operating life.

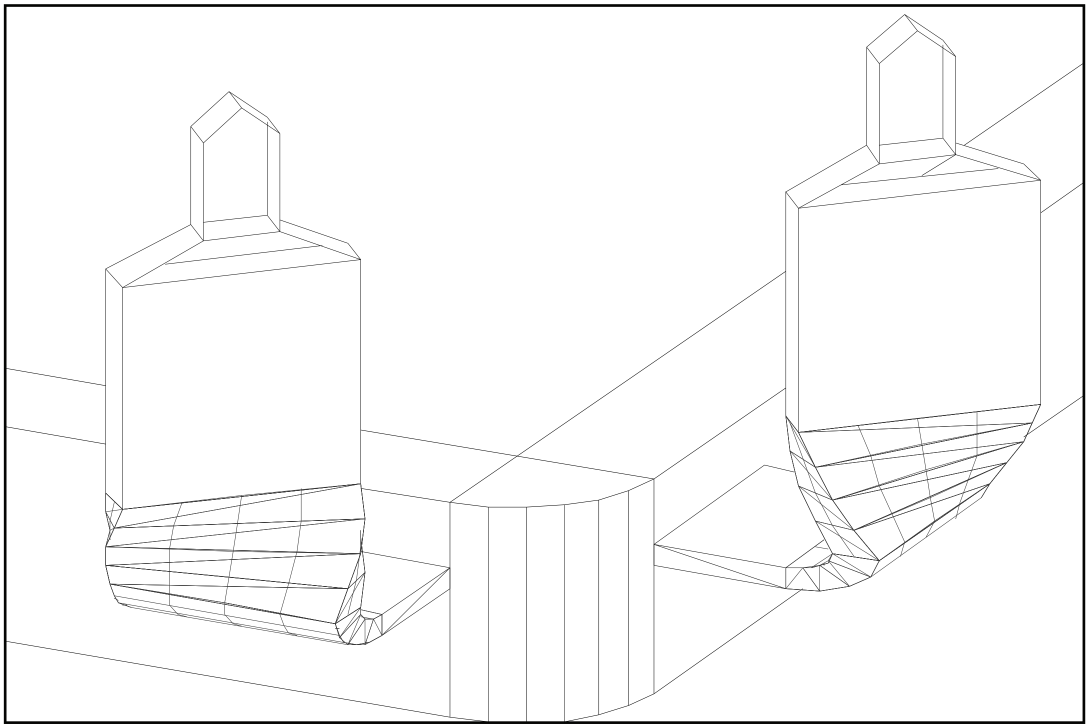


Figure 26 – Enlarged view of the corner leads at the bottom left corner of a package with oriented leads. By "orienting" the leads as shown, the leads will present the least resistance to bending in the direction of the expected thermal deformation. This, in turn, will put the smallest amount of stresses at the base of the leads. The plastic housing of the package will more easily survive these stresses and the operating life of the chip and of the package will increase/improve.

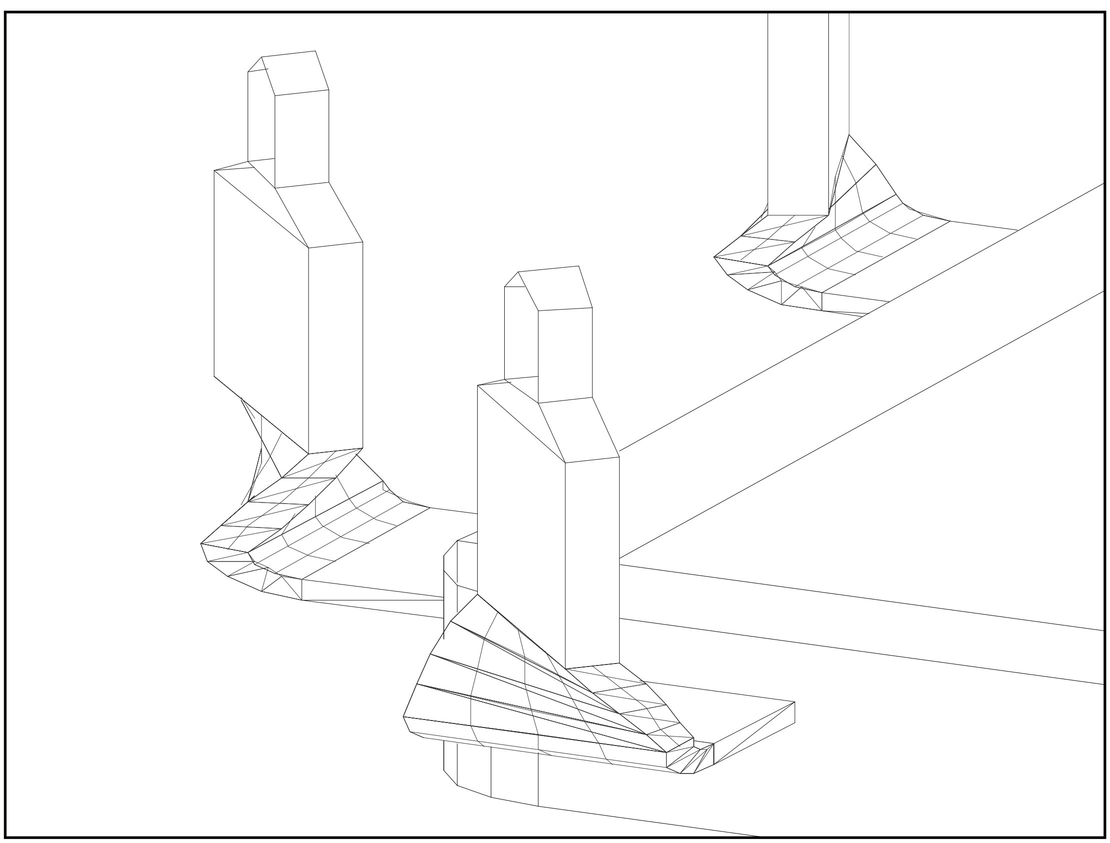


Figure 27 – Enlarged view of the corner leads at the top left corner of a package with oriented leads. Again, we get less stresses in the plastic housing of the package and the chip and package life is improved.

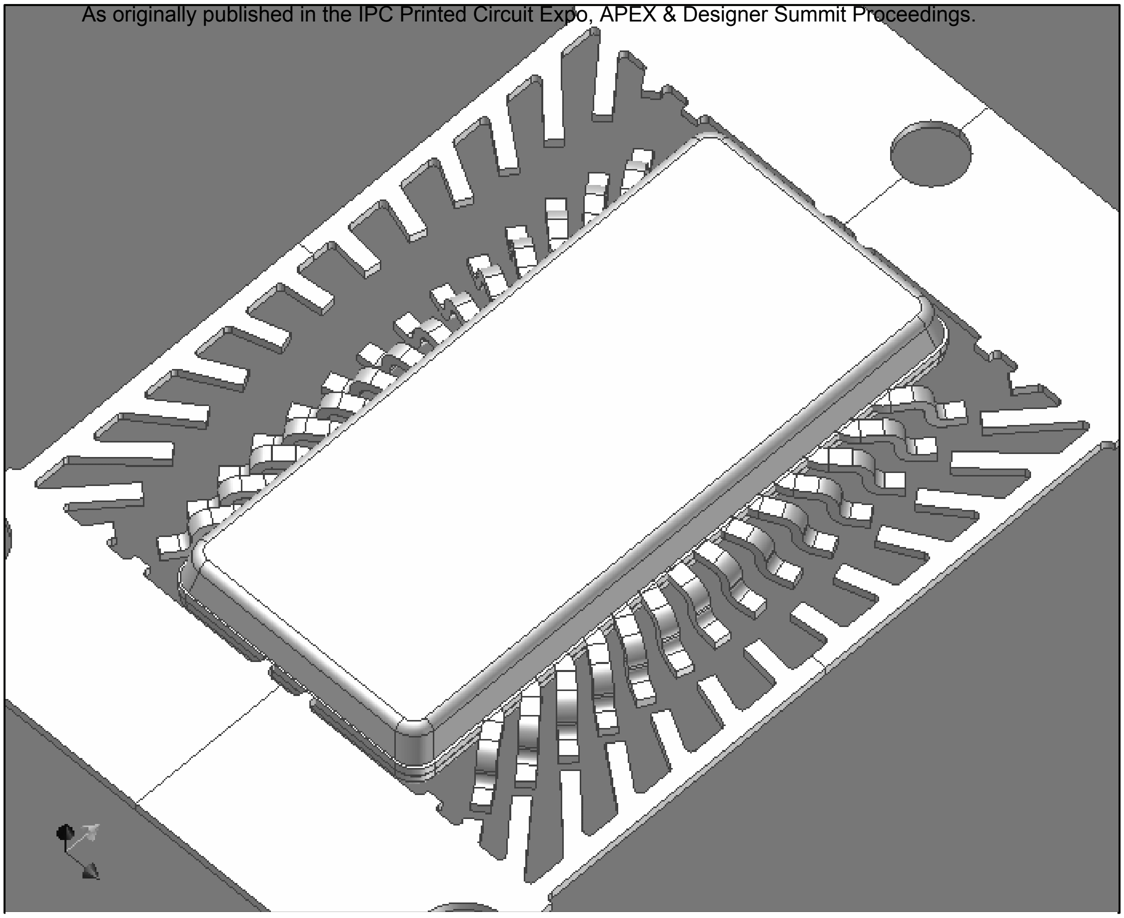


Figure 28 – Another example of a Package with Oriented Leads. This one is showing how the leads are shaped directly on the leadframe, so that the leads would be "oriented" correctly, without the need of "twisting" them, i.e. just by "folding" them.

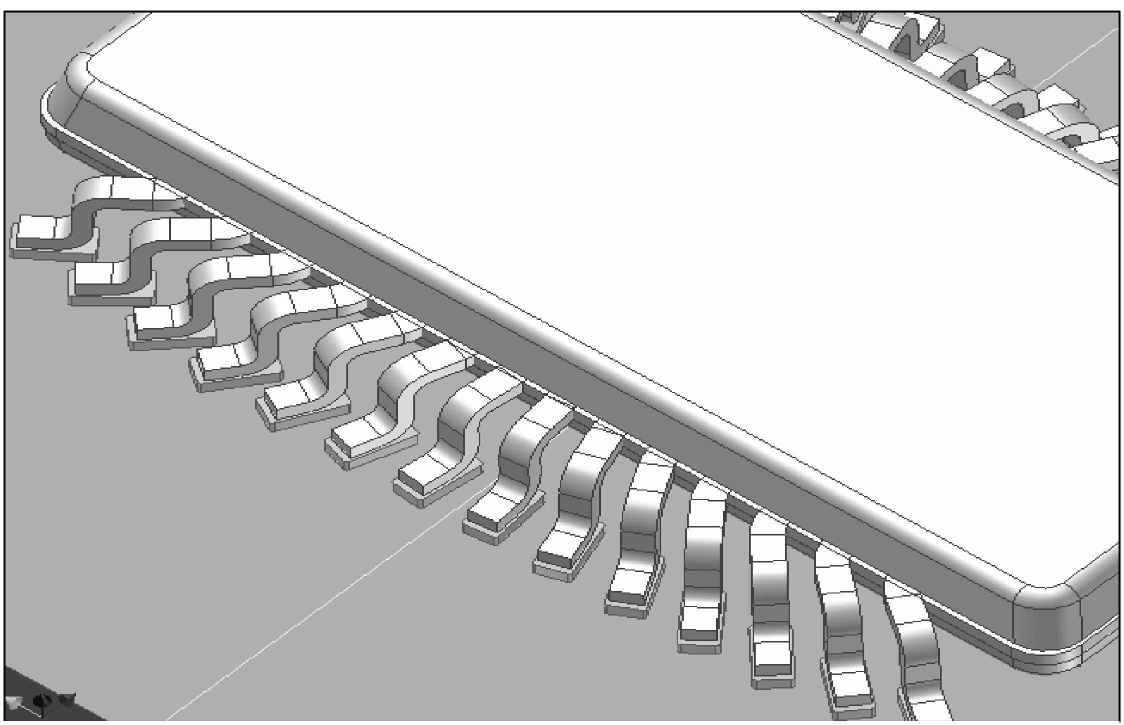


Figure 29 – A Package with Oriented Leads showing how the "oriented" leads are sitting on the PCB contact/solder pads, which have been also "oriented" to match the orientation of the leads. This is an example of the PCB solder pads being "dedicated" to accept such packages with oriented leads.

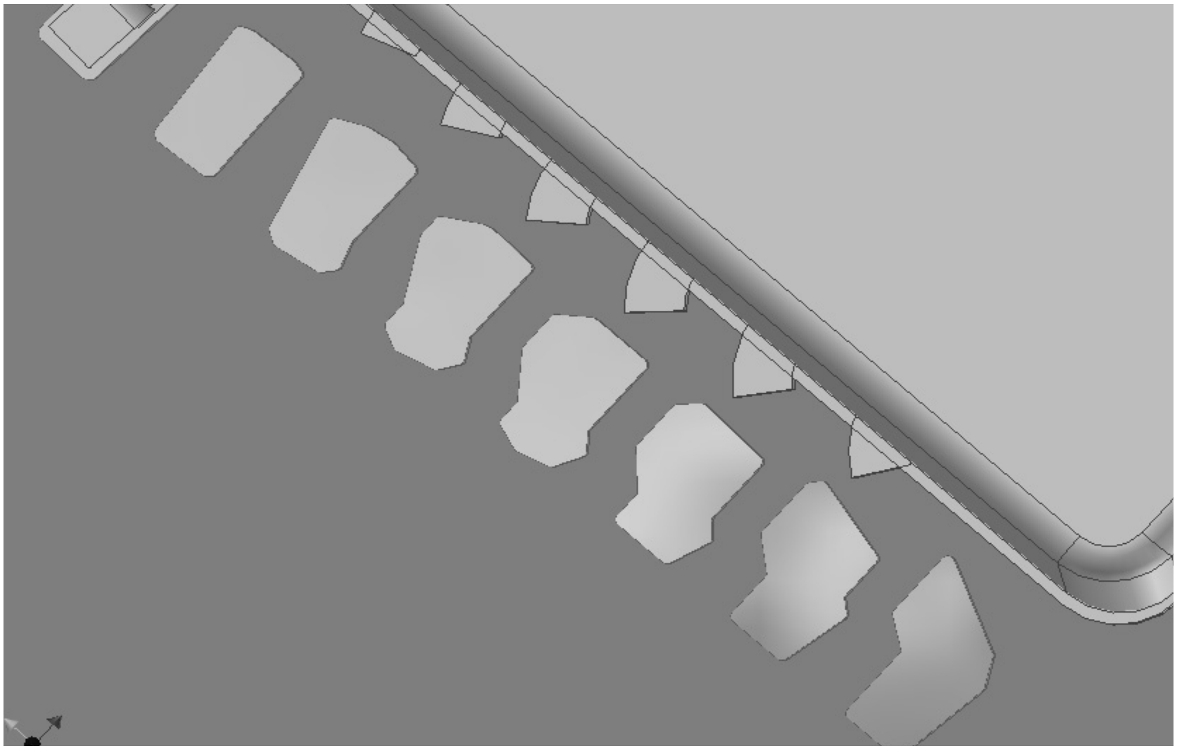


Figure 30 – Example of “UNIVERSAL” solder pads on a PCB, where the pads are shaped, such that they could accept both types of package leads, i.e. the standard conventional “orthogonal” package leads, as well as the new package with “oriented” leads.

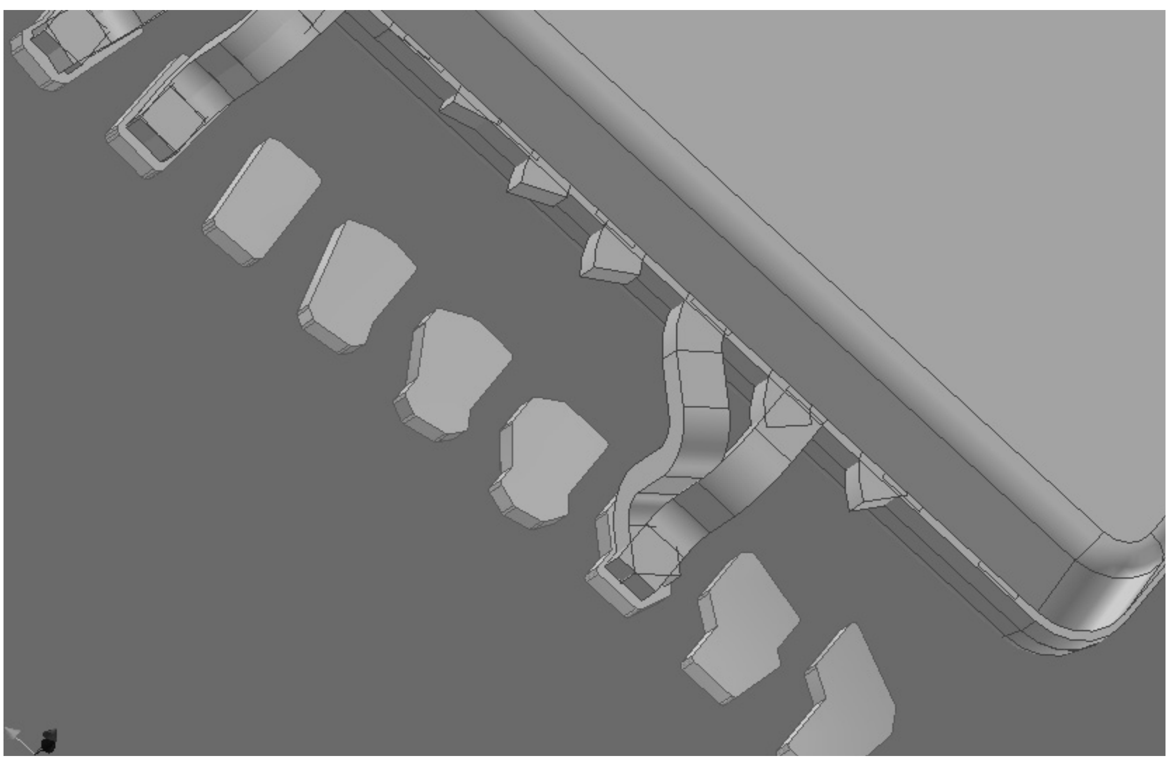


Figure 31 – Details of the “Universal” solder pads on a PCB. Here, some of the leads have been removed, to show the details of the pads. Also, a couple of leads have been superimposed. One lead represents the leads of the standard conventional “orthogonal” leaded packages, while the other lead represents the oriented leads. Both kinds of leads would be accepted on such “Universal” solder pads**.**

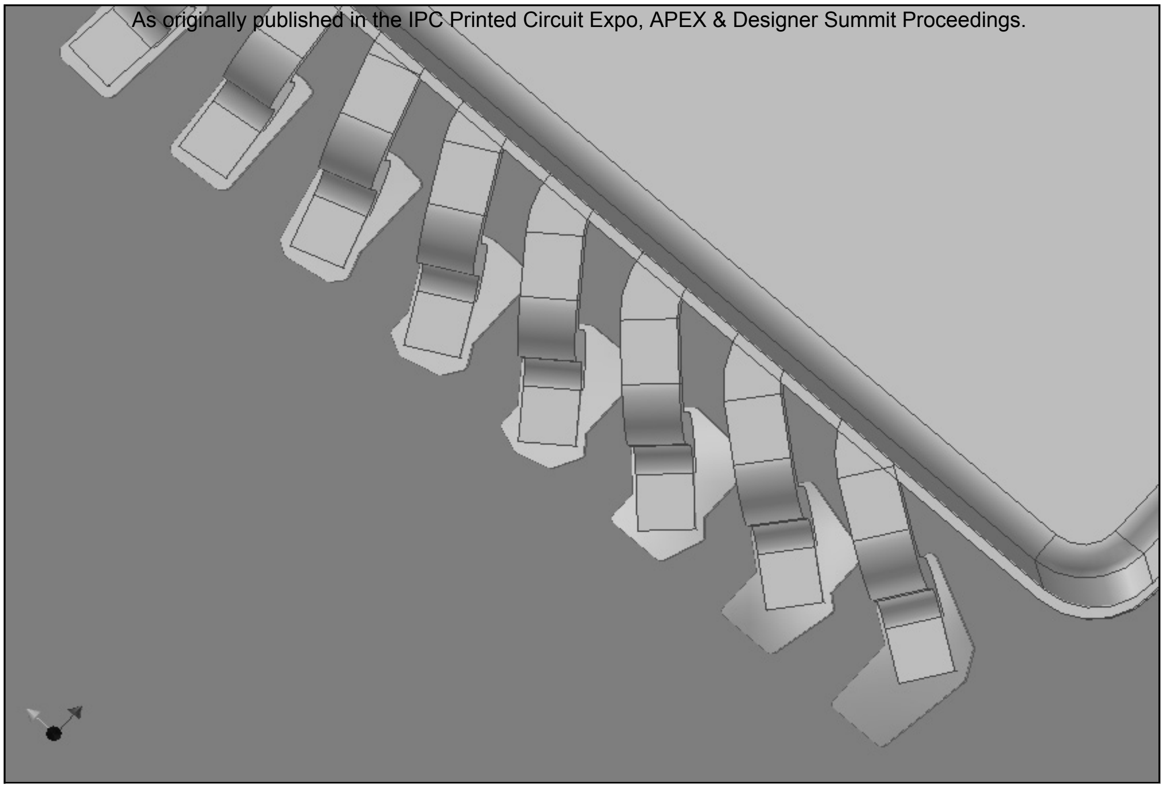


Figure 32 – A Package with Oriented Leads sitting on the "Universal" solder pads of a PCB. Only the bottom left portion of the package with oriented leads is shown.

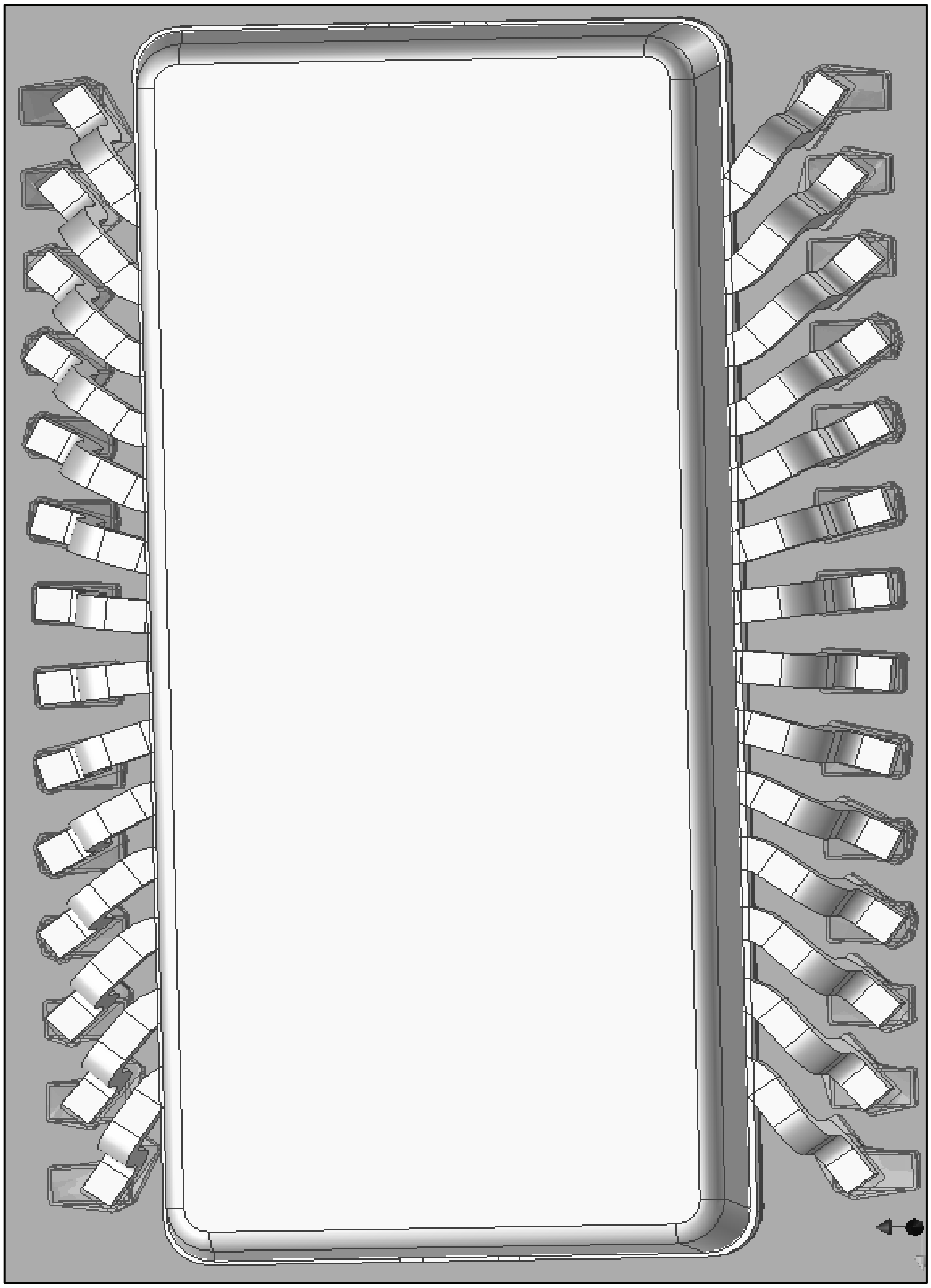


Figure 33 – A full top view of a Package with Oriented Leads showing how the leads are shaped and how they sit on top of the "Universal" solder pads of a PCB. Please note that these same "Universal" solder pads would accept the leads of standard conventional "orthogonal" packages as well.

Normal packages with their "orthogonal" leads could create micro cracks in the plastic housings of the packages, allowing moisture to penetrate inside the package until it reached the chip and as a result, the chip will fail prematurely. The Packages with Oriented Leads prove that we gain an additional advantage by "orienting" the joining leads/columns, so that the "elongated" cross-section of the columns are "oriented" so that the columns would present the least amount of resistance to bending in the direction of the expected thermal deformation. By doing so, we can absorb higher thermal cycling effects, but with reduced induced stresses in the columns and in the package itself, and thus the package itself will survive these thermal cycles longer and easier, and consequently, we would improve the reliability and operating life of assemblies using these plastic packages with oriented leads/columns.

Oriented Solder Joints or Oriented Starved Joints, US Patent Nr. 7,433,201.

The Oriented Solder Joints or Oriented Starved Joints build on ALL of the above innovations, and apply what we have learned, to solder joints of BGAs, chips and similar devices. It utilizes both the value and benefits of using tall slender columns between the joined devices, plus it utilizes the concept of having these columns with an “elongated” cross-section, and where these columns are “oriented” to present the least amount of resistance to bending, in the direction of the expected thermal deformation.

My US Patent Nr. 7,433,201, issued 10/7/2008, Title: Oriented connections for leadless and leaded packages, covers this group of joints and devices.

Figs. 34 through 60 show details of the concepts. Again, please read the captions under the figures for explanations.

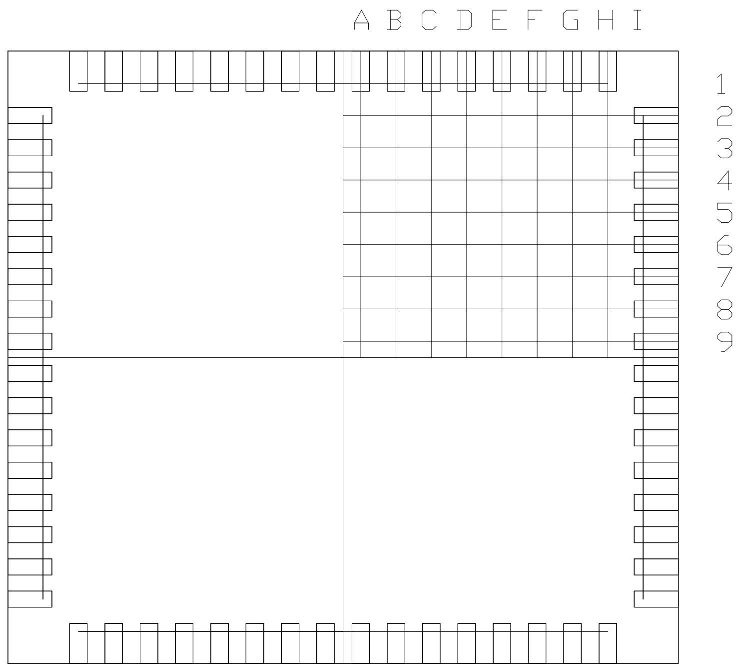


Figure 34 – Example of a “Conventional” Chip Carrier with rectangular solder pads.

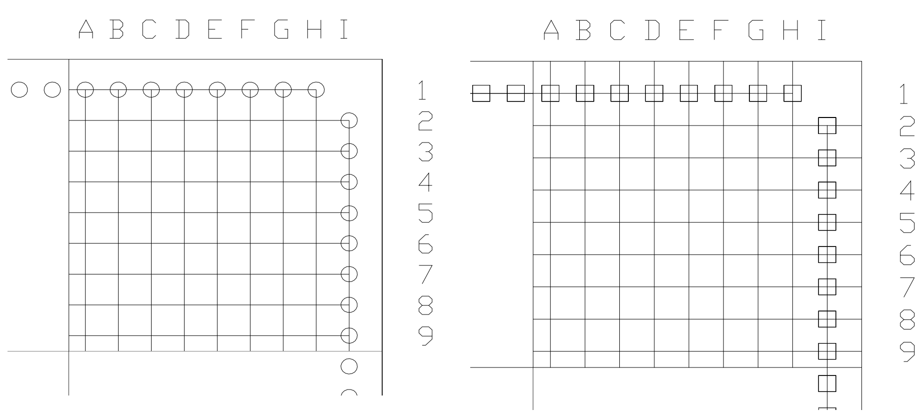


Figure 35 – Examples of “Conventional” Chip Carriers with square or circular solder pads. Only top right quadrant is shown.

Figs. 34 and 35 show examples of various devices, such as Chip Carriers, with rectangular, square or circular solder pads. It is standard practice in the industry to make most of the solder pads with these normal “orthogonal” geometries. Well, I am proposing to change that.

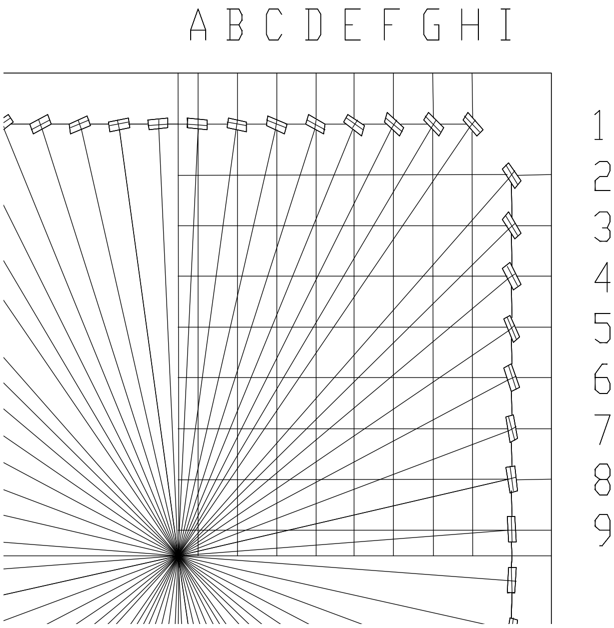


Figure 36 – Proposed shape and orientation of "elongated" solder pads. Top right quadrant is shown.

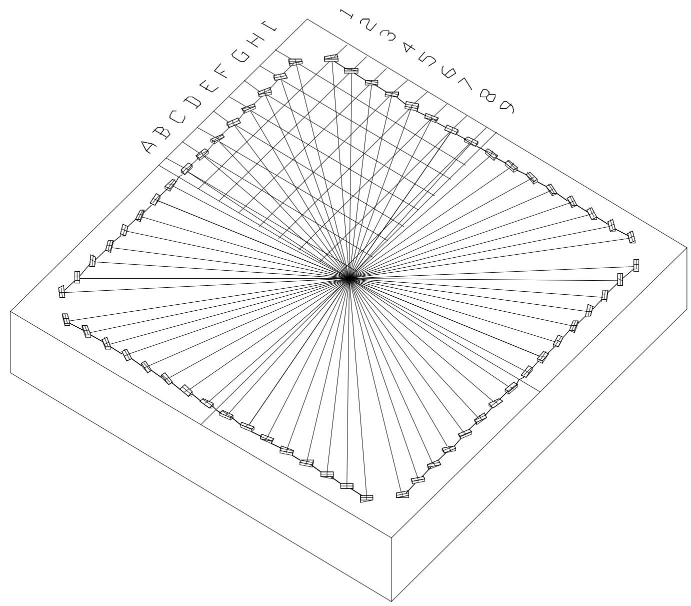


Figure 37 – Proposed shape and orientation of the "elongated" solder pads. A full package is shown.

Figs. 36 and 37 show the proposed shape and orientation of "elongated" solder pads. Figs. 38 through 41 show examples of a device, having such solder pads and where the solder joints, "built" on these pads, look like columns, but not just simple columns. The columns here have taken the general shape of the solder pads, which were at the base of the columns, and have also taken their "orientation" as well.

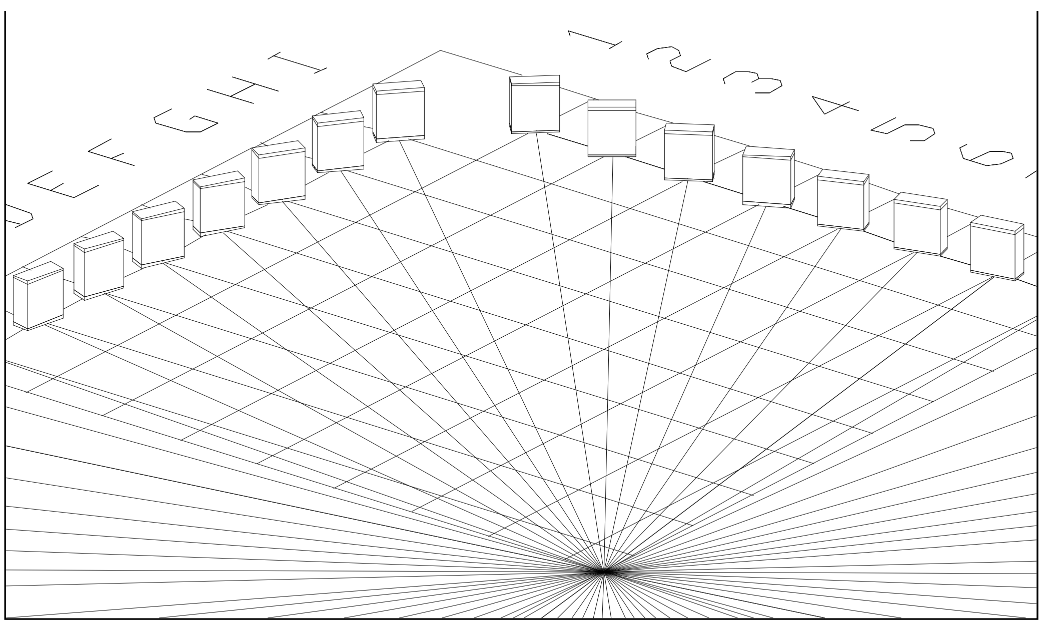


Figure 38 – Proposed shape and orientation of solder columns with "elongated" cross-section. Top right quadrant is shown.

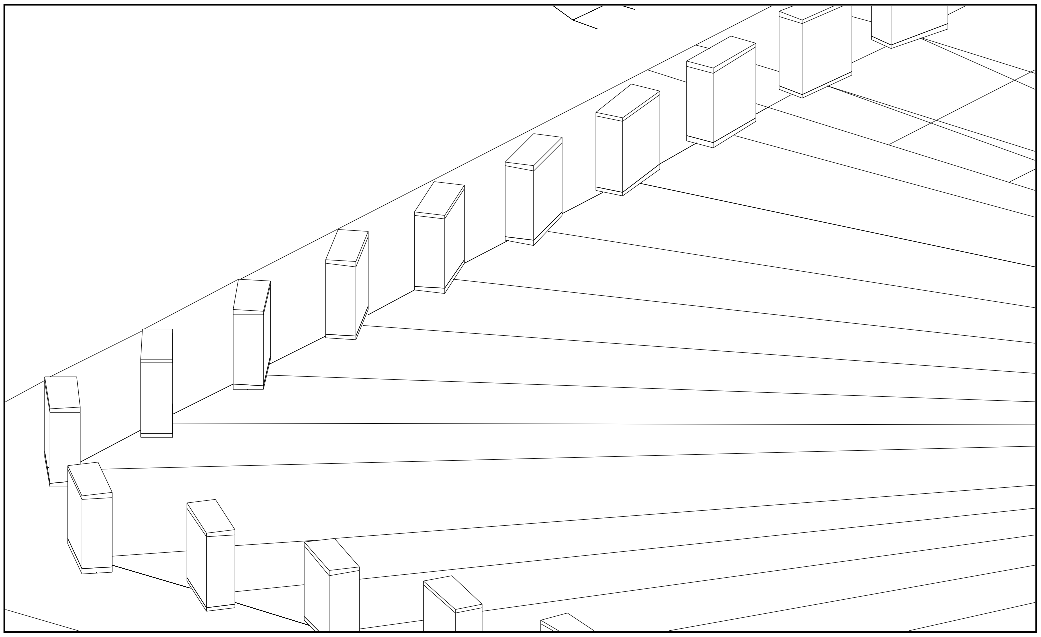


Figure 39 – Proposed shape and orientation of the solder columns with "elongated" cross-section. Top left quadrant is shown.

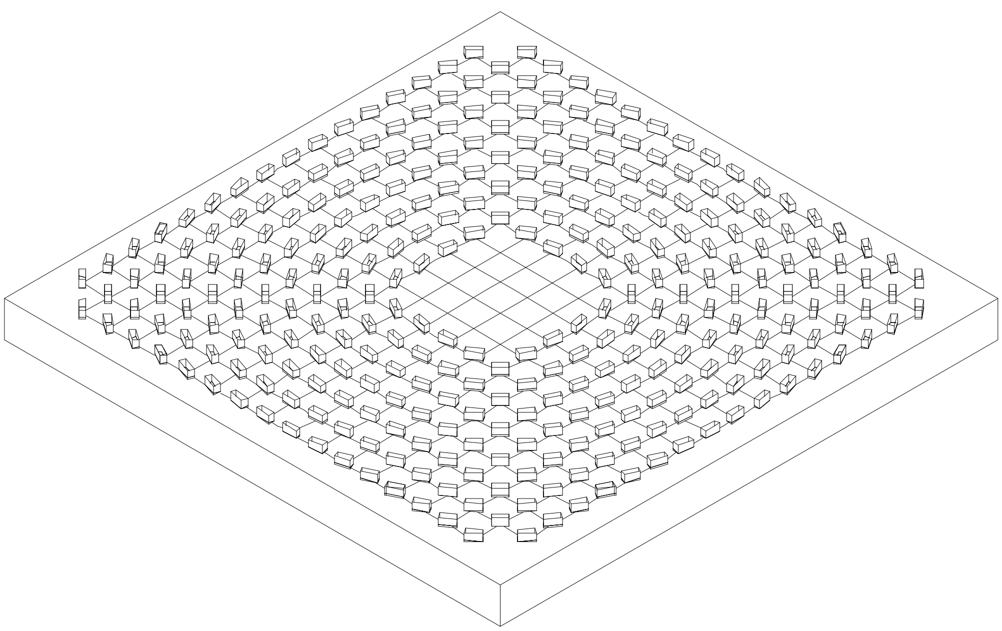


Figure 40 – Proposed shape and orientation of the solder columns on a BGA. Solder columns have an "elongated" cross-section. Full matrix is shown.

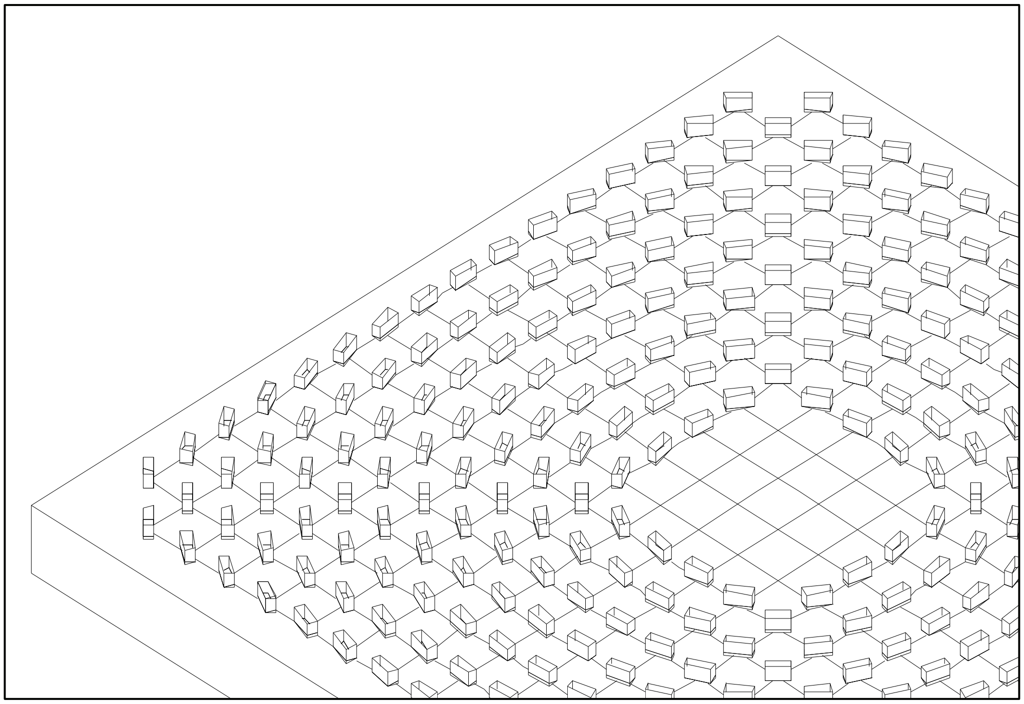


Figure 41 – Proposed shape and orientation of the solder columns on a BGA, as shown above. Partial close-up view is shown.

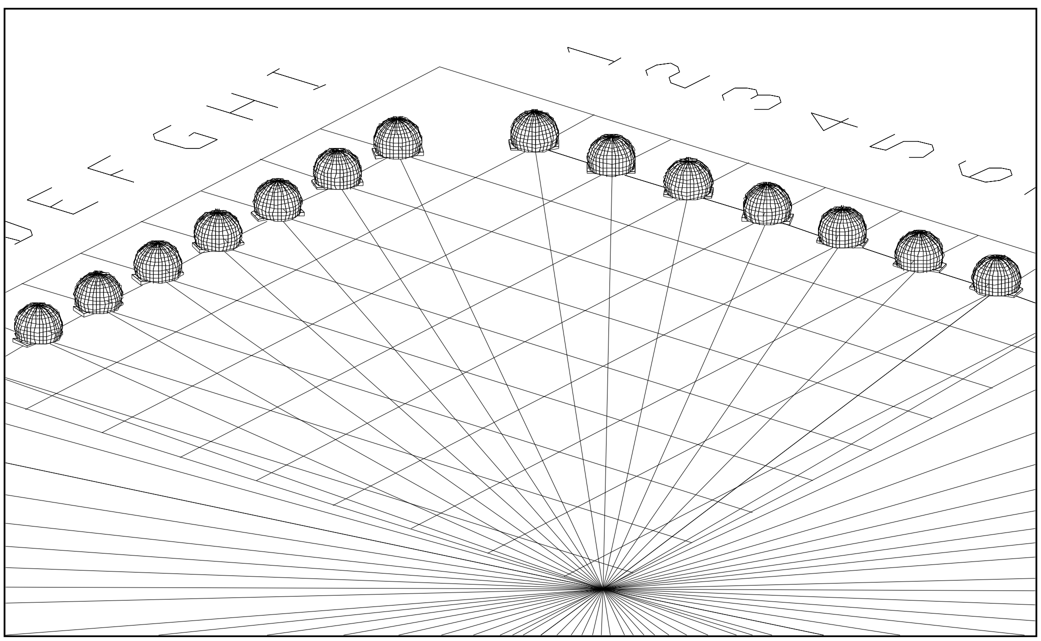


Figure 42 – Example of a Chip Carrier with "standard" solder balls, attached to "elongated" and "oriented" solder pads.

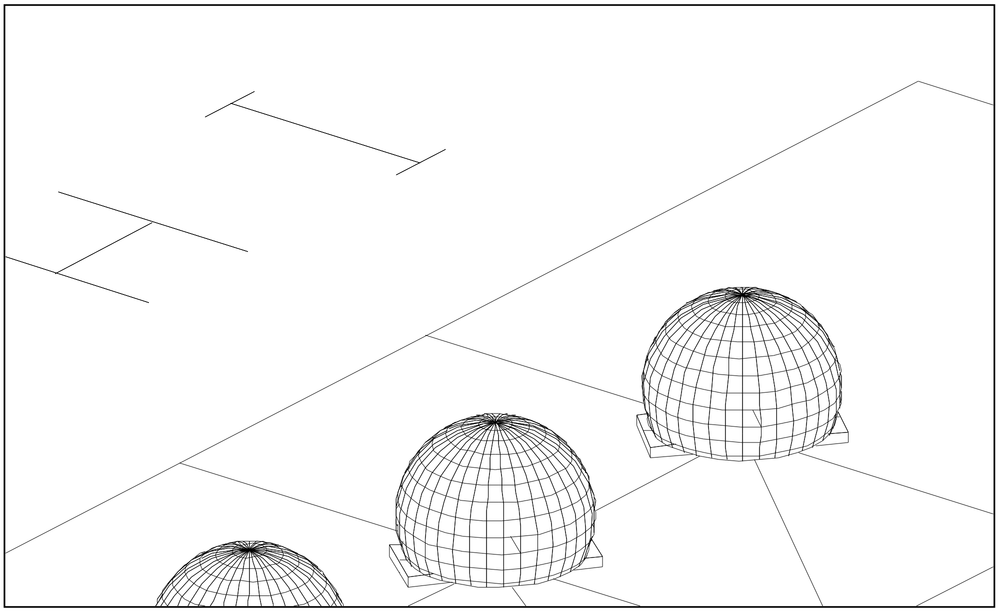


Figure 43 – Close-up view of the "standard" solder balls attached to the proposed "elongated" and "oriented" solder pads. Top right corner is shown.

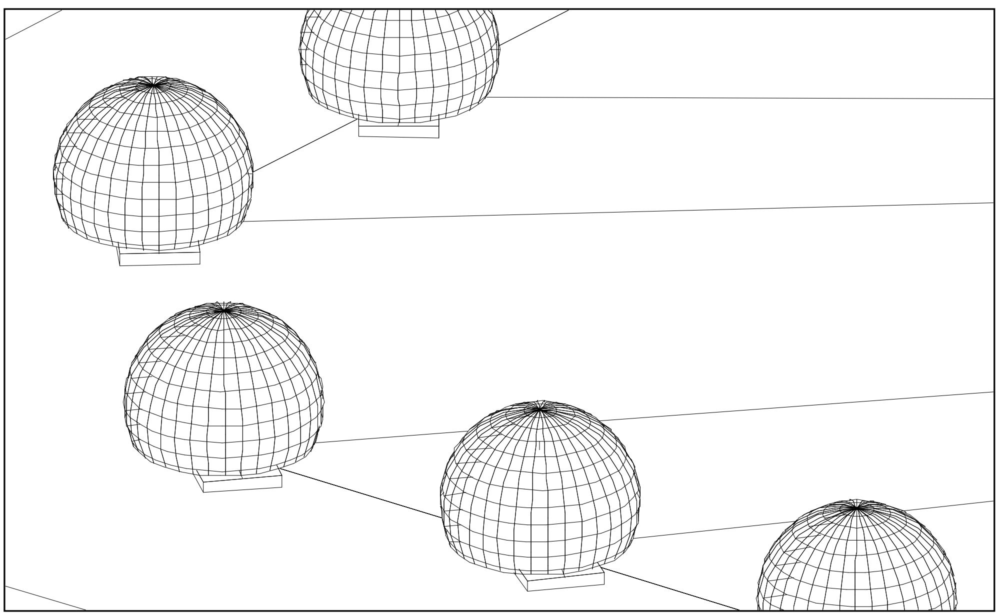


Figure 44 – Close-up view of the "standard" solder balls attached to the proposed "elongated" and "oriented" solder pads. Top left corner is shown.

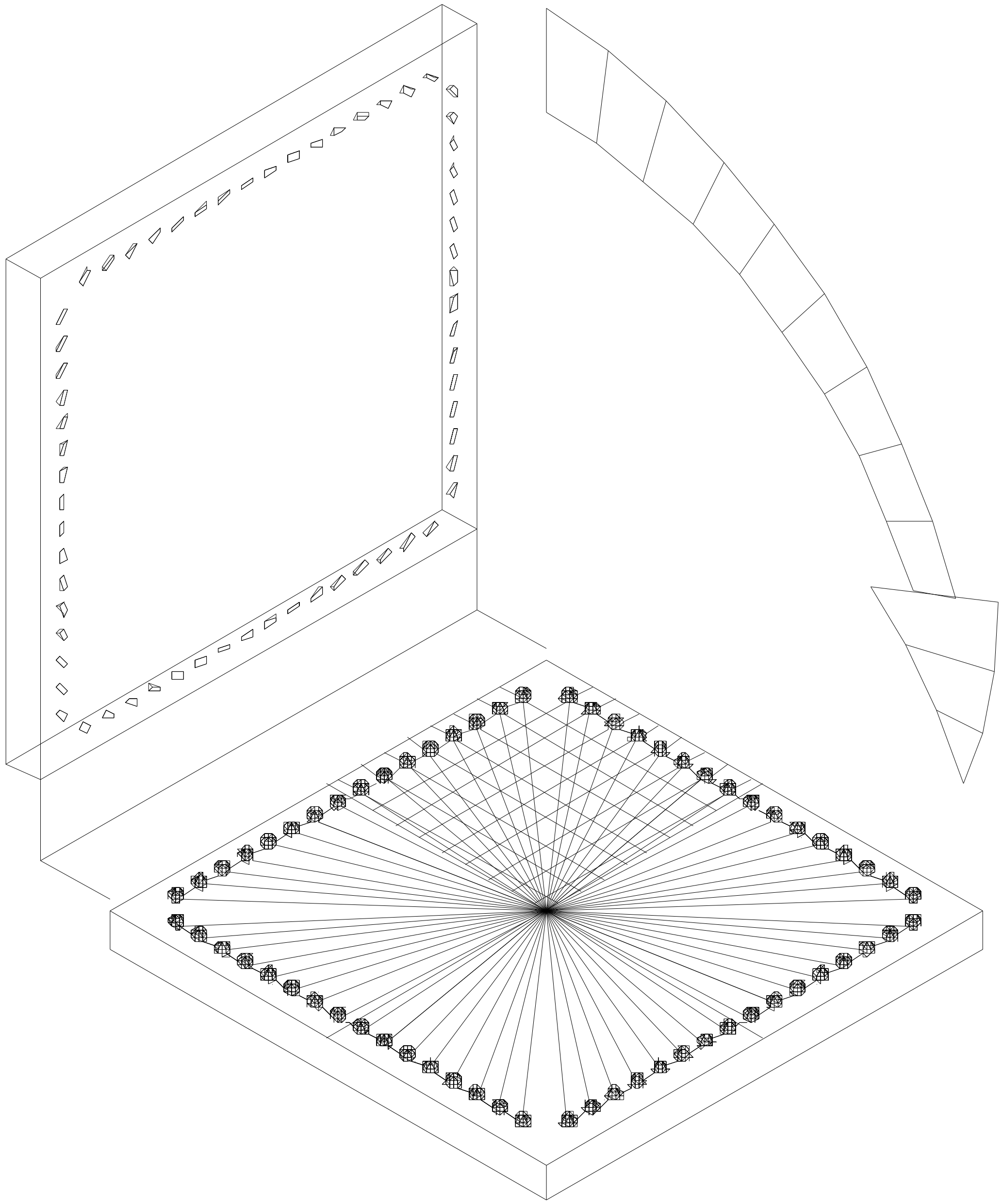


Figure 45 – Two devices to be assembled, using solder balls attached to the proposed "elongated" and "oriented" solder pads. These "elongated" and "oriented" solder pads are provided on both devices, and are matched geometrically in their respective locations.

One way to arrive to such solder columns is illustrated in Figs. 42 through 48. I will go through the typical procedure steps, which could get us there. Figs. 42 through 44 show a device, say a BGA or substrate, with oriented elongated solder pads, as described above, and with the solder balls attached to these pads. The solder balls are like the standard conventional solder balls used presently in the industry, and the balls are attached to the BGA practically using the same present industry methods. The balls at this stage would not show much of any orientation yet. Fig. 45 shows a second device, say another BGA or a chip, having matching solder pads, i.e. pads with elongated shape and oriented according to the methods proposed here, and is ready to be attached to the bottom BGA/substrate.

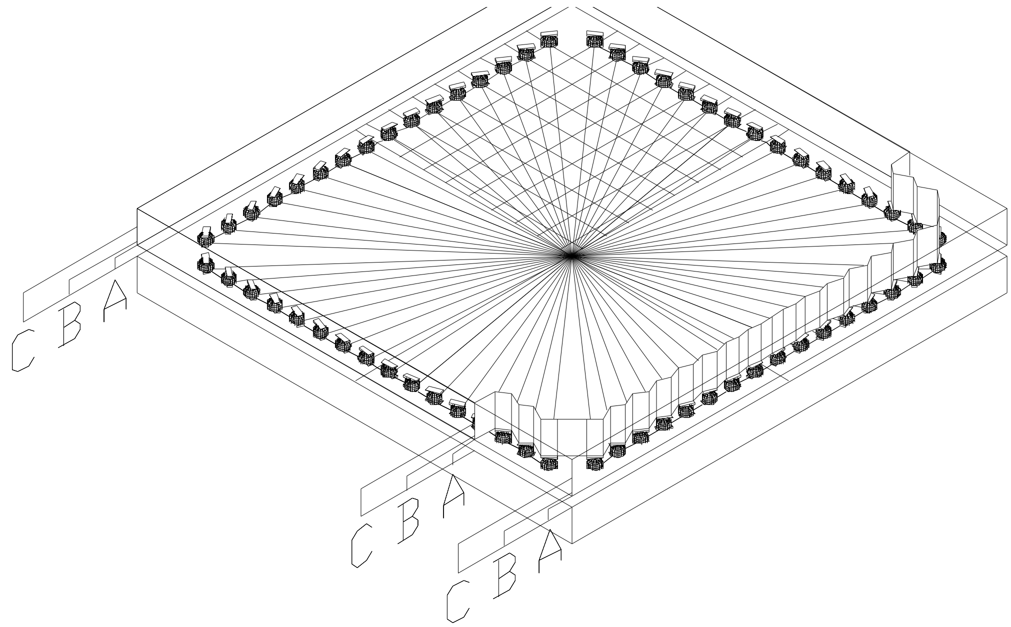


Figure 46 – The two devices sitting on top of one another, before reflow. Notice the broken front edge of the top device, to show the details of the solder balls and the solder pads. Notice also the three distinct heights referred to as A, B, and C.

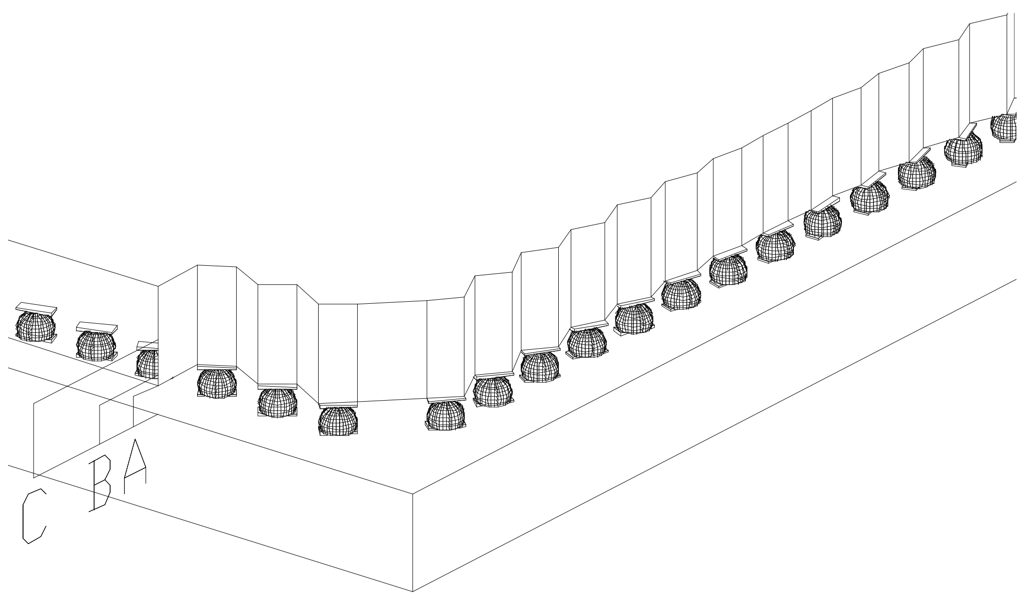


Figure 47 – Notice that, before reflow, the distance between the two devices is represented by the height A. Right at the beginning of the reflow, the solder balls will melt and could slump slightly under the weight of the top device and due to the liquidity of the solder.

Figs. 46 through 48 show what happens next. Fig. 46 shows the top device sitting on top of the solder balls, on top of the lower device. The solder balls are shown just before reflow. When this stack is heated to the point of melting the solder, the top device will most probably be pushed down on the molten solder balls and flatten them. If left on its own, it is very possible that the solder would ooze out and reach to the neighboring pads and may even bridge. However, if we control the situation properly, and see to it that such bridging does not start at all, as will be explained momentarily, then we can proceed to the next step shown in Fig. 48. Fig. 47 shows a close up view, and shows the top device "scalloped" to show what is happening with the solder joints, and it highlights the fact that the distance between the two devices equals the height referred to as "A".

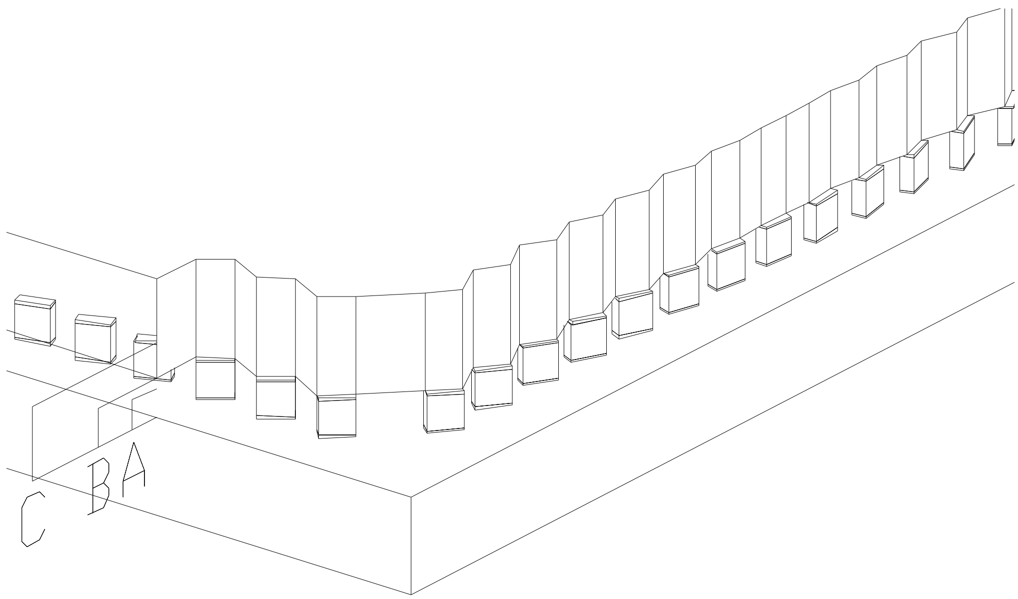


Figure 48 – By applying proper means, while the solder is still molten, we can "raise" the top device, slightly upwards, to the distance/height B, thus extending the solder joint higher, to a "column" shape. And due to the surface tension of the solder, the column will tend to take the shape of the elongated and oriented solder pads, at least near the pads, thus acquiring an elongated cross-section and being oriented properly at the same time.

Fig. 48 shows that the top device has been "pulled" upwards, by some means, from the height referred to as "A", to the height referred to as "B". This height, as will be explained later, is such that the height multiplied by the cross-sectional area of the solder joint is same as the volume in the original solder ball, but the shape of the joint at this moment would be more similar to a column having an elongated cross section, fairly similar to the elongated shape of the underlying solder pads. Because the area of the elongated cross section is smaller than the area of the cross section of the original solder ball, we expect that the height of the column would be higher than the height of the original solder ball. This means that "B" is larger than "A", due to the preservation of volume. We could stop here and let the assembly and the solder cool down and end up with solder columns, having almost uniform cross section, and where the cross section is elongated, fairly similar in shape to the solder pads. There may be some "rounding" or "filleting" of the edges, due to the inherit nature (surface tension, etc.) of solder, but it will be pretty close. The orientation of these columns would replicate the orientation of their respective solder pads. And assuming that the solder pads have been oriented appropriately the solder columns would be oriented so as to present the least resistance to bending in the direction of the expected thermal deformations.

Now, if we continue to "lift" the top device higher, while the solder is still molten, we can "raise" the top device, even slightly higher yet, thus extending the solder joint slightly taller yet, to the height "C", as shown in **Fig. 49**. The column would acquire an "hour glass" shape, because the bases near the solder pads will keep the shape of the solder the same, but the portions of the solder farther away from the pads would become "starved" and consequently smaller in size. And again due to the surface tension of the solder, the column will tend to take the shape of the elongated solder pads, at least near the pads, thus acquiring the desired elongated, and oriented, cross-section. This is where we can start calling the solder joint an "Oriented and Starved Joint".

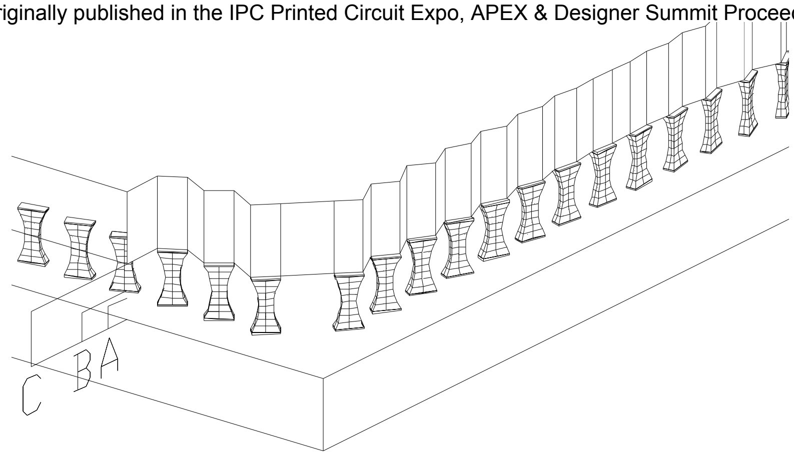


Figure 49 – By further applying the proper means, and again while the solder is still molten, we can “raise” the top device, even slightly higher yet, thus extending the solder joint slightly taller yet, to the distance or height C. The column would acquire the desired “hour glass” or “starved” shape. And again due to the surface tension of the solder, the column will tend to take the shape of the elongated solder pads, at least near the pads, thus acquiring the desired elongated and oriented cross-section.

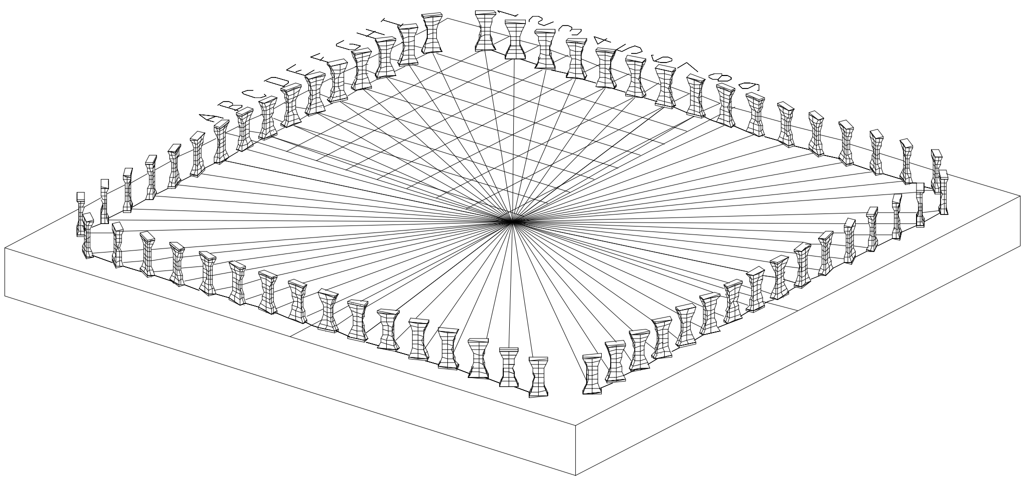


Figure 50 – Proposed shape and orientation of the solder columns with “elongated” cross-section and with “hour-glass” or “starved” shape. Top device removed for visibility.

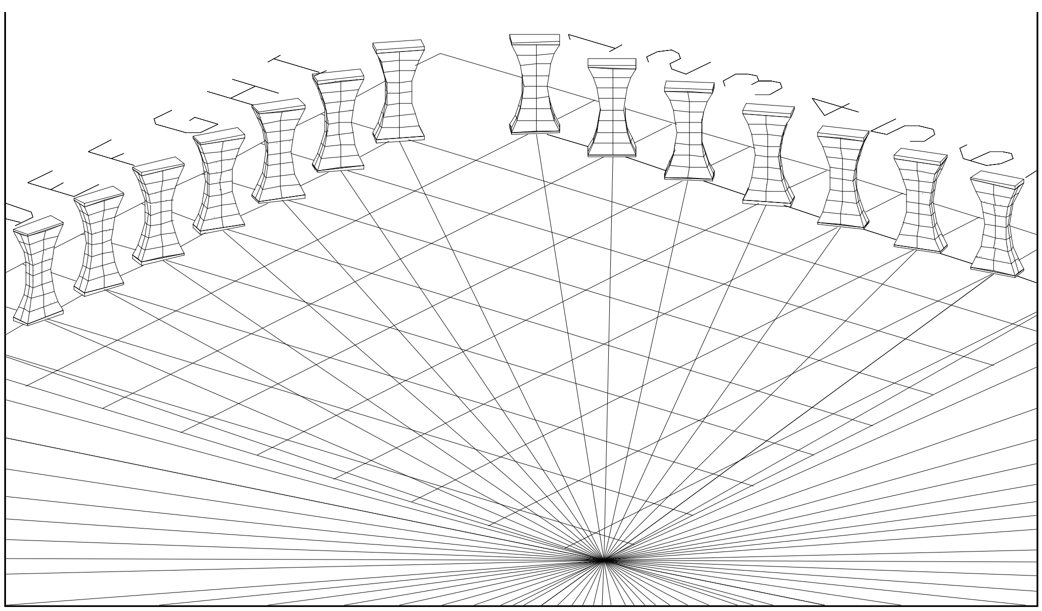


Figure 51 – Proposed shape and orientation of the solder columns with “elongated” and oriented cross-section and with “hour-glass” or “starved” shape. Top right quadrant shown.

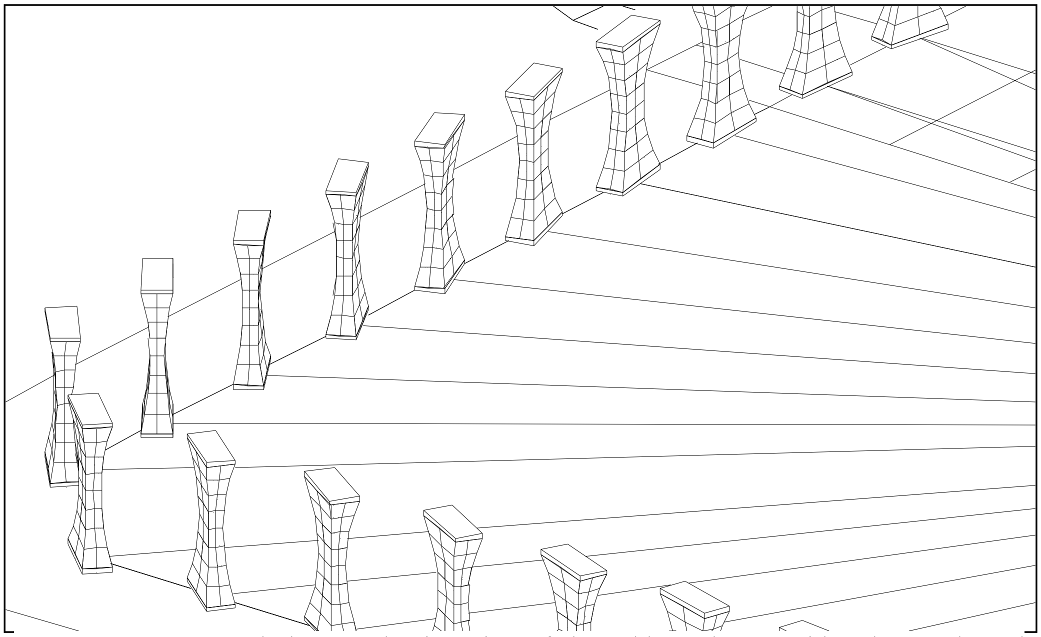


Figure 52 – Proposed shape and orientation of the solder columns with "elongated" and oriented cross-section and with "hour-glass" or "starved" shape. Top left quadrant shown.

Figs. 50 through 52 show the solder columns, as if the top device has been removed, just for visibility. They look like "starved" solder columns, each one having a cross section that is generally "elongated", and "oriented" as desired, and where the center portions of the columns is smaller than the portions near the bases, i.e. near the solder pads.

Fig. 53 shows the general shapes of the solder joints at the three stages described above. The figure at the left shows the starting shape of the solder ball. The middle figure shows the transition from the ball to the rectangular column, and the figure at the left shows the transition from the rectangular to the starved hour-glass shape column.

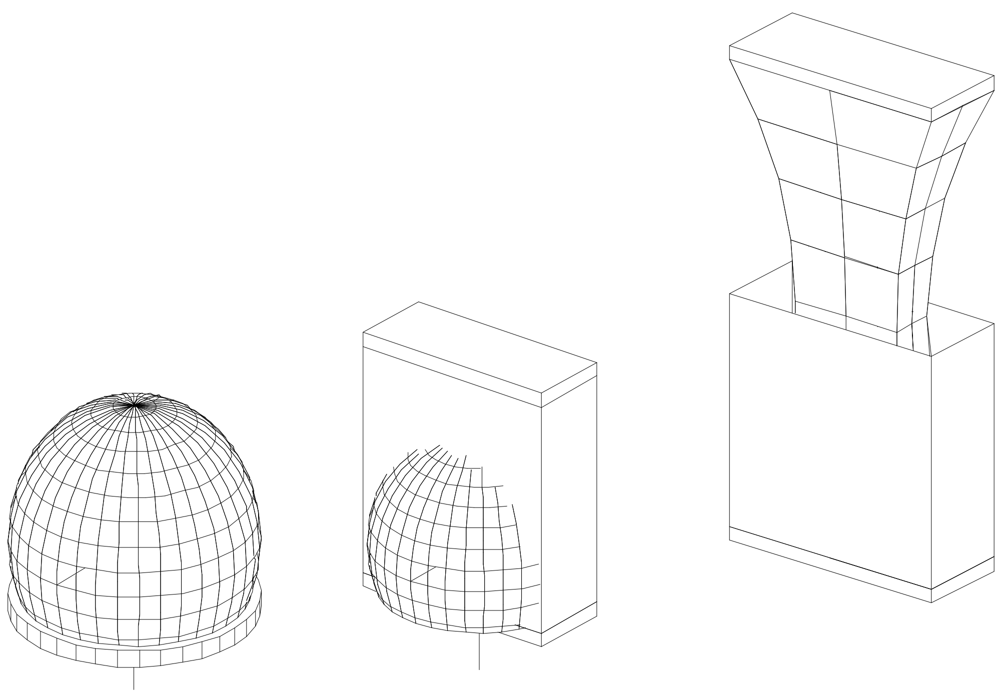


Figure 53 – This drawing shows the transformation of the shape of the solder joint, during the proposed process. From a spherical shape, to a rectangular column, to an hour-glass or starved column shape.

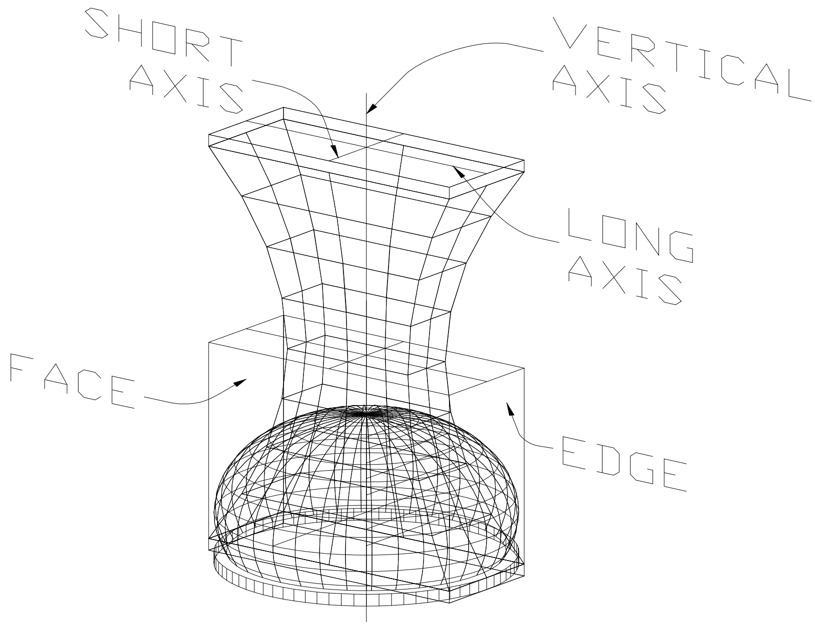


Figure 54 – These drawings show the relationship between the three shapes of the solder joints during the proposed process. All the three shapes have the same "volume" of solder.

Fig. 54 shows the relationship between the three shapes of the solder joints during the proposed process. All the three shapes have the same "volume" of solder.

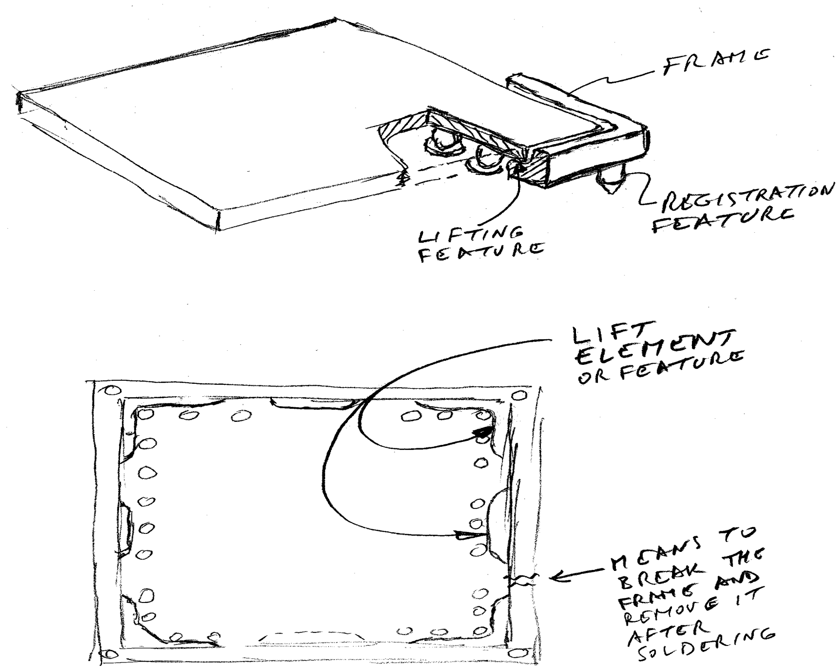


Figure 55 – This drawing shows an example of the proposed "means" to "lift" the package during the solder reflow. The "lift elements" can be made of a "heat recoverable" material, such as the "shape memory plastics" made by certain companies and is available on the market since many years.

Figs. 55 through 57 show one example of a means to do the "lifting" or "raising" of the top device, away from the bottom device, in order to create the shapes described above. **Fig. 55** shows a frame, having "features", which can do the lifting.

The top device, e.g. the BGA, would sit inside the frame, on top of the lifting features. The lifting features would have a small initial height, to match the height "A" described above. The material of the lifting features can be made out of a "shape memory" material. Raychem Corporation, now TICO, used to specialize in such materials. The materials can be "designed" or formulated to change shape at specific temperatures. So, we can formulate a polymer, which would hold its "compressed" shape until it reaches a temperature, slightly above the melting temperature of the specific solder material that will be used. Then when the temperature reaches that predetermined temperature level, the polymer would expand and revert to its original shape, i.e. its shape before being compressed. That original shape would be such that it would match the height "B", if we want to have columns of uniform cross section as shown in Fig. 48. Or the original shape of the lifting features would be so that it would match the height "C", if we want to end up with starved hour-glass joints, as in Fig. 49.

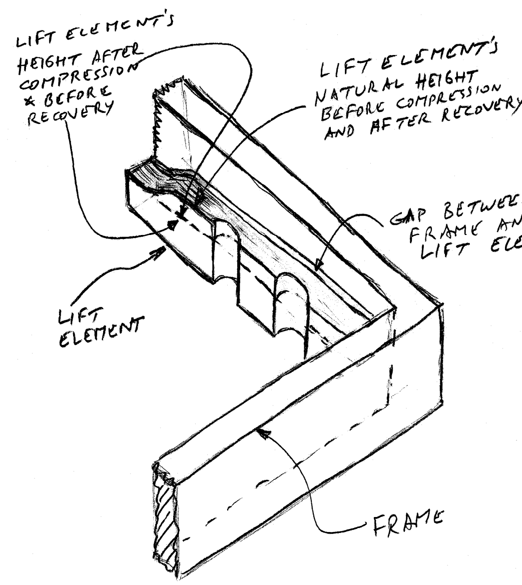


Figure 56 – This drawing shows some details of the "lifting means" example shown in the previous figure.

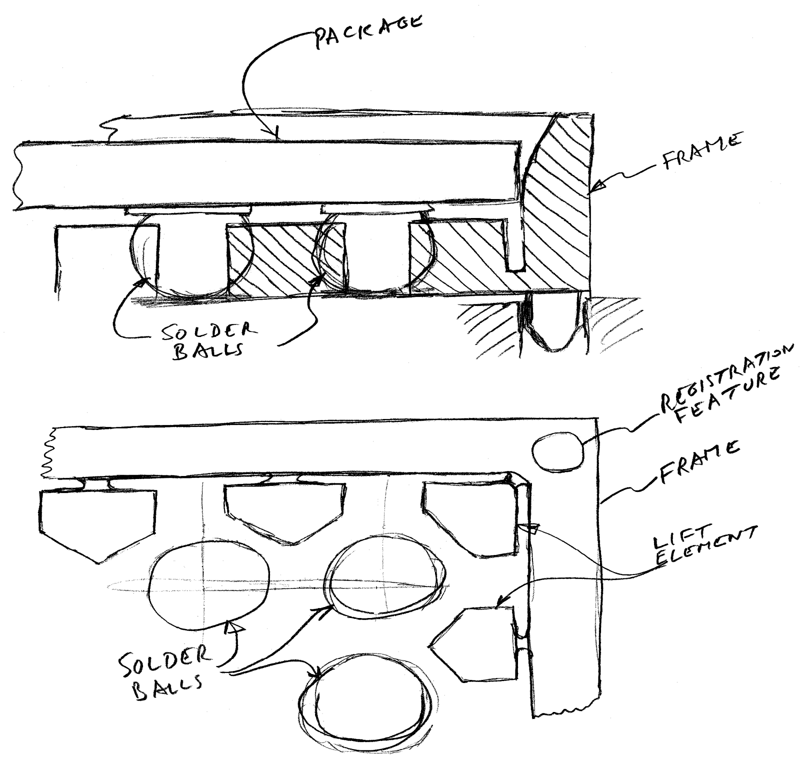


Figure 57 – This drawing shows more details of the proposed "lifting means" example shown in the two previous figures.

Figs. 56 and 57 show some details of the device shown in Fig. 55.

Other options:
The frame of the lifting means can be made of a dissolvable material. Even the lifting features can also be dissolvable. The frame does not need to be shape memory material, only the lifting features. Also, the lifting features can be made out of Tinel, another one of shape memory materials that Raychem specialized in, or any other similar material. A totally different approach would be to create a "mechanical" gadget, which would do the "lifting" according to some control protocol, based on the temperatures and timing of the reflow process.

Other embodiments
Figs. 58 through 60 show some other methods to accomplish similar end results, i.e. to obtain rectangular solder joints and/or starved solder joints, whether oriented or not.

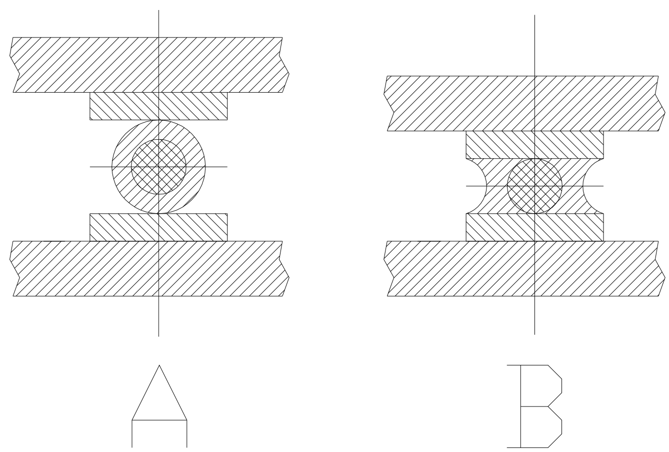


Figure 58 – This drawing shows a solder ball with a copper ball in its center. Fig. A shows it before reflow and Fig. B shows it after reflow.

Fig. 58 shows a solder ball that incorporates a ball, made of a material that would not totally melt during the expected solder process of the ball material. It can be made of copper or a solder material of higher melting temperature. The end effect or desired result is that after the reflow process, there will be a higher space between the top device and the lower one. This would closely simulate the column effect described above. It may create a combination of stresses, including some shear, some bending and most probably some "torque", which would be equivalent to some tension and compression, similar to those induced due to bending.

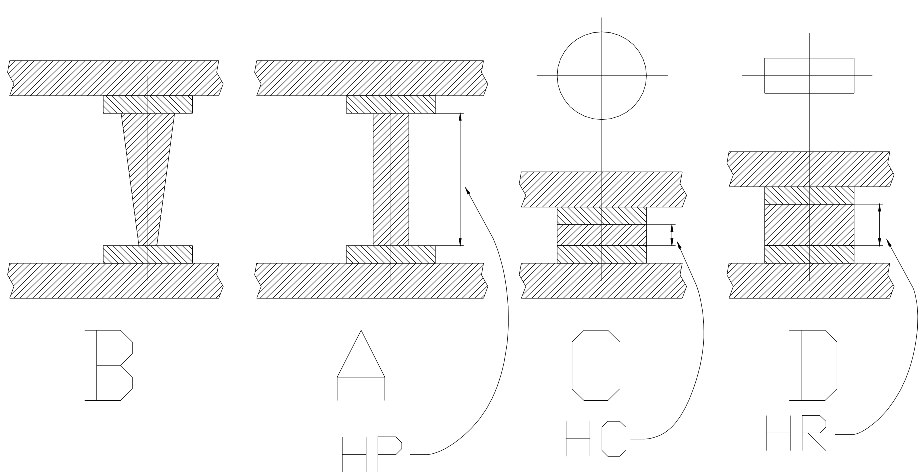


Figure 59 – The two solder columns in Figs. A and B have the same volume. Fig. C shows the expected resulting height, after reflow, if the solder pads are circular. Fig. D shows the resulting height if the solder pads are rectangular.

Figs. 59 and 60 show yet another way of creating tall solder columns, and if the solder volumes are chosen properly, we would even get “starved” hour-glass shaped solder columns. First let us look at **Fig. 59**. Here we see that the two solder columns in Figs. A and B have the same volume, in spite of the difference in their general original shape or profile. Fig. C shows the expected resulting height, after reflow, if the solder pads are circular. Fig. D shows the resulting height if the solder pads are rectangular. The heights in Figs. C and D will be controlled mostly by the weight of the top device, by the shape of the solder pads, and by the inherent characteristics, e.g. surface tension, of the solder material.

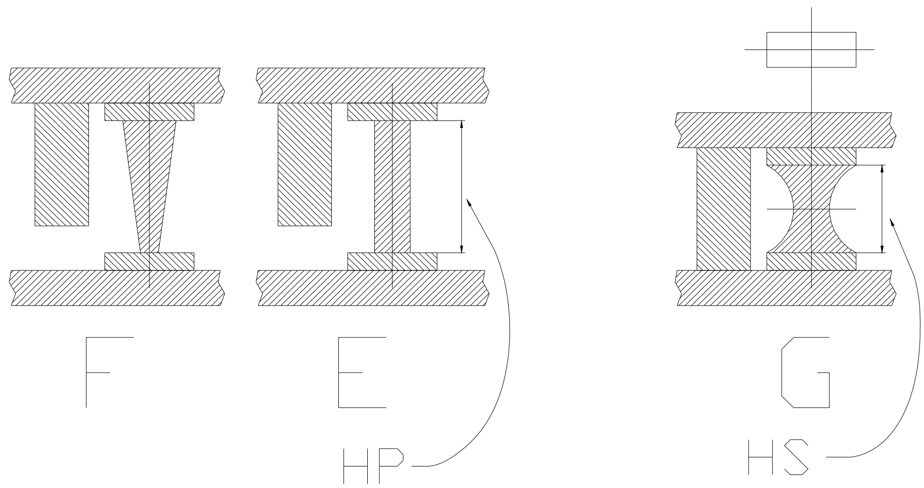


Figure 60 – The two solder columns in Figs. E and F are identical to the ones shown in A and B in the previous figure. The difference here is that adjacent to each column here is a “stop” with a certain predetermined height. The stops do not melt during reflow. The result after reflow is expected to look as in Fig. G.

Next, let us look at **Fig. 60**. First let us look at the left hand side of the figure. The two solder columns in Figs. E and F are identical to the ones shown in A and B in the previous figure. The difference here is that next to each column here is a “stop” with a certain predetermined height. The stops do not melt during reflow. The result after reflow is expected to look as in Fig. G. Again, depending on the volumes of the starting solder material, and the height of the “stops”, the final shape of the solder joints could be either a column of uniform cross section as shown in Fig. 48, or as a starved hour-glass joint, as in Fig. 49.

Filled Solder

In any and most of the above solder joints, we can use “filled solder” to improve the chances that the solder would do what we want it to do. We need to experiment with the kind of filler, e.g. copper powder, and the particle size of the filler as well as the percentage of filler to the base metal.

Conclusion

I have described several concepts for creating solder joints between BGAs and Substrates, or similar electronic assemblies, which could be used to improve the operating life and reliability of such assemblies. Most of these new concepts are just that, just concepts. They need to be prototyped and tested, and most probably, they would need to be tweaked or further developed, before they would become viable products or methods, which can be accepted by the industry.

As this stage, the best that can happen is that some interested parties would come forward and volunteer to provide the effort and facilities, to do the required development work. I am more that willing and ready to work with such parties on such development work.

References

A. Cherian Recent Patents and/or Inventions, issued or pending:

1. US Patent Nr. 6,884,707, issued 4/26/2005, Title: INTERCONNECTIONS [Non-Wicking Connecting Column(s)]
2. US Patent Nr. 7,196,402, issued 3/27/2007, Title: Interconnections [Packages with Oriented Leads]
3. US Patent Nr. 7,433,201, issued 10/7/2008, Title: Oriented connections for leadless and leaded packages [Oriented Solder Columns, or Oriented Starved Columns]
4. Patent Application Nr. 11/689,558, filed 3/22/2007, Title: NO-WICK(TM) 2 INTERCONNECTIONS [Second patent application on the Non-Wicking Connecting Column(s)]

5. Patent Application Nr. 12/154,753, filed 05-27-2008, Title: TFCC (TM) & SWCC (TM) thermal flex contact carriers [Not discussed in this paper]
6. Patent Application Nr. 12/197,309, filed 8/24/2008, Title: OC2 ORIENTED CONNECTIONS 2

A. Older Related Patents:

7. U.S. Patent # 4,655,382, "Materials for use in Forming Electronic Interconnect", Geoffrey Wong et al, Apr 7, 1987, Raychem Corporation, Menlo Park, CA.
8. U.S. Patents # 4,664,309, "CHIP MOUNTING DEVICE", May 12, 1987, Gabe Cherian, et al, Raychem Corporation, Menlo Park, CA.
9. U.S. Patents # 4,705,205, "CHIP CARRIER MOUNTING DEVICE", Nov. 10, 1987, Gabe Cherian, et al, Raychem Corporation, Menlo Park, CA.
10. U.S. Patents # 4,712,721, "SOLDER DELIVERY SYSTEMS", Dec 15, 1987, Gabe Cherian, et al, Raychem Corporation, Menlo Park, CA.

B. Cherian Paper Presentations:

11. "Use of Discrete Solder Columns to Mount LCCC's on Glass/Epoxy Printed Circuit Boards", by Gabe Cherian, Raychem Corporation, Menlo Park, California, USA, Fourth Annual International Electronics Packaging Conference, International Electronics Packaging Society (IEPS), Baltimore, Maryland, October 29-31, 1984, pp. 701-710.
12. "Solder Columns for Surface Mounting of Leadless Ceramic Chip Carriers on Glass/Epoxy Printed Circuit Boards", by Gabe Cherian, Raychem Corporation, Menlo Park, California, USA, 1985 International Symposium on Microelectronics, International Society for Hybrid Microelectronics (ISHM), Anaheim, California, November 11-14, 1985, pp. 17-22.
13. "New Solder Column Alloy Improves Reliability of Chip Carrier Assemblies", by Gabe Cherian, Craig Wynn and Harry White, Raychem Corporation, Menlo Park, California, USA, 18th International SAMPE Technical Conference "Materials For Space – The Gathering Momentum", Society for the Advancement of Material and Process Engineering (SAMPE), Seattle, Washington, October 7-9, 1986, pp. 1056-1070.
14. "BGA MOUNTING USING IMPROVED SOLDER COLUMNS", by Gabe Cherian, Cherian Enterprises, Sun Valley, Idaho, USA, presented at IPC Printed Circuit EXPO, Long Beach, CA, March 2003.
15. "Higher Reliability "Oriented" Plastic Packages", by Gabe Cherian, Cherian Enterprises, Sun Valley, ID, at IPC ECWC10 Conference, IPC Printed Circuits Expo®, SMEMA Council APEX® and Designers Summit 05, Anaheim, CA, February 2005.

C. Third Party Papers:

16. "Thermal Cycling Test Report for Ceramic Column Grid Array Packages – CCGA", by Raymond Kuang, Lijie Zhao, Actel Corp, 2061 Stierlin Ct., Mountain View, CA, 94043, USA, "CCGA Thermal Cycling Test Report", http://www.actel.com/documents/CCGA_board_level_testing_report.pdf.
17. "Ceramic Column Grid Array", Application Note AC190, by Actel Corporation. August 2008, © 2008 Actel Corporation, http://www.actel.com/documents/CCGA_AN.pdf.
18. "Acceleration Factors and Thermal Cycling Test Efficiency for Lead-Free SN-AG-CU Assemblies", by Jean-Paul Clech, EPSI Inc., Montclair, New Jersey, USA, SMTA International, Chicago, IL, Sept. 25-29, 2005.
19. "Underfill Update: NUF, MUF, WUF, and Other Stuff", by Dr. Ken Gilleo, Cookson Electronics.

D. References used with my paper on Plastic Packages with Oriented Leads, presented at IPC ECWC10 Conference, IPC Printed Circuits Expo®, SMEMA Council APEX® and Designers Summit 05, Anaheim, CA, February 2005 [15]**:**

20. "Evaluating the Moisture Barrier" by J. J. Licari, Ph.D., Advanced Packaging Magazine, July-Aug 1997.
21. "Bonding Strengths at Plastic Encapsulant-Gold-Plated Copper Leadframe Interface," by S. Yi, J. Kim et al., Microelectronics Reliability, January 2000, p. 1212.