Reliable Solder Columns to Replace Solder Balls in Large 2.5D Heterogeneous Packages

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Abstract

Solder balls are well suited for interconnecting normal sized ball grid array (BGA) components to printed circuit boards (PCB). However, solder balls are prone to cracking (failure) caused by excessive stresses inherently found in advanced packaging such as large-sized heterogeneous 2.5D packages where multiple dies are placed side-by-side. The growth trend is to make larger and larger BGA processors exceeding 60x60mm in size for AI and data centers. A plethora of new processor substrate and interposer designs are coming on line such as Chip-on-Wafer-on-Substrates (CoWoS). For that reason, more instances of solder ball delamination and cracking on large-sized BGA packages are probable.

Solder columns were produced more than 50 years ago to reduce cracking in large ceramic packages, especially for use in harsh environments found in aerospace and defense applications. However, such legacy solder column technology is limited to Tin-Lead (SnPb) alloys. The challenge is to make Lead Free solder columns that satisfy demand for RoHS compliance, while still providing adequate stress relief (compliancy) for extending the operational life of large sized heterogeneous 2.5D processors for mission critical applications.

This paper describes our ongoing work to innovate non-collapsible, compliant Lead-Free Braided Copper Solder Columns to reduce strain caused by the Coefficient of Thermal Expansion (CTE) mismatch between large BGA packages and FR4 PCBs. A braid, consisting of 16 fine copper alloy wires, serves as an exoskeleton sleeve around a solder column to provide mechanical support as well as compliancy. This novel solder column technology supports market trends to scale up the size of chip packaging while maintaining reliability.

Our focus was to quickly characterize Lead-Free solder column core materials and braiding alloys by employing "Fail-Fast" destructive accelerated mechanical bend testing in our lab. Since there is an ongoing interest in Tin-Lead alloys, this paper also discusses data on Tin-Lead alloys for comparative purposes.

Key words

Braided Copper Solder Column, Column Grid Array, Heterogeneous 2.5D BGA Packaging, Solder Ball.

I. Introduction

This paper describes a new generation of non-collapsible, RoHS compliant Lead-Free Copper Braided Solder Columns that are designed to absorb destructive strain caused by differences in the Coefficient of Thermal Expansion (CTE) of materials between large sized heterogeneous 2.5D packages and FR4 printed circuit boards (PCB). This novel solder column technology is intended replace solder balls typically found on ball grid array (BGA) packages. This paper reviews the methodology used in our lab to characterize materials comprising copper braided solder columns as well as suggestions how to use solder columns as a drop-in replacement for solder balls.

Solder balls are well suited for interconnecting small sized (less than 50x50mm) organic BGA components to a PCB.

Nowadays, BGA components are ubiquitous with billions of units in the field; however, solder balls may be prone to cracking, leading to catastrophic failure particularly in large sized chips. In small sized BGA components, CTE mismatch is manageable, with relatively few failures. Recently, the growth trend is towards larger and larger BGA processors, especially for data centers and AI applications. Typically, materials found in heterogeneous 2.5D BGA packages include: multiple silicon die, copper, nickel, gold, organic substrates, solder mask, build up films, epoxy, adhesives, metal heat spreaders and solder. These multiple materials cause competing CTE mismatch in large heterogeneous 2.5D BGA packages.

Experienced package designers employ a myriad of optimization techniques to compensate for strain (stress) caused by CTE mismatch. Numerous papers [1] have been presented by others that demonstrate the physics of bringing together disparate materials, especially in harsh environments where large temperature swings are common and the Distance from the Neutral Point (DNP) [2] is large. Arguably, even with the most carefully chosen choreography of materials to mitigate stress, in the end, applied physics has the final word as to what design will survive and what will eventually fail.

As presented in this paper, large-sized 2.5D Heterogeneous BGA packages means substrates are 60mm to 120mm per side. BGA packages can be square or rectangular.

II. Selecting a Column

Copper Braided Solder Columns, shown in fig. 1(a) are a recommended drop-in replacement for solder balls for large BGA packages. Solder columns come in a variety of sizes and are available in a variety of alloys. Packaging designers will note differences in appearance and function of solder columns when compared to solder balls. Solder columns are cylindrically shaped and are roughly 25% smaller in diameter than the BGA ball pad.

Solder columns must be smaller in diameter than the ball pad in order to form a secure solder fillet around the circumference of the column as shown in fig. 1(b). Ideally the solder fillet surrounds the column fully 360º around the base of the column; however, in some cases a fillet surrounding at least 270º of the column is acceptable. A solder paste stencil is typically used to apply an appropriate amount of solder paste onto the BGA pads prior to reflow of the columns.

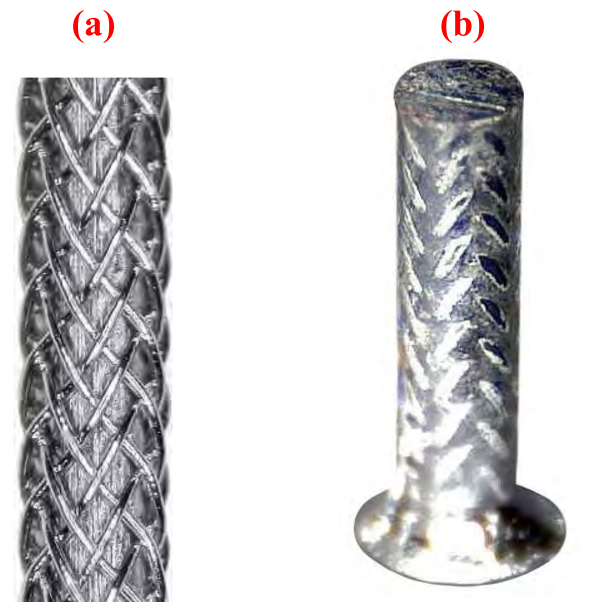

Fig. 1: (a) Copper Braided Solder Column shown prior to solder coating. (b) Braided Solder Column (after solder coating) with solder fillet mounted to a BGA pad.

In stark contrast, solder balls are spherical in shape (before reflow) and are roughly 20% larger in diameter than a solder mask defined (SMD) BGA pad as shown in fig. 2(a). Alternatively, for non-solder mask defined pads (NSMD), solder balls (before reflow) are generally the same diameter as the BGA pad as shown in fig. 2(b).

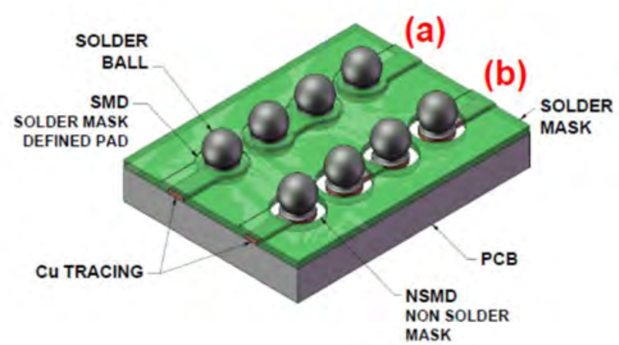

Fig. 2: (a) Solder balls are roughly 20% larger than the SMD solder mask defined pad opening per table 4-4 of IPC-7095B. (b) Solder balls on NSMD pads are generally the same size as the BGA ball pad.

Table I shows recommended column diameter for BGA packages with SMD ball pads. Table II shows the recommended column diameter for NSMD ball pads. The pad pitch and ball diameter are provided for reference only in both tables.

Table I. Recommended column diameter for BGA packages with Solder Mask Defined Pads (SMD)

Pad Pitch	Pad Diameter SMD	Ball Diameter Before Reflow	Column Diameter
0.65mm	0.28mm	0.35mm	0.20mm
0.80mm	0.33mm	0.40mm	0.25mm
0.80mm	0.35mm	0.45mm	0.28mm
0.80mm	0.40mm	0.50mm	0.30mm
0.80mm	0.45mm	0.55mm	0.33mm
1.0mm	0.50mm	0.63mm	0.38mm

Table II. Recommended column diameter for BGA packages with Non-Solder Mask Defined Pads (NSMD)

Pad Pitch	Pad Diameter NSMD	Ball Diameter Before Reflow	Column Diameter
0.65mm	0.30mm	0.30mm	0.20mm
0.80mm	0.35mm	0.35mm	0.25mm
0.80mm	0.40mm	0.40mm	0.30mm
0.80mm	0.45mm	0.45mm	0.35mm
1.0mm	0.50mm	0.50mm	0.38mm
1.0mm	0.60mm	0.60mm	0.40mm
1.0mm	0.80mm	0.80mm	0.50mm

The column length to column diameter (aspect ratio) typically ranges from 4:1 to 6:1, although other ratios are listed in Table III for reference. Generally, longer columns are more compliant and absorb more strain (stress) caused by CTE mismatch. Shorter columns exhibit reduced compliancy. In practice, the entire array of solder columns is planarized to a defined length after mounting and reflow to the BGA package. A suitable column length may be derived experimentally. The solder column length is critical in the interconnection thermal fatigue reliability when joining a chip carrier to a standard FR4 PCB. [3]-[4].

Table III. Typical column length to diameter (Aspect Ratio)

Column Diameter	3:1	4:1	5:1	6:1	8:1
0.20mm	-	-	1.0mm	1.3mm	1.6mm
0.25mm	-	1.0mm	1.3mm	1.5mm	2.0mm
0.28mm	-	1.1mm	1.4mm	1.7mm	2.2mm
0.30mm	-	1.2mm	1.5mm	1.8mm	2.2mm
0.33mm	1.0mm	1.3mm	1.6mm	2.0mm	2.2mm
0.35mm	1.0mm	1.4mm	1.7mm	2.2mm	-
0.38mm	1.3mm	1.5mm	2.2mm	-	
0.40mm	1.3mm	1.6mm	2.2mm	-	
0.50mm	1.5mm	2.2mm	2.5mm	-	

III. Materials

Braided solder columns are comprised of a solid solder core material surrounded by an exoskeleton braided sleeve [5] as shown in Table IV and Table V. For this paper, two copper alloys were tested for the braid: C172 Beryllium Copper (BeCu) and Palladium Coated Copper (PCC). Three braid wire diameters: 25um, 38um and 50um were tested. Six different solder core (mandrels) were tested ranging from 0.20mm to 0.40mm After braiding, columns are coated with hot liquefied solder to bond the braided sleeve to the solder core. We ran trials with four different hot liquefied solder alloys as shown in Table VI. Sn90/Ag3.5/Bi0.5/In6.0 produced the best coating results for lead free columns. Eutectic Sn63/Pb37 hot liquefied solder produced the best coating results for tin-lead columns.

This unique braided column construction provides an electrically conductive interconnect between the BGA chip package and the PCB. The column is mechanically compliant to absorb strain (stress) caused by differences in CTE mismatch. The exoskeleton sleeve prevents the column from collapsing during secondary reflow of the BGA chip package to the PCB.

Table IV. Lead-Free Column Materials.

Result	Solder Core - Diameter	Braid	Fig.
1st	$SnSb_{(1)}$ – 0.40mm	BeCu 25um	7
2nd	SAC305 – 0.40mm	BeCu 25um	7
3rd	$SnSb_{(2)}$ – 0.40mm	BeCu 25um	7
4th	SCN305 - 0.40mm	BeCu 25um	7

Column Size: 0.5mm x 2.2mm

Table V. Tin-Lead Column Materials.

Result	Solder Core - Diameter	Braid	Fig.
1st	Pb80/Sn20 - 0.35mm	BeCu 38um	8
2nd	Pb80/Sn20 - 0.40mm	BeCu 25um	8
3rd	Pb80/Sn20 - 0.30mm	BeCu 50um	8

Column Size: 0.5mm x 2.2mm

Table VI. Solder Coating Materials

Solder Coating Alloy	Lead Free	Tin Lead	Result
Sn90/Ag3.5/Bi0.5/In6.0	X	-	Pass
Sn63/Pb37 Eutectic	-	X	Pass
Sn96.5/Ag3.0/Cu0.5	X	-	Fail
Sn62/Bi37/Cu0.5/Sb1.0	X	-	Fail

Column Size: All

IV. Accelerated Destructive Bend Testing

We employed a technique known as "Fail Fast" in order to quickly narrow the range of acceptable materials that warranted further investigation. We organized a series of accelerated destructive bend tests using thousands of individual columns across multiple alloys and wire diameters. Our intention was to rapidly identify the material alloys, core diameters and braid wire diameters that performed the best (most reliable). Likewise, we wanted to identify the materials with the worst performance (least reliable) and discard those from future testing.

We populated a comparison matrix of the different materials to undergo testing which included both Lead-Free and Tin-Lead alloys in order to better understand how Lead-Free alloys compare in reliability to lead-bearing alloys.

Solder columns were mounted and reflowed onto a BGA Device Under Test (DUT). We divided each BGA substrate into quadrants and reflowed hundreds of solder columns for each test. We used separate substrates for Lead-Free and Tin-Lead to avoid misidentification. We applied solder paste to the DUT substrates. Sn90/Ag3.5/Bi0.5/In6.0 (particle size T4) solder paste was applied to the Lead-Free DUT substrates as shown in Table VII. Eutectic Sn63/Pb37 solder paste (particle size T4) was applied to the lead-bearing solder columns. Columns were reflowed daisy chain BGA substrates using different stencil thickness shown in Table VIII. After reflow a solder fillet formed around each column as shown in fig. 3.

Table VII. Solder Paste and Reflow Temperature

Type	Paste Alloy	Reflow Temperature
Lead-Free	Sn 90/Ag3.5/Bi0.5/In6.0	235°C
Tin-Lead	Sn63/Pb37	215°C

Table VIII. Solder Paste Stencil Thickness

Pad Diameter	Column Diameter	Paste Stencil Thickness
0.60mm	0.25 to 0.35mm	150um
0.80mm	0.50mm	200um

Fig. 3: Copper Braided Solder Columns attached to daisy chain test vehicle ceramic package.

We modified a MARK-10 Series F Advanced Test Frame with IntelliMESUR® Software with fixturing made in our lab. DUT substrates were mounted in a graphite chuck and the free end of the solder columns were articulated with push-pull bending action shown in fig. 4.

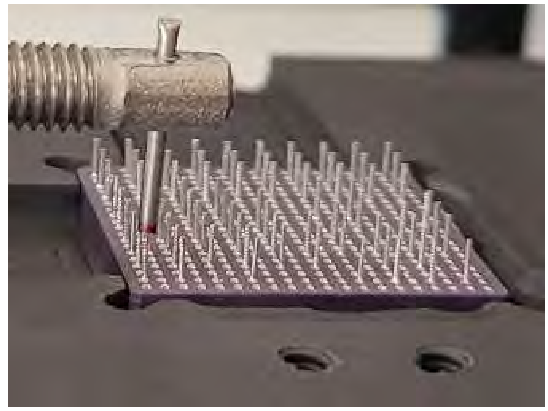

Fig. 4: DUT substrates with solder columns ready for destructive bend testing

One bend cycle consists of bending the free end of the column downward 317µm (12.5 mil) and then pulling the column upward 317µm (12.5 mil). The free end of the column under test traveled 634µm (25 mil) to approximate a strain that is far in excess of what large BGA packages would experience in real-world conditions. We selected these extreme bending conditions to in keeping with our goal to achieve Fail-Fast results.

The onset of mechanical failure is caused by coldworking the column as shown in Fig. 5. The point of failure (coldworking) is observed during bend testing in Fig. 7 and Fig. 8 as the curve flattens.

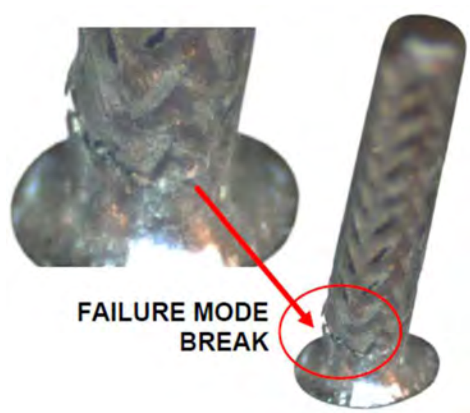

Fig. 5: The failure mode of braided columns is observed when the braid and core break.

Bending strain can be observed in a Finite Element Analysis (FEA) comparing the ability of Copper Braided Columns to absorb strain and distribute the load more evenly than solder balls as shown in Fig. 6.

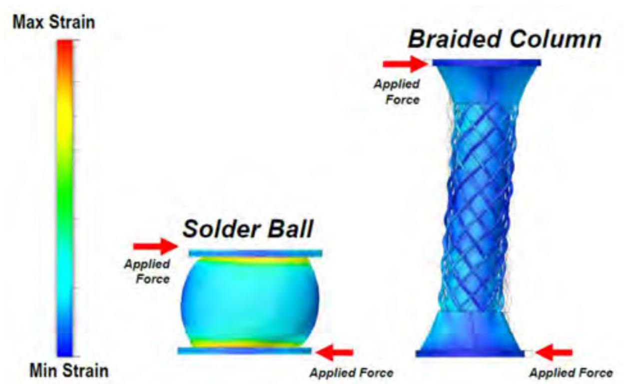

Fig. 6: Finite Element Analysis (FAE) comparing solder balls to Braided Columns with applied force. Braided columns absorb strain and distribute the load more evenly than solder balls. The darker blue color indicates less strain. Lighter blue and green/yellow colors indicate more strain.

Typically, in thermal testing for Aerospace and Defense, temperature excursions swing 180ºC (-55ºC to +125ºC) with average CTE mismatch of 10 ppm/ºC between the BGA chip package and an FR4 PCB. The resultant strain to solder balls or solder columns (located on the corner pads) approximates an amount shown in Table IX. For purposes of this table, we assumed that the corner pads were located at the longest distance from the neutral point (DNP) of the chip package.

Table IX. Calculated movement at the corner pads with temperature swing 180ºC and CTE mismatch of 10ppm/ºC between the package and FR4 PCB.

BGA Size	DNP to Corner Pad	+/- Bending	
		µm	mils
60x60mm	42mm	75 µm	3.0 mil
70x70mm	49mm	88 µm	3.5 mil
90x90mm	63mm	113 µm	4.5 mil
100x100mm	70mm	126 µm	5.0 mil
110x110mm	77mm	138 µm	5.5 mil
120x120mm	84mm	151 µm	6.0 mil
250x250mm	176mm	317 µm	12.5 mil

In the future we plan to partner with customers and employ traditional temperature profile testing by electrically monitoring changes in DC resistance in daisy chain DUT components and test vehicle boards. During our next phase of reliability testing, we will consider the onset of a failure to occur when the resistance changes of more than 20% of the initial DC resistance.

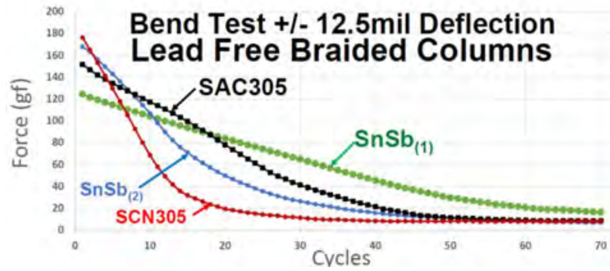

Fig. 7: Lead Free Columns subjected to Accelerated Bend Test +/-12.5mils Deflection. Best performance was observed with SnSb(1). Column diameter 0.50mm (20mil). Length 2.2mm (87mil). Braided BeCu wire diameter 25µm (1.0mil)

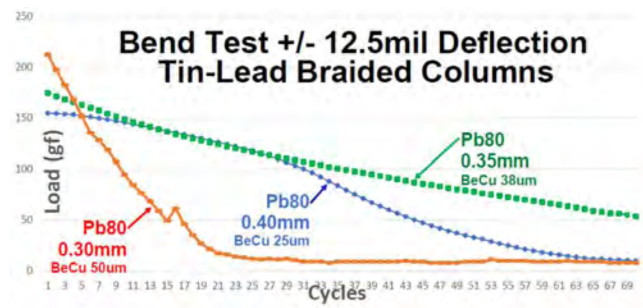

Fig. 8: Tin-Lead Columns subjected to Accelerated Bend Test +/-12.5mils Deflection. Pb80/Sn20 (80 cycles) Diameter 0.50mm (20mil). Length 2.2mm (87mil). Comparison of core and braid diameters

V. Conclusion

This paper describes a next generation of non-collapsible Lead-Free Copper Braided Solder Columns as a drop-in replacement for solder balls to absorb destructive strain (stress) caused by differences in CTE between the chip package and the PCB. Its cylindrical shape and mechanical compliancy enable solder columns to support large packages analogous to the way palm trees flex on a windy day without breaking. The industry trend is to design larger and larger Heterogeneous 2.5D BGA packages to meet the massive processing needs of AI and data centers. BGA packages have an increasing potential for solder balls to crack and delaminate, resulting in catastrophic failure of the system. Package designers are encouraged to consider incorporating solder columns into their large BGA package designs to increase operational reliability for mission critical applications.

Acknowledgement

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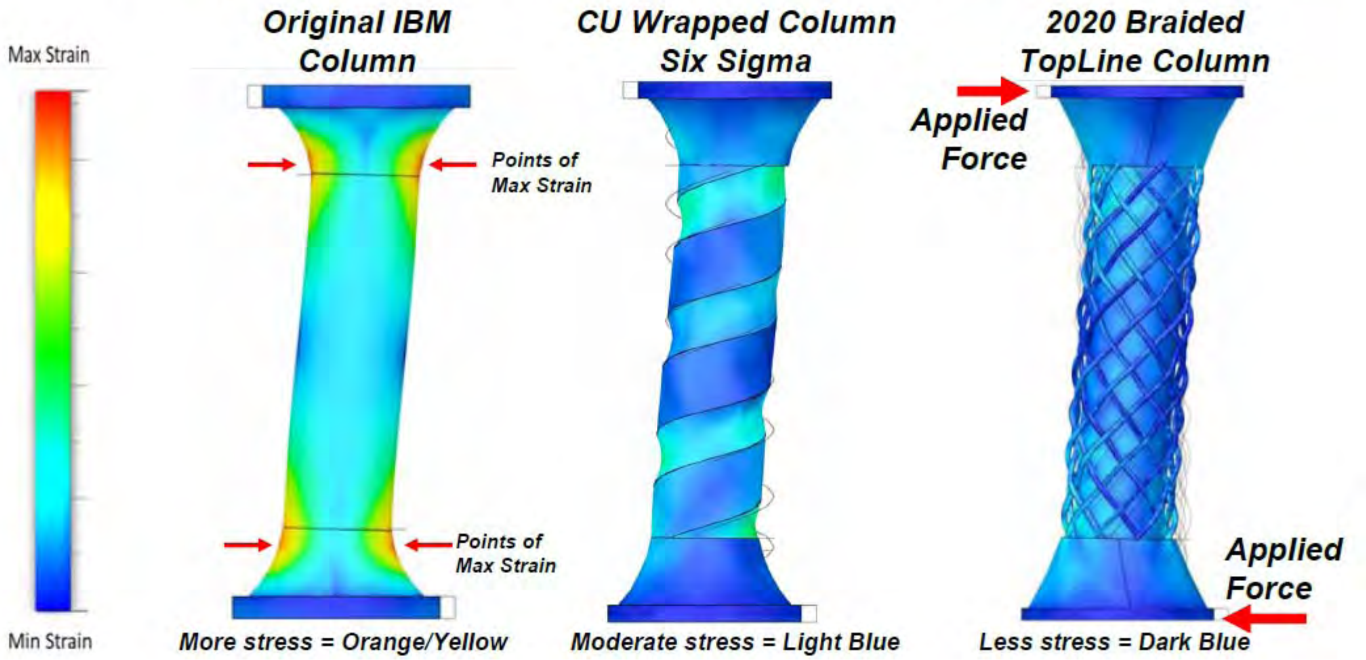
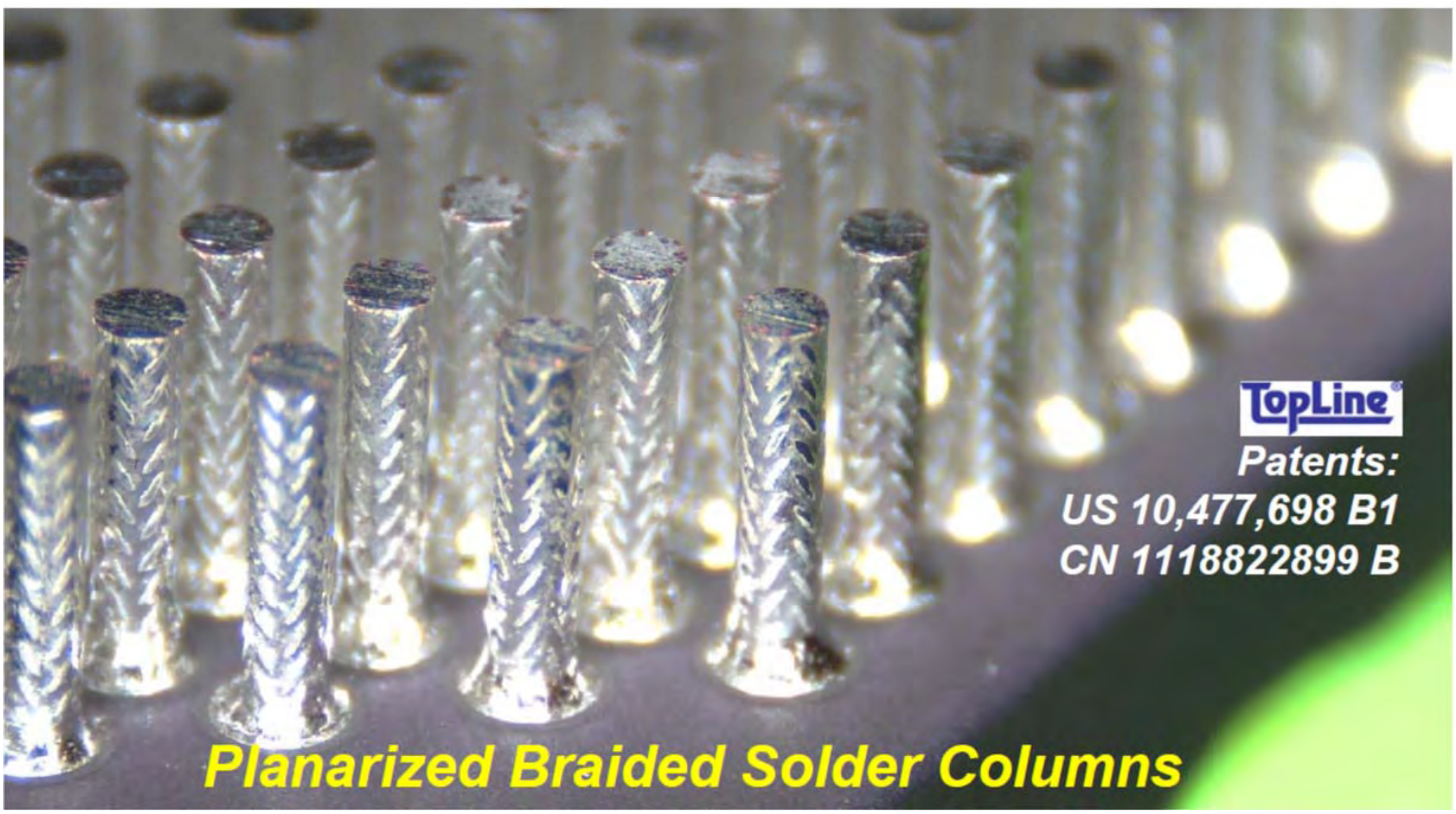
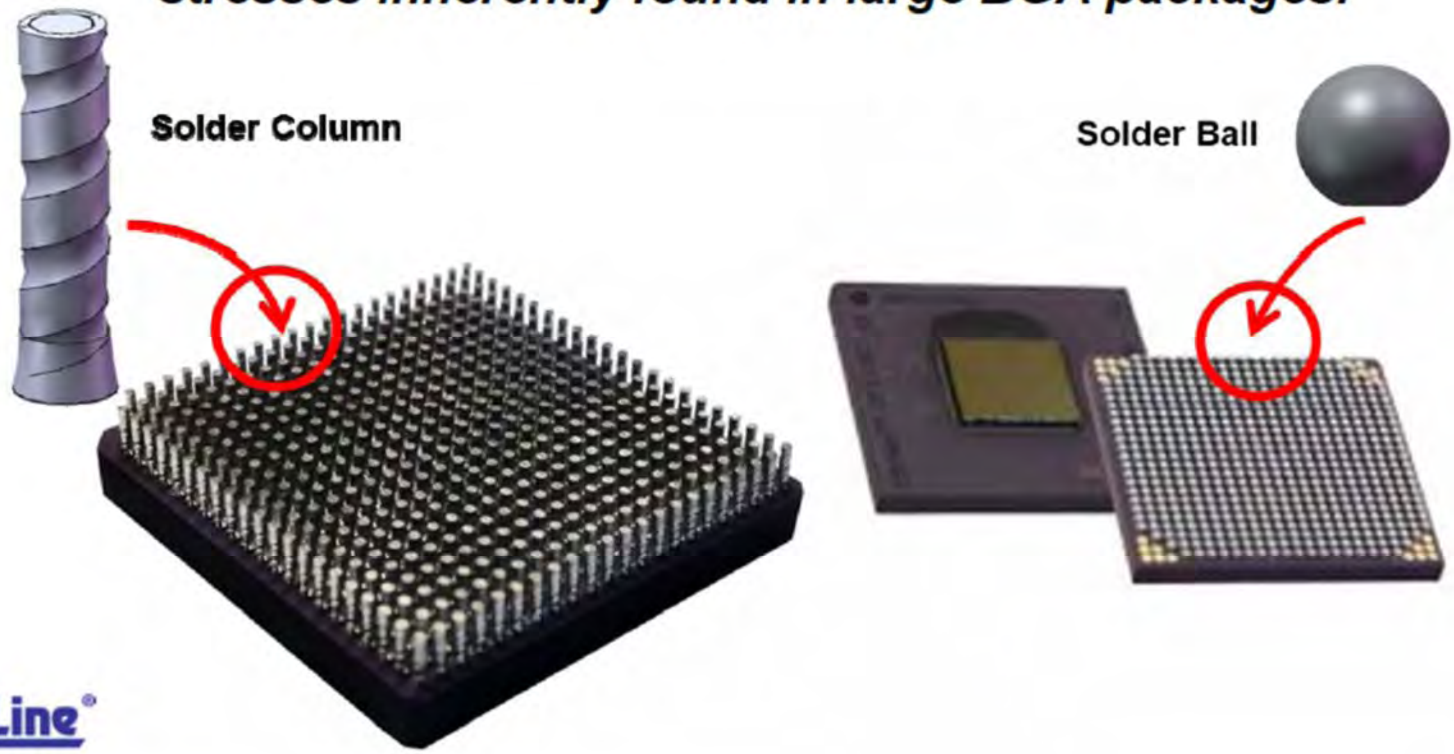
Comparative Strain in Different Columns

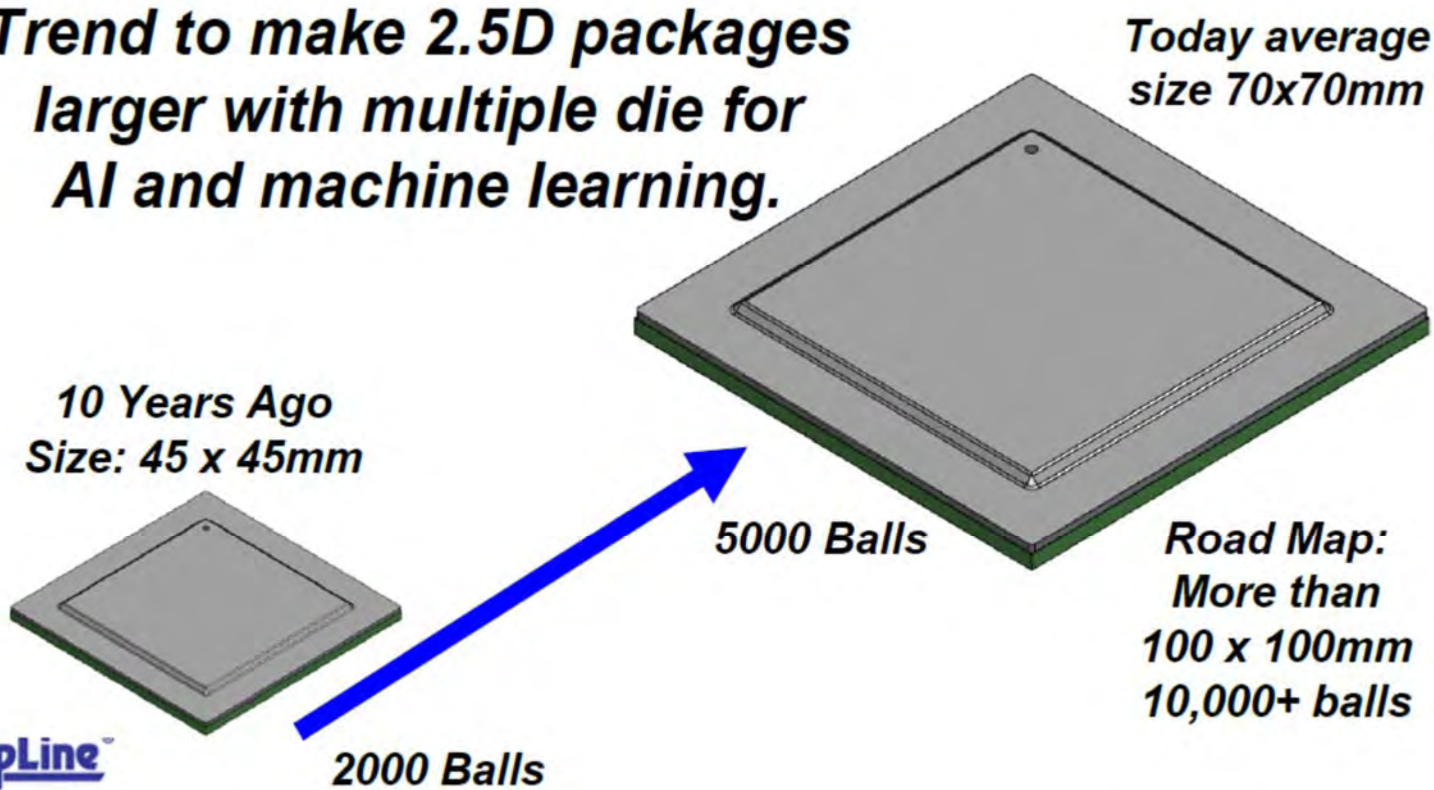




Solder balls are prone to fail (delaminate) due to excessive stresses inherently found in large BGA packages.



Trend to make 2.5D packages larger with multiple die for AI and machine learning.

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