# APPLICATION REPORT

## Ball/Wedge wire bonding with gold wire on a Direct Immersion Gold (DIG) surface for printed circuit boards

**This article focuses** on the bondability of a DIG layer by using the ball/ wedge method at different process temperatures. The abbreviation DIG stands for Direct Immersion Gold, thus a gold layer deposited directly on the copper of the printed circuit board. The typical gold thickness is in the range of 0.1 - 0.3 µm. DIG is of particular technological interest for wire bonding for two reasons:

- Compatibility with Al and Au wire
- Ni-free system and therefore no risk of Ni corrosion in the coating process and associated layer cracks during bonding

In addition, the DIG surface has the greater potential for fine-pitch applications. In the study summarized herein, a 25 µm HD2 wire from Heraeus was bonded using the ball/ wedge method and the strength of the connections was investigated using pull and shear tests. A gold wire bonding process reacts particularly sensitively to surface changes. These include, in particular, layer defects caused by a locally disturbed/inhomogeneous coating or local oxides formed from dried remains from the coating baths. Therefore a gold wire bonding process is ideal as a stress test for a surface finish. A total of 4 scenarios were investigated:

- Bond quality at the 2nd bond (wedge/stitch) with a typical setup for a PCB bonding process
- Bond quality at the 2nd bond (wedge/stitch) at process temperatures of 90°C, 110°C and 130°C
- Bond quality at the 1st bond (ball) in a typical setup for a PCB bonding process
- Bond quality 1st bond and 2nd bond in a room temperature bonding process for gold wire

The investigation of the bond quality in a setup typical for PCB processes is of fundamental interest to those planning to use the DIG surface for PCB-based setups. A study at different, especially lower, bonding temperatures provides a good indication of whether the process window of a surface is large enough. Tests of the bonding behaviour at room temperature are of interest to those users who are considering the substitution of an aluminium wire bonding process (usually AlSi1 Wedge/Wedge) by a gold wire process. Typically, an aluminum bonding process is much more robust at room temperature than a gold wire bonding process and is difficult to replace. Especially for narrow designs, high bond levels, small bond pads and applications with high reliability requirements, the ball/ wedge bonding process with gold wire is the more attractive option.

## 1. DIG – Surface finish

Light microscopic images of the DIG surface on the sample PCB under investigation are shown in Figure 1. The topography is dominated by small, homogeneously distributed elevations. This is the topography of the copper layer under the immersion gold. This is shown almost unchanged, as the thin gold levels the surface only minimally (Au thickness of the sample PCB examined: 240 nm, σ = 16 nm). Therefore, the surface roughness of a DIG surface corresponds closely to the Cu roughness from the last Cu process step of the PCB. This roughness is typically formed by a mechanical or chemical pre-treatment to produce a defined topography that allows a solder resist coating to adhere sufficiently well to the surface. In the FIB section (see Figure 2) this topography effect is particularly well visible. The image is taken from a similar study carried out by Fraunhofer IZM Berlin on DIG surfaces produced in-house (authors: Ralf Schmidt and Felix Fischer).

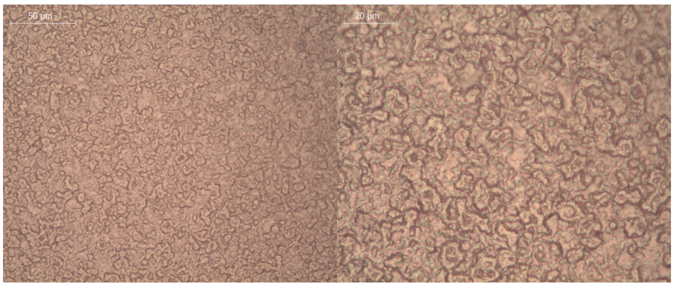


**figure 1: DIG-Surface under the light microscope**

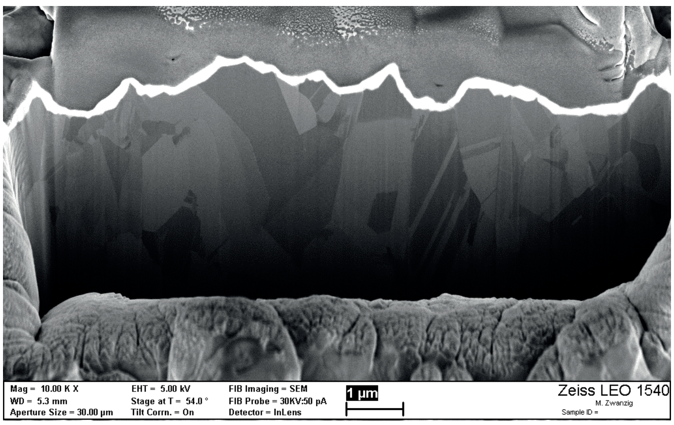



**figure 2: FIB-cut into a DIG surface (source: Fraunhofer IZM)**

The topography of the surface was measured using a Confovis measuring device (product name: TOOLinspect, measuring principle: confocal microscopy). Three characteristic values (Sz, S10z, Sdr*) were calculated from each measurement and averaged over the total of 100 individual measurements at different positions on the surface. Table 1 summarizes the results of the DIG layer investigated. Table 2 contains comparative values of typical ENIG layers, i.e. a structure of nickel (approx. 3 - 6 µm) and gold (approx. 0.1 µm).

**table 1: Topography measurements DIG-layer**

| | MW | s | s-rel [%] (s in % von MW) |
|---|---|---|---|
| **Sdr** | 23,1 % | 1,11 % | 4,8 |
| **Sz** | 3,7 µm | 0,61 µm | 16,5 |
| **S10z** | 2,5 µm | 0,28 µm | 11,2 |

**table 2: typical topography measurements ENIG layer**

| | MW | s | s-rel [%] |
|---|---|---|---|
| **Sdr** | ~2 – 4,5 % | ~0,1 – 0,5 % | ~5 – 15 |
| **Sz** | ~2,1 – 4,4 µm | ~0,3 – 0,6 µm | ~10 – 13 |
| **S10z** | ~1,2 – 3 µm | ~0,2 – 0,4 µm | ~10 – 15 % |

The values for Sz and S10z are in the range of the values that can also be expected for ENIG surfaces. This applies to the mean values as well as to the standard deviations. Unfortunately, the measured values, which were only determined on ENIG coatings deposited in an optimized way, do not reflect the fact that on a nickel-based finish the chance for a locally very high topography (e.g. a strong Ni bump around a Cu particle) is significantly higher. Such very high bumps are critical in bonding processes, as the bonding tool can attach to these elevations, thus interrupting the deformation of the wire during the bonding process. The Sdr value, meaning the measure for the actual surface area available, is about a factor of 10 higher for a DIG layer than for a typical ENIG layer. The DIG surface is much more fissured than an ENIG layer, which is levelled by the Ni coating. The extent to which the bonding process is influenced in detail by such a fine roughness has been little studied to date. However, there are indications that the deformation in the bonding process starts to occur rather earlier on rougher surfaces and - as is known at least from aluminium wire - tends to lead to greater deformation of the bond points. In addition, interactions of the roughness on the result in the shear test are possible, but there are no precise investigations of these as yet. First of all, it can be stated that the DIG surface has a very pronounced, fine roughness, which is very evenly formed over the entire surface. The DIG topography is very comparable to the topography of the very well known and proven ENIG layer.

The surface was applied to a standard FR4 material, which was also provided with solder resist and marking lacquer and contoured by milling processes afterwards. The samples used have thus passed through all typical production processes of a printed circuit board and therefore form a representative comparison sample.

## 2. Bonding results at 150°C for the wedge

The bond tests were performed with 25 µm gold wire in a typical ball/wedge setup for a fine pitch application. Based on an initial experience-based parameter selection, a range was established within which a parameter (in this study: US-power) was varied in predefined steps. For each parameter setting 110 bonding contacts were bonded and tested in a pull test. The criteria for the examination of the bonding contacts were in accordance with DVS spec sheet 2811 in the version of February 2017. The US power was varied in the range of 9 digits to 30 digits in steps of 3 digits. This corresponds to a change in the US power of ±50% around the average value of approx. 20 digits. In industrial bonding processes, changes of ±10% are typical and a maximum of ±20% is allowed. The investigated parameter range of ±50% thus covers a very large process window in comparison. All other basic settings of the used bonding process are summarized in the grey box.

**Bond and test parameters (2nd bond, wedge/stitch):**
Touchdown force: 10 cN
Bond time: 20 ms
Bond temperature: 150°C (surface of bond table)
Bond Force: 15 cN
US performance (varies): 9 - 30 digits
Default force: 60 cN
Wire bonder: F&S Bondtec 5810
Bond wire: Heraeus HD2 25 µm
Bond frequency: 68 KHz
Bond tool: SBNS-38AS-AZ-1/16-16MM
Pull tester: F&S Bondtec 5600
Pull hook diameter: 80 µm
Pull speed: 500 µm/s

Figure 3 summarizes the measured pull forces graphically in box plots for each US setting. As reference lines, the breaking load of the wire - meaning the maximum of the achievable pull force - and the minimum pull force defined according to DVS-2811 for a single wire are given.

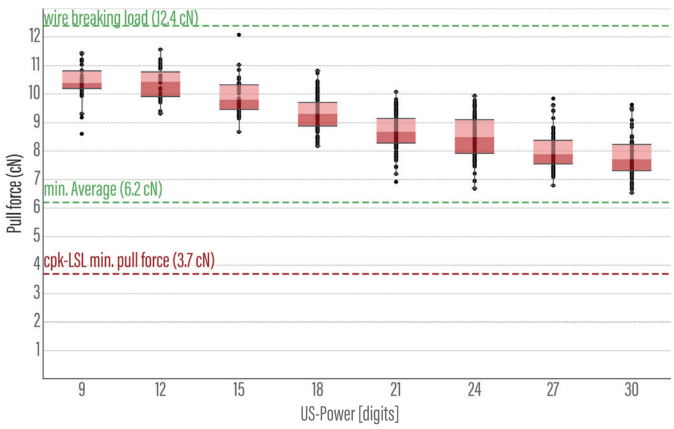



**Figure 3: Pull test results at a bond temperature of 150°C (failure modes: only heel break and lift-off)**


**Figure 4: Distribution of failure modes in the pull test at a bond temperature of 150°C**

*The measured topography values were not filtered. Strictly speaking, they are primary data (P values).

This minimum pull force is 30% of the breaking load of the wire. The third reference line drawn corresponds to a recommendation of DVS-2811 for the average pull force value of a sample group. It is recommended that this average value is ≥50% of the breaking load of the wire.

All individual and average values of the samples are clearly above the minimum values according to DVS-2811. The pulling force has its maximum at 9 - 12 digits and decreases with increasing US-power by a maximum of approx. 30 %. The reason for this is the increasing deformation - and thus mechanical weakening - of the heel area with increasing US-power. The standard deviation averages about 5 - 9 % of the measured mean value over all samples taken. This results in a cpk value of 2.0 - 4.5 (based on the LSL of 3.7 cN). Lift-offs occurred with a small proportion of approx. 10% only at the lowest US-power. Based on these results, it can be concluded that the ball/ wedge bonding process with 25 µm wire on a DIG layer at 150°C bonding temperature is robust and quality assured.

## 3. Bonding results at 90 - 130°C for the wedge

Bonding tests in analogy to the procedure described in chapter 2 were also carried out at bond temperatures of 90°C, 110°C and 130°C. The results are summarized in the diagrams in Figures 5 - 7, which clearly show that as the bond temperature decreases, the bond problems increase at low US-power. In other words, the bonding contacts are already detached in the tear-off process (tail formation) after the bonding process on the wedge. A stable bonding process is no longer possible in this way. However, even

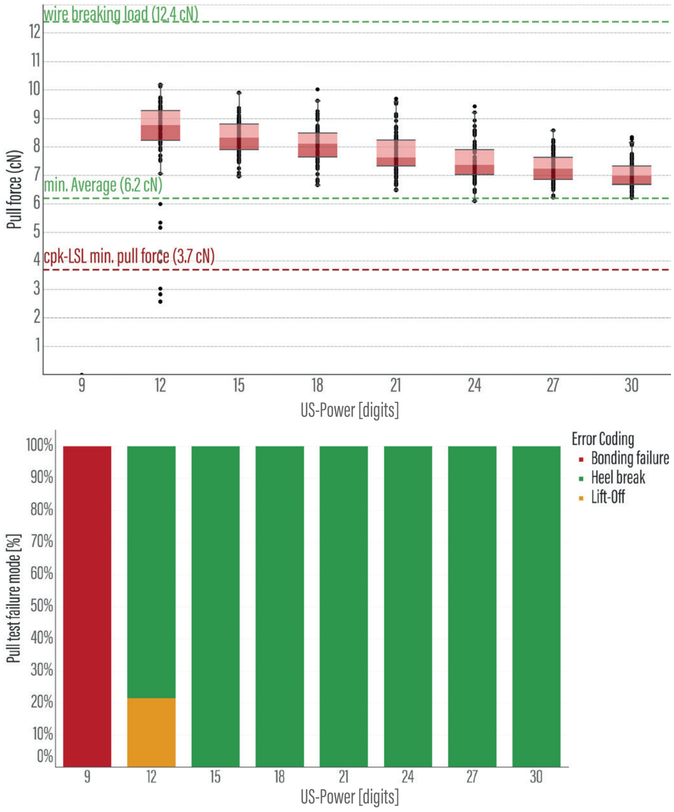



**Figure 6: Pull test results $T_{BOND}$=110°C**

in the range of a US-power of 18 - 21 digits, the bonding behavior stabilizes even at 90°C to such an extent that high-quality bond connections are possible.. The cpk value at 90°C bond temperature and a US power of 21 digits is 2.6. Light microscopic images of wedges are shown in Figure 8. Bond contacts that did not have a continuous sickle shape after the pull test were classified as lift-off.

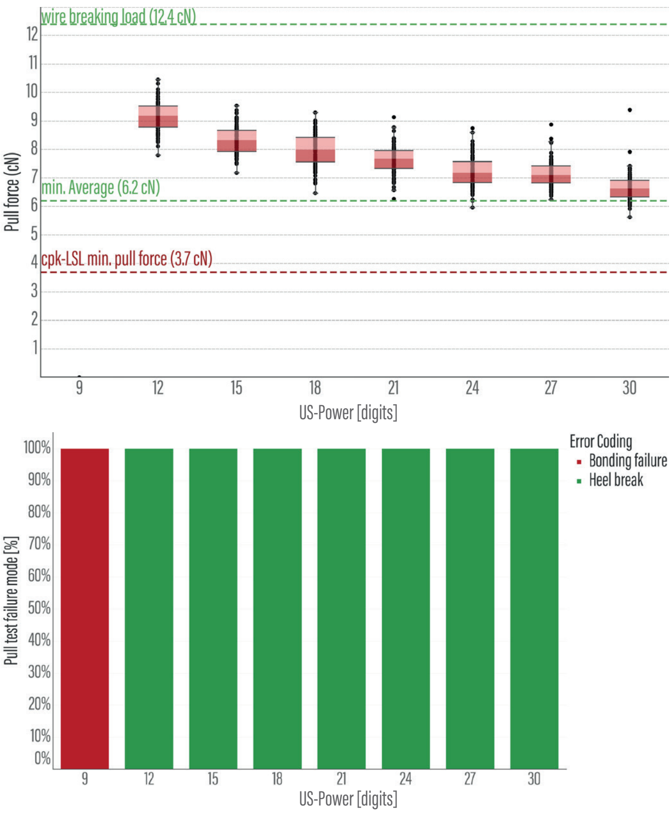



**Figure 5: Pull test results $T_{BOND}$=130°C**

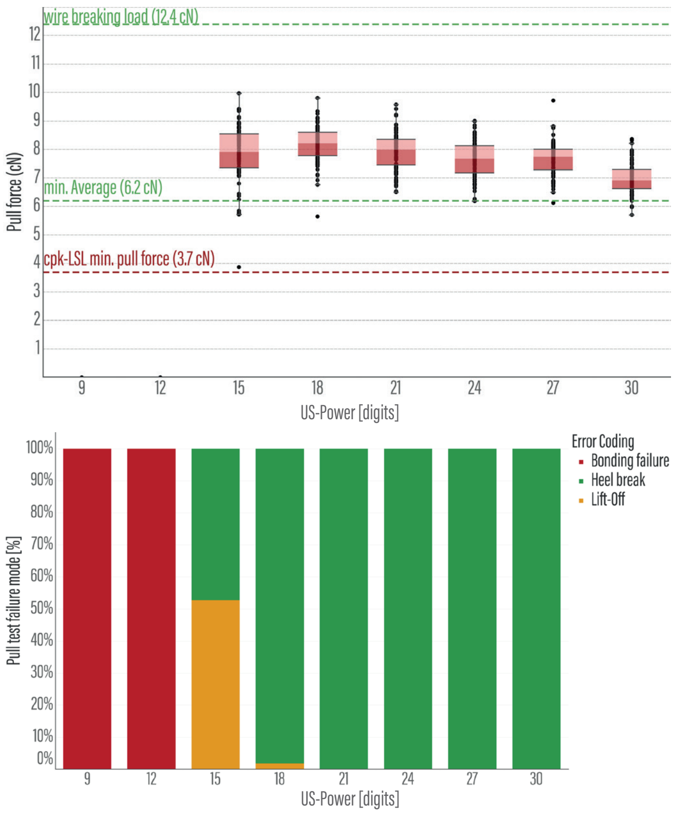



**Figure 7: Pull test results $T_{BOND}$=90°C**

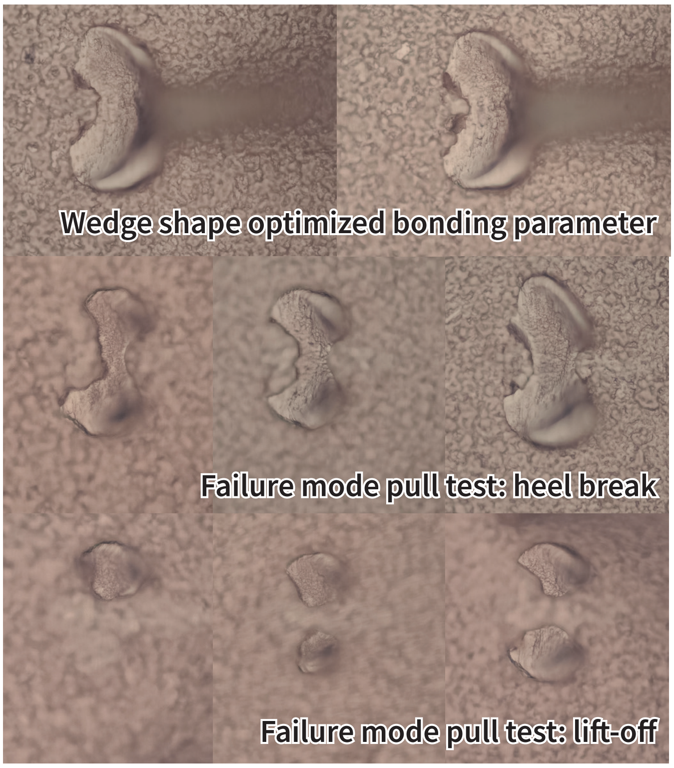



**Figure 8: Images of the bonding contacts & failure modes**

## 4. Bonding results at 150°C for the ball

Shear tests were performed to evaluate the bond quality of the ball. The bond parameters were optimized in advance based on previous experience and a fixed parameter set was selected for more extensive bond tests at 150°C bond temperature. With this set of parameters about 300 bonding contacts were made and mechanically tested in shear tests. The selected bond parameters are summarized in the grey box.

**Bond- and test parameters (2st bond, ball)**
Touchdown force: 10 cN
Bond time: 20 ms
Bond temperature: 150°C (surface of bond table)
Bond Force: 13 cN
US-power: 15 digits
Default force: 60 cN
Wire bonder: F&S Bondtec 5810
Bond wire: Heraeus HD2 25 µm
Bond frequency: 68 KHz
Bond tool: SBNS-38AS-AZ-1/16-16MM
Shear tester: F&S Bondtec 5600
chisel width: 120 µm
shear rate: 150 µm/s

Figure 9 shows a statistical analysis of the determined shear forces. In all cases, complete shearing of the balls occurred (see also the images of the fracture pattern in Figure 10). During the shear test it was observed that the wire material behind the shear point was further smeared over the surface and partly sheared through again. The shear force determined during this following continuous shearing

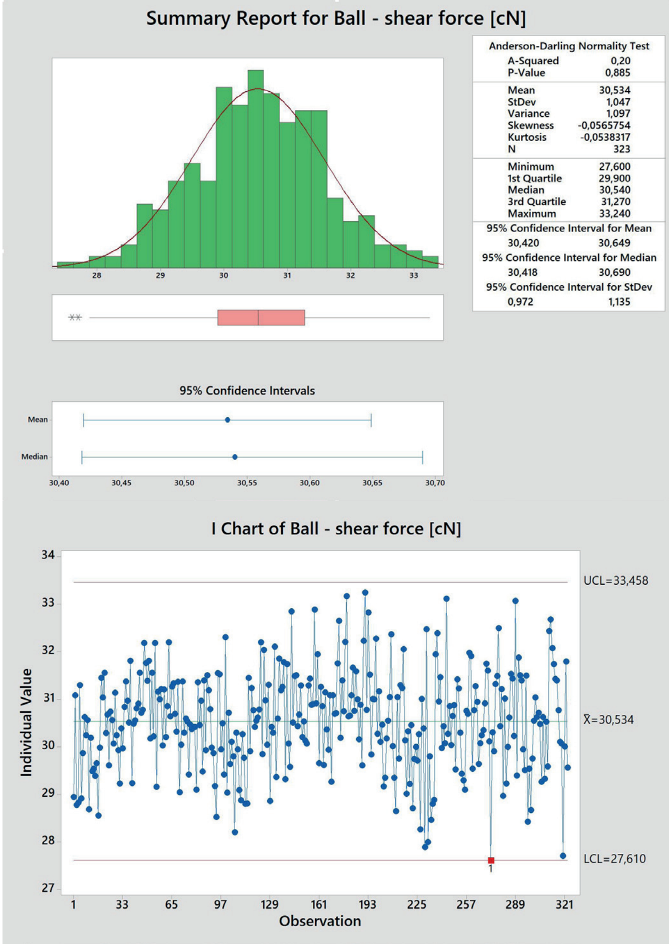



**Figure 9: Shear force evaluation $T_{BOND}$=150°C**

process was not taken into account in the evaluation. All

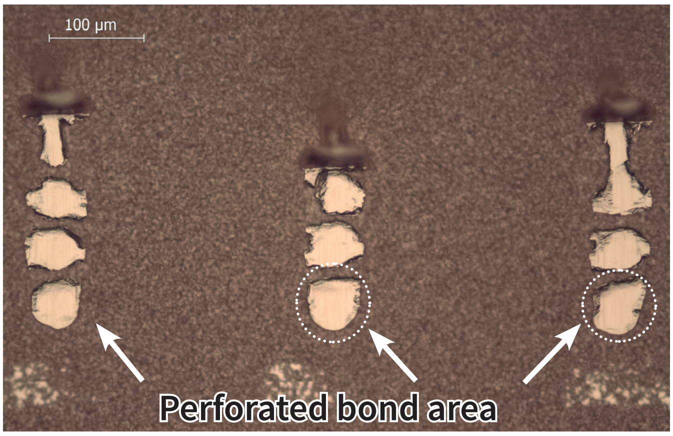



**Figure 10: Fracture pattern in shear test (shear-through)**

shear forces summarized in figure 9 correspond only to the force that was necessary to shear through the bonded contact. The shear strength was calculated on the basis of the determined ball diameter (mean value: 57.5 µm, example see Figure 11). The shear strength can be compared with the specifications in DVS data sheet 2811. Figure 12 shows the measured values in relation to the specified single value minimum of 60 MPa and the recommended mean value limit of 84 MPa. With the calculated mean shear strength of 117.6 MPa at a standard deviation of 4.03 MPa (~3.4% of the mean value) a cpk value of 4.76 is achieved. This bonding test also confirms the very good bondability of the DIG surface.

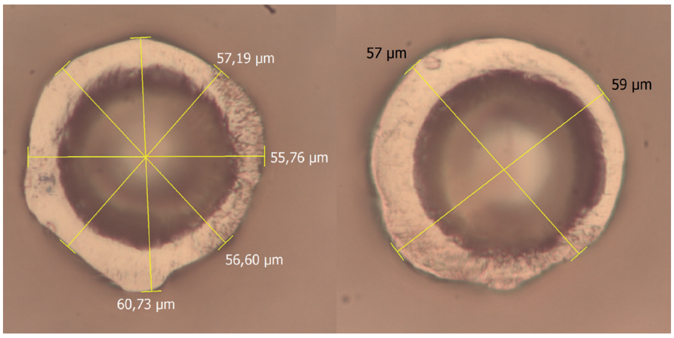



**Figure 11: Ball diameter (optimized parameter)**

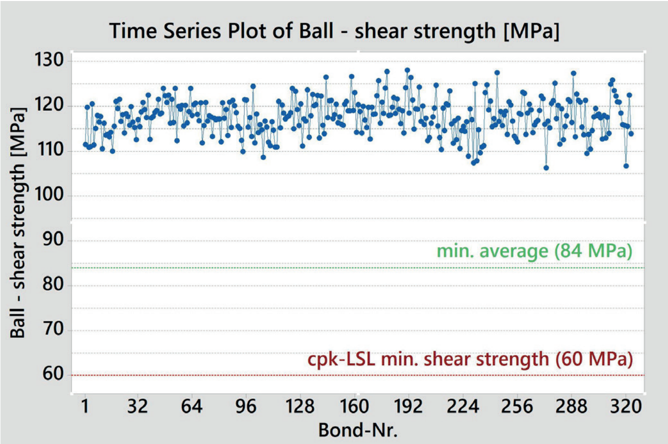



**Figure 12: Shear strength analysis $T_{BOND}$=150°C**

# 5. Bonding results at room temperature

The possibility of implementing Au bonding processes at room temperature – thus without the aid of a bond table heater – has been successfully confirmed several times in the past and documented in the relevant technical literature. In all studies, it was shown that processing at room temperature requires a particularly high level of cleanliness and layer quality of the bond surface. The room temperature process parameters used are mostly outside the typically recommended bonding parameters. The expected process window is significantly smaller than that for bonding on heated samples and the mechanical load capacity of correspondingly bonded contacts is somewhat lower. Advantages of room temperature bonding include reduced process time (no heat-up/setting phase necessary for the assembly), lower thermal stress on the materials used in the assembly and their property changes (e.g. softening of adhesives and organic substrates), and less influence on image recognition and alignment (due to streaking and inhomogeneous thermal expansion).

Approximately 100 bond contacts were created on the samples examined with a previously adjusted set of bonding parameters. The ball was mechanically tested by using a shear test and the wedge by performing a pull test. The results are summarized in figure 13 and 14. 90% of the shear test results showed a full shear-through (see figure 10). 10% of the sheared bond points showed a remaining shear base of 50 - 70% (according to DVS-2811). In the pull test 100% of heel cracks occurred. The cpk value for the shear test on the ball was 2.41 and for the pull test on the wedge 1.54.

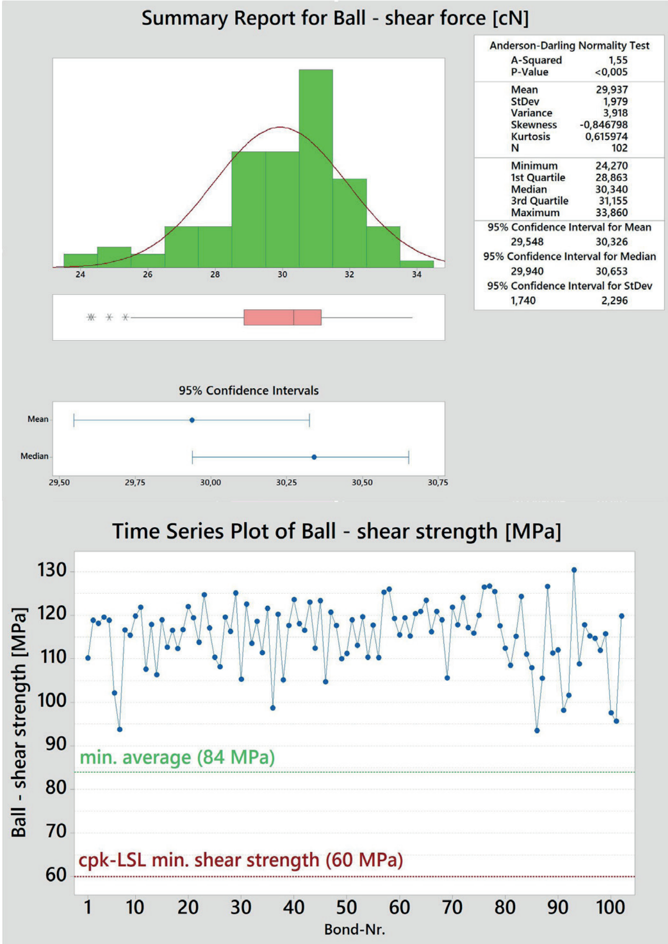



**Figure 13: Shear test results ball $T_{BOND}$=20°C (RT)**

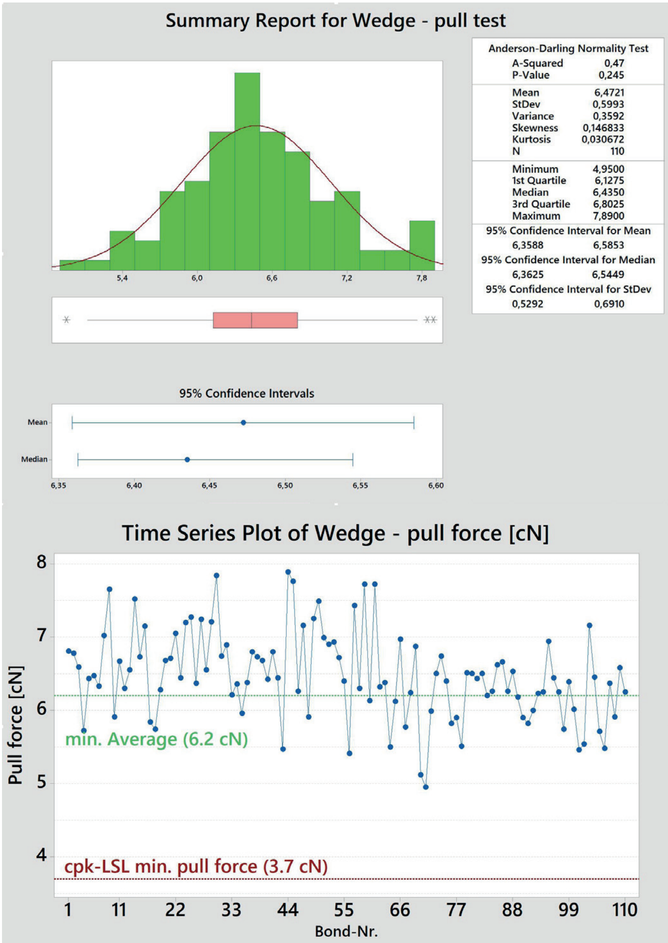



**Figure 14: Pull test results wedge $T_{BOND}$=20°C (RT)**

## Summary & Conclusion

Bonding tests with 25 µm gold wire and a fine-pitch bonding tool were carried out on test samples which were coated using a DIG process optimised at Hofstetter. Due to the very homogeneous structure of the surface, which was quantified by topography measurements, very constant bonding conditions could be achieved. The determined standard deviations and the calculated cpk values indicate the potential of the surface for a very good process capability.

In the course of the first bond tests it was shown that all typical bond parameter combinations produced quality bond contacts. In order to demonstrate the limits of the bondability of the DIG surface, it was necessary to vary the bonding parameters – and here in particular the bond temperature – in wide ranges. These investigations in the borderline areas showed that quality bonds can also be made in these areas after optimizing the bonding parameters. As generally usual for bonding processes with gold wire at room temperature, a slightly poorer bond formation of a slightly lower mechanical strength of the connections compared to bonding temperatures >100°C must be expected.

Since the DIG surface is in principle to be produced in a configuration that is also suitable for aluminium wire bonding, this layer system is universally applicable for soldering, glueing, all wire bonding and encapsulation processes.

# FACTSHEET

### Direct Immersion Gold (DIG, semi-reductive)*

**Typical layer thickness**
0.1 - 0.3 µm (recommended for Au wire: 0.2 - 0.3 µm)

**Shelf life**
≥6 Months after plating, depending on application

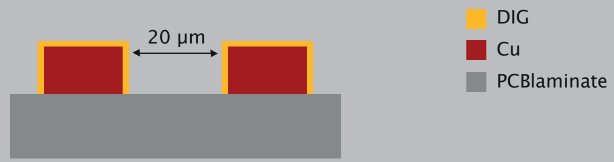
**Panel thickness**
0,025 mm to 10 mm

**Format size min. // max.**
100 mm x 100 mm // 610 mm x 610 mm

**Aspect Ratio PTH // BV**
1:16 // 1:1 (after copper plating)

**Outstanding features**

- Ideal for high frequency technology
- Finest structures due to the low layer thickness
- Nickel-free for special application requirements




DIG plating on PCB

*Data from Hofstetter PCB AG in Küssnacht/Switzerland, supplier of various coatings in microelectronics, among others for the DIG coating system

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