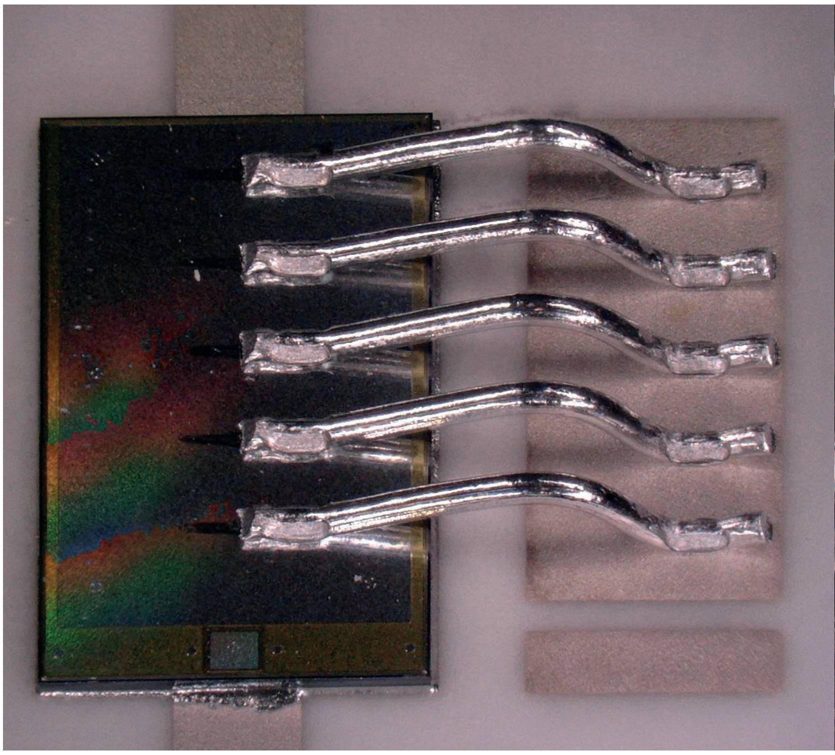

# WIRE BONDING SURFACES IN POWER ELECTRONICS

Author: **Stefan Schmitz, Bond-IQ GmbH**

Despite ongoing miniaturization and performance improvements in power electronics, wire bonding is still essential today. Wire bondable surfaces must provide an optimal combination of electrical conductivity, mechanical stability, and resistance to aging and corrosion processes. This article introduces the most important industrially established metallizations for wire bonding, highlights typical sources of error and their effects on bond quality, and summarizes cleaning processes.

## 1.
## OVERVIEW OF METALLIZATION AND LAYER STACKS

Ultrasonic wire bonding creates a metallic bond by interdiffusion between the wire material and the metallization. This bond is not formed by a melting phase, but rather during the application of ultrasound by the atomic approach of the bonding partners, the breaking and grinding of oxide layers and surface contaminants, the deformation of the wire material and the diffusion of the metals involved. The quality and reliability of wire-bonded interconnections depend to a large extent on the material combinations used. They must not only have good electrical conductivity, but also high bonding strength to each other and to the metallizations used. In addition, good resistance to aging and corrosion is essential. The following sections provide a more detailed explanation of the metallizations commonly used in the industry for wire bonding in power electronics systems. In power electronics, wire diameters >125 µm and aluminum and copper wire materials are common - this is known as thick wire bonding. For the sake of completeness, the coating systems listed include some references to thin wire bonding with gold wire.

**Electroless Ni/Au (ENIG)** consists of a wet chemical autocatalytic NiP coating selective to copper, which is protected from oxidation by a thin layer of gold plating (ENIG, see Figures 1 and 2). It is an extremely temperature- and long-term stable surface finish, which, in addition to all soldering applications, can also be bonded with aluminum wire. This coating is not recommended for gold wire bonding. Caution is advised when using open, unencapsulated Al wires on ENIG layers. In reliability tests at 85°C and 85% relative humidity, a very high proportion of bond contact detachments can be observed after 250-500 hours. In this case, the intermetallic Au/Al phases detach from the underlying nickel layer. This fault mechanism can be eliminated by encapsulating the bond contacts, e.g., with Glob-Top material.

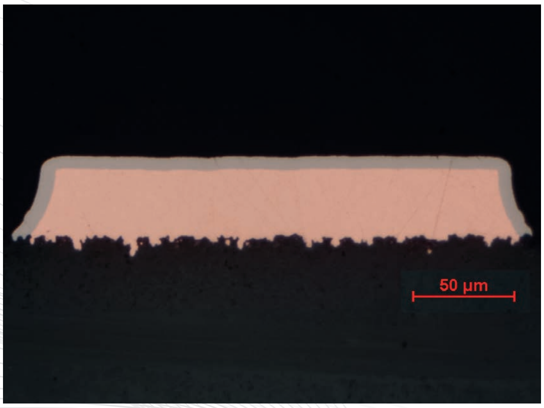


Figure 1: **Cross-section of an ENIG coating system on a printed circuit board (Cu and Ni layers visible)**

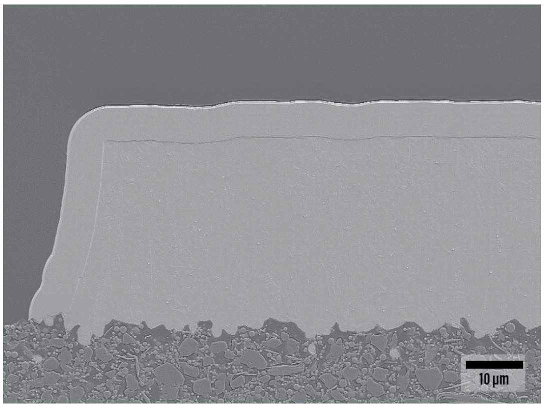


Figure 2: **SEM image of an ENIG cross section (Au layer visible as thin bright line above the nickel)**

**Electroless Ni/Pd/Au (ENEPIG, ENIPIG)** is comparable to chemical Ni/Au in terms of the coating process, with an additional coating step in which the Pd layer is applied to the fresh Ni surface. The coating can be applied by immersion or in an autocatalytic process. The system is suitable for all relevant joining techniques – soldering, bonding, wire bonding, sintering. Ni/Pd/Au metallization is of particular interest in efforts to replace expensive ceramic circuit carriers with Au layers with high-Tg printed circuit boards, as process-reliable bondability with Au wire in the ball/wedge process is an essential goal here. Experience in industrial processes confirms that the use of ENEPIG is preferable to ENIPIG (immersion palladium). Caution is advised when using open, unencapsulated Al wires on ENEPIG/ENIPIG layers. In reliability tests at 85°C and 85% relative humidity, a high proportion of bond contact detachments can be observed after 500-1000 hours. The exact location of the failure (interface with the palladium layer or the nickel layer) has not yet been fully clarified. This failure mechanism can be eliminated by encapsulating the bond contacts, e.g., with Glob-Top material.

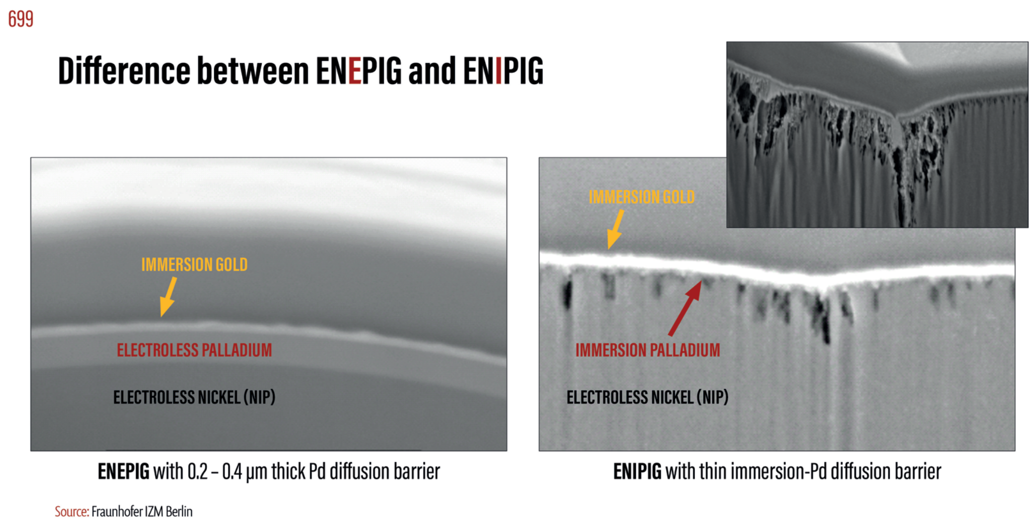


Figure 3: **FIB sections in an ENEPIG and ENIPIG layer system**

The deposition of metallic surfaces in **thin-film technology** is carried out using sputtering processes with interchangeable masks. High-vacuum processes are used, and the metal system deposited is determined by the sputtering target. It is also possible to deposit defined layer systems (e.g., consisting of a bonding agent and bonding surface) or alloys (e.g., AlSiCu layers) in a process chamber. To produce bondable layers, additional bonding agent layers (e.g., Ti, TiW, or Cr) are usually required. Without these adhesion promoters, layer delamination, i.e., detachment of the layer in the area of the bond, is highly likely to occur. Thin-film systems are mostly used when very finely structured geometries or functional layers are to be produced. Subsequent increases in layer thickness are usually achieved by electrolytic metallization processes.

In **thick-film technology**, screen- or stencil-printable pastes with a metallic content (approx. 70-80%) are used. The conductor track structure is determined by the printing process. Conductive metallic structures are produced in a sintering process at approx. 700–900°C, depending on the paste system used, on substrates suitable for high temperatures – usually ceramics. Typical paste systems are Ag, AgPd, AgPt, and Au pastes with thicknesses in the range of 5–20 µm. Ag-based pastes are significantly less expensive than Au pastes and can also be processed in soldering processes. Ag-containing pastes can usually be bonded with Au and Al wires, although significantly different process windows may occur depending on the composition of the pastes and the sintering process. The combination of Al bonding wire and Ag paste is susceptible to corrosion in the presence of condensing moisture. This Al/Ag contact system must therefore be protected against moisture, which is usually achieved in electronic assemblies by means of a silicone-based soft encapsulation. However, silicone is known to provide only limited protection, as water molecules can easily penetrate it. Au pastes are preferred when Au thin wire bonding processes are used and are generally characterized by very good bondability.

**DCB (Direct Copper Bonding) surfaces** are a proven technology for power electronics modules in which copper is applied directly to a ceramic substrate. The manufacturing process is based on a high-temperature diffusion reaction in which the copper is bonded to the ceramic through an intermediate oxide layer. This technology makes it possible to combine the excellent thermal and electrical conductivity of copper with the high insulation properties of ceramic. The resulting surface has high mechanical stability and good wire bondability, especially for Al wire bonding, while also offering excellent heat dissipation. However, the oxide layer on the copper can affect bondability and usually requires targeted surface pretreatment or ensuring that the surface is free of oxide to create a stable bond.

**Roll-clad AlSi** is an established and reliable bonding surface. Roll cladding is carried out at elevated temperatures and under pressure, followed by tempering of the bimetal composite to improve the adhesive strength (bond quality) between Al and Cu through the formation of distinct intermetallic phases. The strip is then measured, precision-rolled to the final dimensions if necessary, and then re-rolled and protected by an intermediate layer. Subsequent processing involves punching and plastic injection molding into **housing frames**, which are then fitted with electronic components and connected to the housing pins by wire bonding. If **solderable bond pads** and **pins** are produced, only a punching and bending process is carried out, followed by sorting of the parts, e.g., into belts for automatic assembly machines.

Electroplated **nickel layers** with a thickness of approx. 2 µm are usually coated with approx. 0.2 µm NiP (nickel with a phosphorus content of 6-10%) for wire bonding applications with aluminum wire. This increases the shelf life and process reliability of this layer during wire bonding. Fresh nickel layers can be processed very reliably with aluminum wire. If the thickness of the nickel oxide increases, e.g., due to very long and uncontrolled storage, the bonding quality deteriorates, in some cases considerably. Nickel surfaces can also be processed with copper wire. In this case, there is an increased risk of cracking within the nickel layer.

In addition to layer systems on substrates, **solid metal parts** (e.g., milled and turned parts, pressure die-cast parts, sheet metal, or busbars) made of aluminum and copper can also be wire bonded. The higher the purity of the material, the better its bondability. Aluminum with a purity of at least 99.7% (e.g., EN-AW 1070A) or copper with a purity of 99.95% (e.g., OF copper) are very good bonding partners in many cases. If, in addition to wire bondability, bending and punching behavior also play a role in the selection of the material alloy, bonding tests must be carried out to determine its suitability for a wire bonding process.

## 2.
## WHICH METALLIZATION FOR WHICH SUBSTRATE TYPE?

Table 1: **Coating systems for thick aluminum wires**

<table>
<tr><th>Substrate type</th><th>Base material below the metallization system</th><th>Metallization system</th></tr>
<tr><td>DCB Ceramic</td><td>Copper</td><td>Wire bonding directly on copper</td></tr>
<tr><td>DCB Ceramic</td><td>Copper</td><td rowspan="3">ENIG (4-6 µm Nickel / 0,04-0,08 µm Gold)<br>ENEPIG (4-6 µm Nickel / 0,2 - 0,4 µm Palladium / 0,04-0,08 µm Gold)</td></tr>
<tr><td>PCB</td><td>Copper</td></tr>
<tr><td>Flex PCB</td><td>Copper</td></tr>
<tr><td>Ceramic</td><td>Ceramic</td><td>AgPd, AgPt (6-15 µm) Thick film paste</td></tr>
<tr><td rowspan="2">Die</td><td rowspan="2">Silicon</td><td>Al, AlSi, AlSiCu (0,5 - 8 µm) thin film PVD</td></tr>
<tr><td>ENIG (4-6 µm Nickel / 0,04-0,08 µm Gold)<br>ENEPIG (4-6 µm Nickel / 0,2 - 0,4 µm Palladium / 0,04-0,08 µm Gold)</td></tr>
<tr><td rowspan="2">Leadframe (Injection molded housing)</td><td rowspan="2">Copper</td><td>10-30 µm AlSi1 roll cladding</td></tr>
<tr><td>Electroplated Ni (2-3 µm), electroplated Gold (0,05 µm)</td></tr>
<tr><td>Aluminum bulk material</td><td>Aluminum</td><td>min. 99% purity</td></tr>
<tr><td>Copper bulk material</td><td>Copper</td><td>OF-Cu, Cu-ETP, CuSn6</td></tr>
<tr><td>Metal sheet</td><td>Copper, stainless steel</td><td>Ni (2-4 µm), NiP (0.2 µm)</td></tr>
<tr><td>Batteries</td><td>Stainless steel</td><td>2-4 µm Nickel (Hilumin-Sheet)</td></tr>
</table>

Table 2: **Coating systems for thick copper wires**

| Substrate type | Base material below the metallization system | Metallization system |
|---|---|---|
| **DCB Ceramic** | **Copper** | Wire bonding directly on copper |
| **DCB Ceramic** | **Copper** | ENIG (4-6 µm Nickel / 0,04-0,08 µm Gold)<br>ENEPIG (4-6 µm Nickel / 0,2 - 0,4 µm Palladium / 0,04-0,08 µm Gold)<br>Crack formation in the layer stack is very likely |
| **PCB** | **Copper** | |
| **Flex PCB** | **Copper** | |
| **Die** | **Silicon** | Die-top-metallization made of Copper minimum, 10 µm thickness |
| **Leadframe (Injection molded housing)** | **Copper** | Wire bonding directly on copper |
| **Copper bulk material** | **Copper** | OF-Cu, Cu-ETP, CuSn6 |
| **Metal sheet** | **Copper, stainless steel** | Ni (2-4 µm), NiP (0.2 µm) |
| **Batteries** | **Stainless steel** | 2-4 µm Nickel (Hilumin-Sheet) |

## 3. YOU SHOULD AVOID THESE MISTAKES AT ALL COSTS!

A common mistake in wire bonding is the assumption that layers are rubbed through during the bonding process. For **aluminum thick wires** (99.9% and 99.99% purity), this can be ruled out for all common coating systems. Even gold layers only 60 nm thick are not rubbed away by a 400 µm thick bonding wire, but are part of the contact system. Therefore, the coating quality and the associated layer adhesion play a central role in robust wire bond contacts. If the layers do not adhere sufficiently, a stable bonding process is not possible. Regardless of the bond parameters selected, the contact will detach together with the coating. In this case, action must be taken by the coating manufacturer. The user cannot remedy this fault pattern by selecting different bond parameters.

The situation is different with **thick copper wires**, which are (currently) much less commonly used. Here, the hard wire material and the very high bonding forces and ultrasonic energies push aside even layers that are a few micrometers thick and can also cause cracks in the underlying layer structures, depending on the hardness and stability of the metal layers to which the bonding is applied.

The coating systems listed below are commonly used on electronic assemblies but are not suitable for wire bonding applications or, in some cases, should be considered highly critical.

**Hot air solder leveling (HASL, HAL)** is a reliable and cost-effective surface coating made from liquid solder, provided that it is sufficiently thick. This surface is not suitable for wire bonding processes.

**Solid solder deposits** were developed to avoid unevenness in the connection pads and to obtain a (solderable only) surface for SMD assembly, including the necessary solder deposit (no solder paste printing required by the user!). This surface is not suitable for wire bonding processes.

**Organic Surface Passivation (OSP)** on copper is a very simple and cost effective process to protect copper surfaces from oxidation by dip coating. Layer thicknesses range from monolayers to 0.5 µm, depending on the system. The processes are suitable for soldering down to the ultra-fine pitch range. The surface is not considered to be process-reliable for wire bonding (especially with Au wire), but this has been disproved in some unpublished industry studies. Possible processability with Al thick wire (≥ 125 µm) has not been confirmed and must be tested depending on the OSP variant used.

**Chemical tin (ISn)** itself is also a highly planar surface based on wet chemical metal plating, which is suitable for fine pitch and SMD assembly as well as for press-fit technology, but not for wire bonding applications.

Contrary to frequently expressed concerns, **hard gold** can be processed very well with aluminum wire. The bond quality meets all criteria required for wire bond contacts. However, its use is not recommended. It is very likely that the combination of hard gold and aluminum wire will degrade when exposed to temperature changes, leading to failures due to bond contacts coming loose after a few hundred hours at the latest. This fault pattern has already been successfully eliminated by adjusting the layer thicknesses (exact data has not been published and would have to be determined in each case), but it is too early to give the all-clear.

(see Schmitz S., Brenscheidt O.: Drahtbonden mit Aluminium auf Goldschichten – Mythen vs. Fakten, https://www.wotech-technical-media.de/womag/ausgabe/2022/10/17_brenscheidt_bonden_10j2022/17_brenscheidt_bonden_10j2022.php)

## 4.
## SURFACE PROPERTIES OF WIRE-BONDABLE METALLIZATIONS

This article highlights three key properties of bonded surfaces:

- Cleanliness
- Layer adhesion
- Surface topography, roughness

In addition to the three topics mentioned above, there are other properties that are more or less obvious, such as layer thickness, layer sequence, alloy, composition, oxidation state, hardness, homogeneity, and microstructure. However, these are either of lesser relevance to typical process defects or simply beyond the scope of this article.

**Task No. 1 – Ensure cleanliness.**

Cleanliness is by far the number one cause of bonding problems. Approximately 80% of the bonding failures encountered by the author in over 20 years of wire bonding can be attributed to contamination (usually visible to the naked eye). Although experienced process managers will confirm that even ultrathin, “barely visible” contaminants can cause problems, practical experience and a look behind the scenes show that most of these causes could have been detected under an optical microscope. And this is where the problems usually start, because the right equipment is often not available.

A suitable light microscope for the reliable assessment of contaminated surfaces can generally be found under the term “metallography and material microscope.” These are usually equipped with lens turrets that allow the magnification to be changed by rotating the optics. The optical magnification (by definition between the object and the image in the eye when looking through the eyepiece) in typical devices ranges up to a factor of 1000. There is a clear answer to the question of what minimum magnification is required for such devices: At least 200x magnification (a so-called 20x lens) and, in addition, a lens with 500x magnification (50x) and high optical quality. In addition, process managers must consider the minimum working distances from the lens that must be maintained and which smaller magnifications are useful for orientation on the sample.

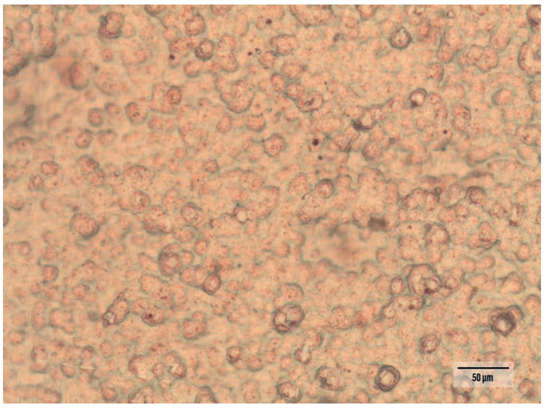

Figure 05: **Red, finely distributed discoloration on a printed circuit board after too long storage (> 2 years)**

Figure 04: **Stains after inadequate cleaning on PCB pad**

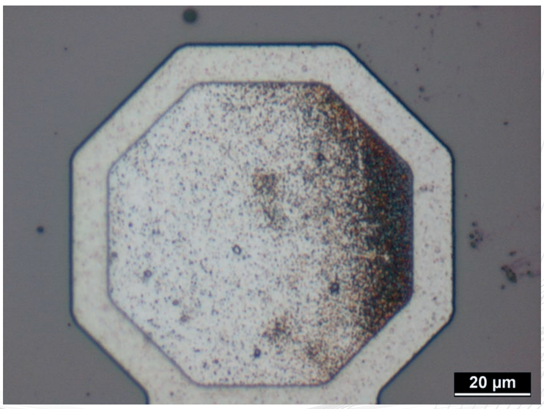


Figure 6: **Brown discoloration of an aluminum pad on a silicon chip, indicating inadequate storage of the surface**

Equipment configured in this way combines the following advantages:

- Easy to use (compared to more complex surface analysis devices)
- Fast and usually clear results
- The highest return on investment of all testing devices in your production – this low to medium five-figure purchase prevents expensive errors from the very first use.

**Keep your eyes open and look closely! – Discover layer adhesion problems.**

A wire bond contact that detaches from its bond pad – known as lift-off – is not permitted in thick wire bond connections. The cause is quickly suspected – “Maybe a bit of dirt,” “Possibly lying around too long and oxidized,” “The layer thickness is definitely too thin or the roughness too high.” A solution is also quickly found – increase the ultrasonic power. But here’s the thing: keep your eyes open!

If lift-off occurs, there are two possibilities:

1. The bond does not adhere to the metallization due to insufficient connection.
2. The bond has a very good connection to the top metal layer, but this in turn does not adhere to the layer below.

The second case describes what is known as layer delamination. This defect can only be detected with a high degree of certainty by looking through a microscope, as described in the previous chapter. If this defect is overlooked, troubleshooting will be carried out in the wrong place and with the wrong resources. The cause of layer delamination usually lies in the layer manufacturing process. In such cases, it is therefore essential to involve the supplier. Furthermore, the supplier plays a significant role in correcting this defect. It is therefore important to provide them with the correct information. Microscope images and SEM images (EDX analyses if necessary) are required to determine the exact location of the defect in the layer and in the process.

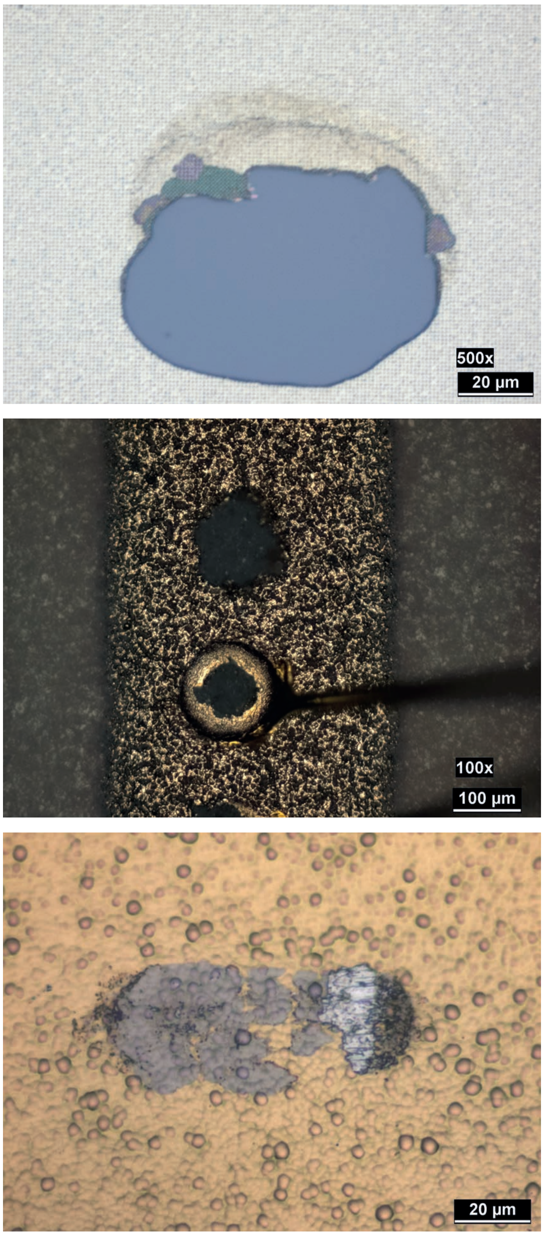


Figure 7: **Layer delamination on different coating systems**

**Measurement possible, limit values not (yet) in sight – check roughness.**

During the wire bonding process, friction and interactions between surfaces occur. It is obvious to assume that the topography (roughness) of the wire surface and the metallization play a central role here. However, practical experience shows that although the influence of roughness can be observed in the process, it has a significantly less pronounced effect on the process result than other factors. Nevertheless, monitoring roughness is interesting for manufacturing reasons – unlike cleanliness, alloy, hardness, or the oxidation state of a surface, roughness is very easy to monitor and measure. The challenge lies elsewhere. Over the last 10 years, the DIN EN ISO 25178 and DIN EN ISO 21920 standards have set important benchmarks for optical measurements and brought tactile testing methods up to date. The task now is to derive the surface characteristics relevant for stable wire bonding processes as parameters from such measurements and to determine specification limits for these parameters. This much is known and can currently be given as a recommendation:

- Ra values are not a good measure for evaluating a bond surface. The very different properties of rounded and finely structured, sharp surfaces are not reflected by the Ra value.

- Rz values are suitable for quantifying the risk of the bonding tool coming into contact with very high roughness peaks on the surface. S10z values from surface measurements are even more suitable.
- The Sdr value (ratio of elongated surface to projected measurement surface) contains information about the actual size of the surface that comes into contact with the wire. This value is a promising candidate for a parameter relevant to the wire bonding result.
- Sk parameters (Sk, Spk, Svk) can be derived from the Abbott curve of a surface measurement, which contain information about the formation of contact areas between materials that are in contact with each other. In the future, these are likely to be replaced by volume parameters (Vmp, Vmc, Vvv) from surface measurements.

Deviations in roughness that do not require advanced measurement methods include scratches and grooves. The following figures show microscope images of such surface defects, which can be easily identified under a light microscope.

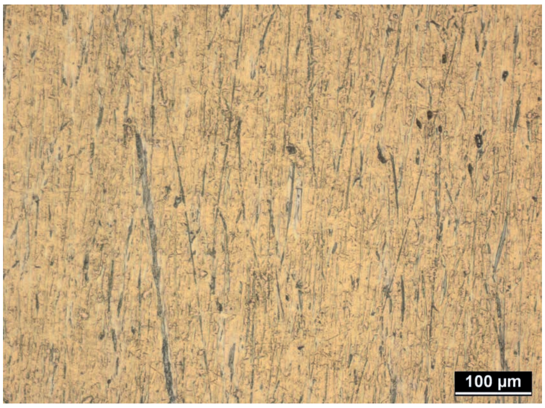


Figure 8: **Scratched ENIG surface due to missing paper spacers when packaging the circuit boards**

Figure 9: **Scratches on a PCB surface caused by mechanical pretreatment of the copper**

Looking back on this chapter, one thing cannot be emphasized enough: the light microscope has the highest return on investment of any testing device in your production. Invest in it and use it!

### Cleaning method for wire bonded printed circuit boards

Cleanliness is extremely important in wire bonding. Therefore, cleaning printed circuit boards before the wire bonding process is part of (almost) every wire bonding production. Cleaning does not necessarily have to be carried out during the process, but can also be done in advance by the supplier. Depending on the type of contamination, the sensitivity of the components, and the purity requirements, different cleaning methods are used.

### Wet chemical cleaning

Wet chemical cleaning encompasses various processes that use aqueous, solvent-based, or pH-neutral cleaning agents. It is used when organic or inorganic residues need to be removed. Depending on the application, spray cleaning, ultrasonic or megasonic cleaning, or dip cleaning is used.

In **spray cleaning,** the cleaning agent is applied to the assembled circuit boards under high pressure. The physical action of the spray jet and the chemical action of the cleaning fluid dissolve contaminants. This method is particularly suitable for large-area cleaning applications where intensive rinsing is required.

**Ultrasonic cleaning** takes place in a bath containing a cleaning fluid that is permeated by ultrasonic waves in the frequency range from approximately 25 to 130 kHz. These waves generate cavitation bubbles that detach dirt particles from the surface when they collapse.

**Megasonic cleaning** is based on the same principle, but operates at higher frequencies between 250 and 1000 kHz. It is particularly advantageous for sensitive components, as the mechanical stress on the components is reduced.

**In dipping cleaning**, the circuit boards are completely immersed in a cleaning bath. Mechanical aids such as stirring movements or air bubbles can be used to improve the cleaning effect.

### Vacuum plasma cleaning

Vacuum plasma cleaning takes place in a closed chamber under reduced pressure. A wide variety of contaminants can be removed through the targeted control of plasma parameters. The frequency selected depends on the type of contamination. Microwave plasma with a frequency of 2.45 GHz has a high plasma density and achieves maximum cleaning rates, but carries the risk of damaging sensitive components. High-frequency plasma at 13.56 MHz ensures uniform removal of contaminants and is therefore particularly suitable for complex geometries and components with narrow gaps. It also helps activate the surface, allowing subsequent layers, such as adhesives or coatings, to adhere better. Low-frequency plasma in the 40 kHz range is used when thin organic contaminants need to be removed without affecting the base material. This method is less aggressive and therefore particularly suitable for sensitive surfaces.

**$CO_2$ snow jet cleaning**

$CO_2$ snow jet cleaning uses liquid carbon dioxide, which is expanded under high pressure through a nozzle and forms solid $CO_2$ particles. These particles hit the surface at high speed and remove contaminants through various physical mechanisms. A key advantage of $CO_2$ snow jet cleaning is that no residues remain, as $CO_2$ is gaseous at room temperature and normal pressure. Another advantage is the possibility of precise application, which allows even complex, densely populated printed circuit boards to be cleaned in a targeted manner.

However, $CO_2$ snow jet cleaning cannot remove oxide layers. In addition, depending on the material combination of the components to be cleaned, electrical charging may occur, which can lead to ESD effects if insufficiently dissipated.

If you have read this article carefully up to this point, you can already guess what is coming next: Any cleaning for wire bonding is only as good as the visual inspection of the surfaces under a light microscope and the before/after results. The following images show photographs of surfaces before and after cleaning processes – not always successfully cleaned.

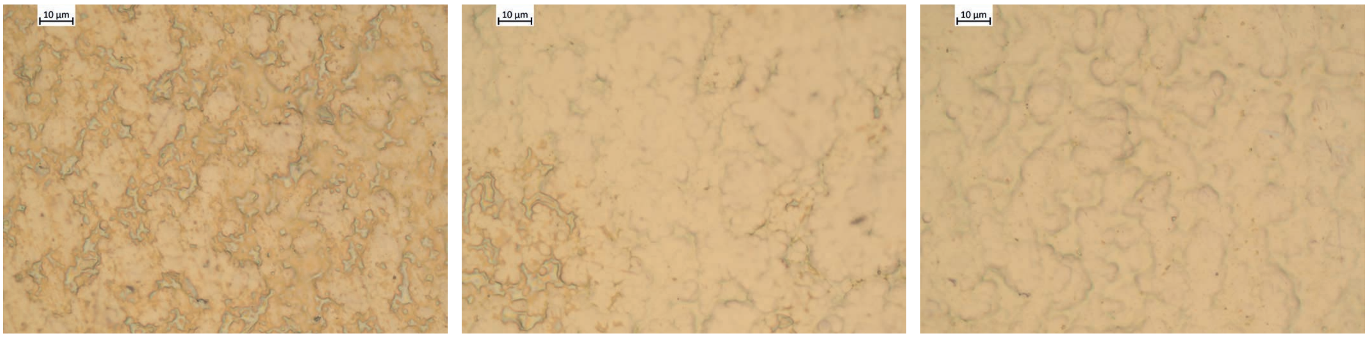


Figure 10: **Three states of a surface cleaned with CO2 snow jets (duration approx. 5 s), from left to right: contaminated with grease, insufficiently cleaned, well cleaned**

## SPECIAL CASE: **GAN**

In some cases, wire-bonded GAN semiconductors have surfaces metallized with thick gold. In this case, it is recommended to use gold wire bonding in the ball/wedge process. A complete discussion of the special features of this bonding process and material system would go beyond the scope of this article. Please contact us at info@bond-iq.de if you have any questions.

## ABOUT THE AUTHOR

Stefan Schmitz is a specialist in assembly and connection technology using chip and wire bonding. His company **Bond-IQ** in Berlin supports onboarding processes for new employees and the training of technology managers in companies through seminars, in-house events, process analysis and support for wire bonding applications. His online regulars' table for wire bonding provides an opportunity for professional exchange.

To find out more about, visit
**www.wirebonding-roundtable.com**

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