ULTRA LOW PROFILE COPPER FOIL FOR VERY LOW LOSS MATERIAL

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ABSTRACT
Copper foil roughness has become a significant factor influencing conductor loss in high speed PCBs, particularly as they move above the 50 GHz range. At high frequencies, the current tends to flow mostly on the surface of the conductor (skin effect). When the so-called skin depth reaches the same dimensions as the roughness profile of the foil, the current follow its contour, inducing additional loss due to the longer propagation path. For regular very low profile copper foil, the roughness is around 3.0 µm (Rz ISO), meaning that the loss becomes significant at frequencies close to 1 GHz. To achieve good results over 20 GHz, the profile roughness must be below 1.25 µm.

A new almost no profile copper foil has been developed to achieve this property while maintaining a good adhesion with low loss resins. Electrodeposited copper foil production is divided in two steps. First, the foil is plated on a titanium drum from a copper sulfate solution. Then a treatment is applied to increase roughness and ensure oxidation resistance. By using organic additives in the plating bath, the structure of the product can be controlled. Copper foils with a roughness below 1.25 µm have been obtained with a mixture of additives. Further improvement was achieved with titanium drums that had been polished with a specific grinding wheel to achieve a lower roughness on their surface.

The adhesion is usually increased with the treatment step by applying nodular copper particles. However, regular treatments have a significant impact on the roughness and therefore on the signal loss. A good compromise between adhesion and transmission properties was achieved with a specific nodular deposit. For ultra-low loss application, a version of the foil without treatment is also under development. Sufficient adhesion is ensured by silane-based coupling agent or organic coating.

Key words: Copper foil, insertion loss, high frequency, low profile

INTRODUCTION

Insertion loss

High frequency printed circuit boards applications have seen rapid growth during the last few years. Main driving factors are the combination of ever-increasing amount of information transferred on wireless networks with the widespread use of mobile devices. The emergence of radar sensors in the automotive sector, especially for the upcoming autonomous vehicles also requires electronic devices capable to carry high speed, high frequency signals with a limited size.

With frequencies above 50 GHz, the signal loss in a transmission line becomes significant. The total loss, or insertion loss, is the addition of conductor, dielectric, radiation and leakage losses [1,2]. The latter is associated with semiconductor materials and is usually not taken into account for PCBs. Radiation loss is the energy dissipated in the surroundings of the conductor. It increases with the frequency and depends on the design of the circuit. Dielectric losses are linked to the substrate used in the PCB. For high frequency applications, low loss substrate with a dissipation factor (Df) in the order of 0.003 are commonly used [3]. The conductor loss depends on the nature of the transmission material and its surface morphology. It is the task of the copper foil manufacturer to provide products with the appropriate properties (at least on the side bonded to the prepreg) to minimize the conductor loss.

When an alternative current is going through a conductor, the changing magnetic fields induce the formation of additional electric fields (Eddy's currents). Those fields are opposed to the "main" current in the center of the conductor, but strengthen it on the outside (Figure 1), resulting in an increased current density on the surface.

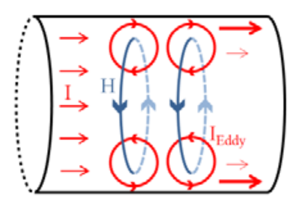

Figure 1. Formation of Eddy's currents due to changing magnetic fields in a conduction transporting AC.

This phenomenon, called skin effect, is stronger with higher frequencies. The effective section of the conductor where most of the current flows (the so-called skin depth) can be estimated with the equation below:

$$\delta = \sqrt{\frac{1}{\pi \cdot f \cdot \mu \cdot \sigma}}$$

Where δ is the skin depth (m), f the frequency (Hz), μ the magnetic permeability ($H.m^{-1}$) and σ the electrical conductivity ($S.m^{-1}$) of the material (copper). The skin depth is a measure of the distance from the surface of the conductor at which the current density falls to 1/e of its value on the surface [4]. Around 98% of the current flow at a distance of four times the skin depth. It is below the micrometer range for frequencies over 4 GHz (Table 1).

Table 1. Calculation of skin depth in copper depending on the frequency.

Signal frequency	Skin depth in copper
1 Hz	65.2 mm
1 MHz	65 µm
1 GHz	2.1 µm
10 GHz	0.65 µm
50 GHz	0.29 µm

Skin depth effect has two impacts on the conductor loss. Firstly, the effective cross-section of the conductor carrying the current is reduced, inducing a higher AC resistance. Secondly, for conductors with a rough profile, a low skin depth will cause the current to follow the contour of the material, increasing the effective length of the propagation path (Figure 2). It has been demonstrated that surface roughness can double the conductor loss [5].

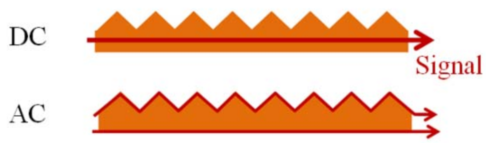

Figure 2. Comparison of current flow for DC and high frenquency AC in a rough copper foil.

To mitigate this effect, copper foil manufacturers must develop new profile-free products. For regular copper foils, the roughness is voluntary increased to improve the adhesion. It is considered that over 90% of the peel strength between a rough copper foil and a prepreg is due to mechanical forces, while the remaining 10% account for chemical adhesion. On a low or no-profile copper foil, the mechanical strength is drastically reduced. Two different approaches are possible to deal with this challenge:

(1) Almost no profile copper foil ensuring good mechanical adhesion with minimal signal loss
(2) No profile copper foil with only chemical adhesion

IPC-4562 defines 3 major classes for roughness profiles, irrespective of the foil's thickness (Figure 3). Below 5.1 µm (200 µinch) is defined as "very low profile". However, this definition is behind the industrial progress. Another gap is found among definitions of Rz since Rz ISO is not identical to Rz JIS. For very low roughness, this difference is significant and close to 20-25%.

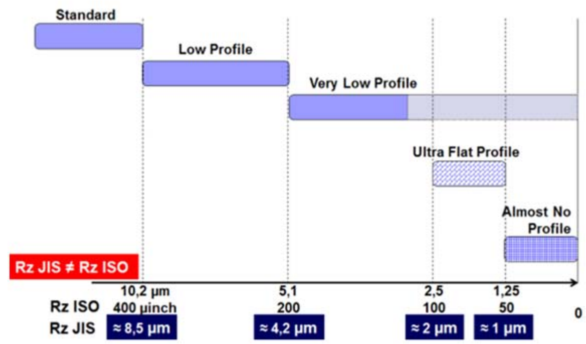

Figure 3. Grades of copper foils roughness [6]

This paper discusses the development of almost no profile and no profile copper foils with a roughness below 1.0 µm in Rz JIS, i.e. 1.25 µm (50 µm inch) in Rz ISO (all the roughness data presented below are expressed in Rz ISO).

Electrodeposited copper foil manufacturing

Electrodeposited (ED) copper foils are produced in two steps. Bare copper is first deposited on rotating titanium drums (cathode) to form a continuous film (plating step). The parameters of the foil can be adjusted depending on the plating conditions. Unlike rolled annealed foils, the process is asymmetrical and ED copper foils have two different sides: the drum side was in direct contact with the cathode and its structure is the negative copy of the drum surface. The electrolyte side was in contact with the solution. Its roughness can be controlled with organic additives impacting copper deposition process.

The second step of copper foil manufacturing is the treatment. Several electro-chemical processes improve the foil adhesion and ensure oxidation resistance. Firstly, copper nodules are deposited on the foil to increase its surface area and therefore the adhesion. To obtain this, specific electrolysis conditions must be used: low copper concentration with high current density (Figure 4).

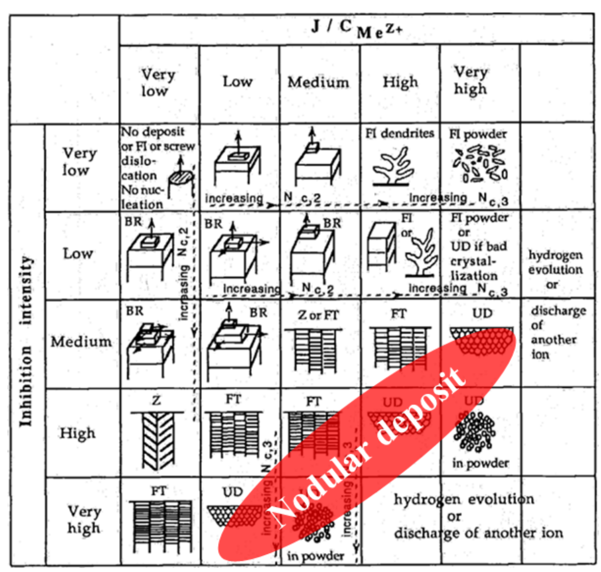

Figure 4. Copper deposit structure depending on deposition parameters (where J / C $_{Me}^{Z+}$ is the current density and inhibition density is copper centration, temperature or the presence of additives) [7]

Zinc and chromate passivation layer is subsequently deposited to provide oxidation resistance at temperatures over 200°C. Chemical adhesion is guaranteed by a silane coupling agent.

Roughness measurement

The roughness of copper foils is usually measured with a contact profilometer: a stylus follows the surface to recreate a linear profile from which the Rz can be calculated. However, this contact method may not be appropriate for low roughness foils with fine treatment nodules. A comparison with light interferometry measurements will be made in this paper.

DEVELOPMENT OF ALMOST NO PROFILE COPPER FOIL

Background

The physical parameters of an ED copper foil can be controlled with the addition of organic additives into the plating bath. Certain additives – known as levelers – can decrease the roughness of the surface. During the electrodeposition process, the current density and electric field strength tend to be higher on the peaks of the substrate which therefore tend to grow faster. This yields a rough surface. However, some organic molecules are adsorbed preferentially on the peaks of a surface and the deposition is therefore favoured on the valleys, yielding a product with a much smoother profile (Figure 5).

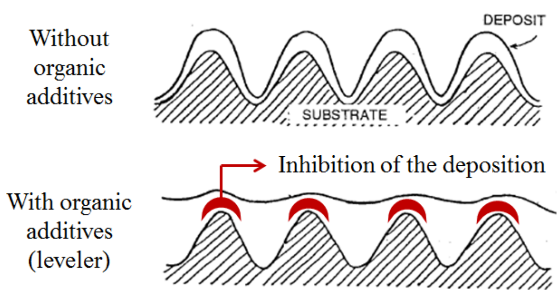

Figure 5. Copper deposition with and without organic additives (levelers) [8].

The roughness of foils currently produced with levelers falls into the range of "low profile" product (4-6 µm for 35 µm (1 oz./ft²) thick foil). Very low profile are produced by using much higher concentration of additives (roughness of 5.1 - 10.2 µm). Further improvement can be achieved by using other types of organic additives that can give the electrolyte side of the foil a smooth and shiny aspect (Figure 6). The roughness of those ultra flat profile foils is between 1.3 and 2.5 µm (Table 2).

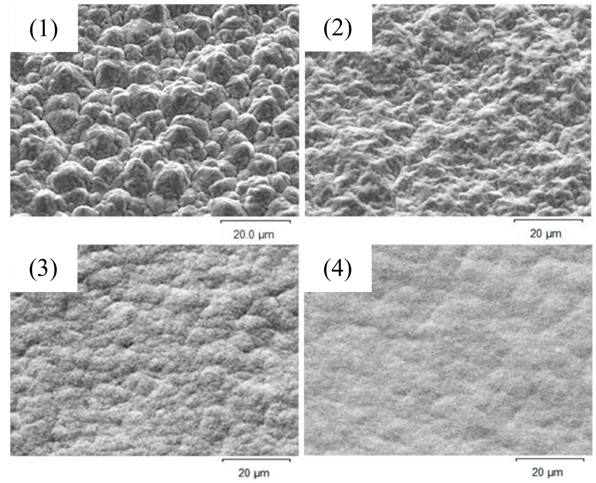

Figure 6. SEM imaging of 35µm (1 oz./ft²) copper foil prior treatment: (1) low profile foil; (2) very low profile; (3) ultra flat profile; (4) almost no profile.

Table 2. Grades of 35µm (1 oz./ft²) thick copper foil (roughness measured after plating) with additives used and roughness achieved.

Copper foil grade	Additive 1	Additive 2	Average roughness (Rz ISO)
Regular	Leveler	/	6.3 µm
Very low profile	Leveler (high concentration)	/	3.3 µm
Ultra flat profile	Leveler	A	1.9 µm
Almost no profile	Leveler	B	1.2 µm

Production of almost no profile foil

To reduce the roughness below 1.25 µm, several improvement of the plating process were made. The most obvious way is to change the organic additives for more effective ones. This can easily be tested in the laboratory. Copper deposition is made in a large beaker with solution parameters as close as possible to the production bath. The results can never exactly be the same than on the line, but the trends are very informative. Several additives have been compared in the laboratory (Table 3). It appears that the roughness of ultra-low profile foil can be decreased by 0.1 to 0.2 µm with a simple change of additive.

Table 3. Comparison of additives (laboratory tests).

Additive 1	Additive 2	Roughness (Rz ISO) (µm)
Leveler	A	1.24
Leveler	B	1.08
Leveler	C	1.42
Leveler	D	1.53

The second improvement is linked to the titanium drum on which the copper foil is plated. As explained earlier, its surface impacts directly the copper foil drum side morphology, but also to some extent the electrolyte side.

Indeed, for very low thicknesses such as 9 and 12 µm (1/4 and 1/3 oz./ft²) there is a correlation between drum side and electrolyte side roughness (Figure 7).

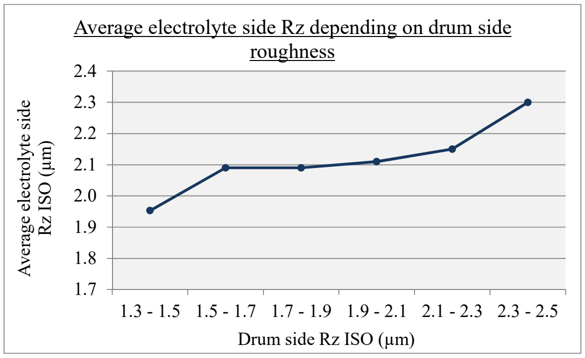

Figure 7. Impact of drum side roughness on electrolyte side for low thickness foil (9 µm).

With a specific drum preparation method, the surface roughness could be decreased down to 1.25 µm. The impact on electrolyte side roughness is estimated to be in the 0.1 to 0.2 µm range. Long term production runs have highlighted that the polishing done after each roll to remove the oxidation on the drum's titanium surface had little to no impact on its roughness (Figure 8).

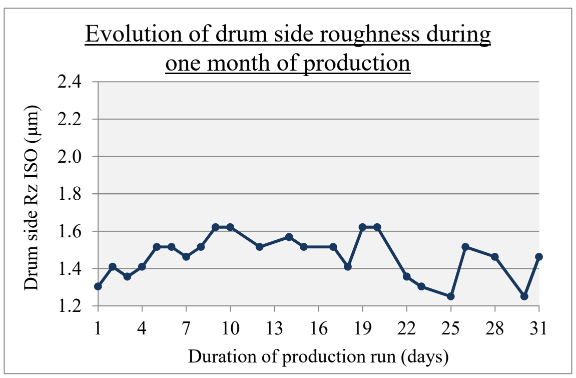

Figure 8. Evolution of drum side Rz during one month of production on low roughness drum (each measurement was done after a polishing of the drum surface).

With both additives and drum surface improvements, the roughness could be decreased by 0.3 µm for all thicknesses (9, 12, 18 and 35 µm). In 9 and 12 µm, the Rz reduction is due mostly to the drum surface, while the new additives were primarily effective for 18 and 35 µm. Those improvements are reflected in the insertion loss measurements (Table 4). From a mechanical point of view, almost no profile foils behave like any regular low profile copper foil.

Table 4. Impact of copper roughness on insertion loss for different grades of foils on low loss prepreg (DS-7409DV) using Cisco's S3 test method [9].

Foil grade	Rz ISO (µm)	$\lvert S_{21}\rvert$ at 10 GHz (dB)	$\lvert S_{21}\rvert$ at 20 GHz (dB)
Very low profile	3.9	-7.37	-12.99
Ultra flat profile	2.8	-6.22	-11.32
Almost no profile	1.2	-5.51	-9.93

The insertion loss of almost no profile foils is significantly improved compared to ultra-flat profile foils.

TREATMENT OF ALMOST NO PROFILE COPPER FOIL

Background

Copper foil treatment improves both adhesion and oxidation resistance. Standard zinc-chromate passivations are considered to have little if no effect on the insertion loss. Indeed, the layers are extremely thin (around 3 nm on treated side and 10 nm on untreated side which are etched away in the PCB manufacturing process) and mostly nonconductive. However, the copper particles applied to improve the adhesion can impact significantly the insertion loss due to their conductivity and the increased roughness. On regular ED copper foils, the nodule size is around 5 µm.

Almost no profile foil nodular treatment

Nodular treatment is essential on copper foils to ensure sufficient adhesion. For low loss applications, a compromise must be found between insertion loss and peel strength on low loss prepregs (the target is > 2.8 pli or 0.5 N/mm). A new ultra-low profile nodular treatment was therefore developed specifically for this foil.

First attempt to produce a low profile treatment resulted in a uniform layer of round-shaped nodules covering the foil surface (Figure 9). The roughness measured with a contact method was not increased compared to the base foil, but the peel strength was not sufficient. Deposition parameters were further adjusted to increase the number of nodules deposited.

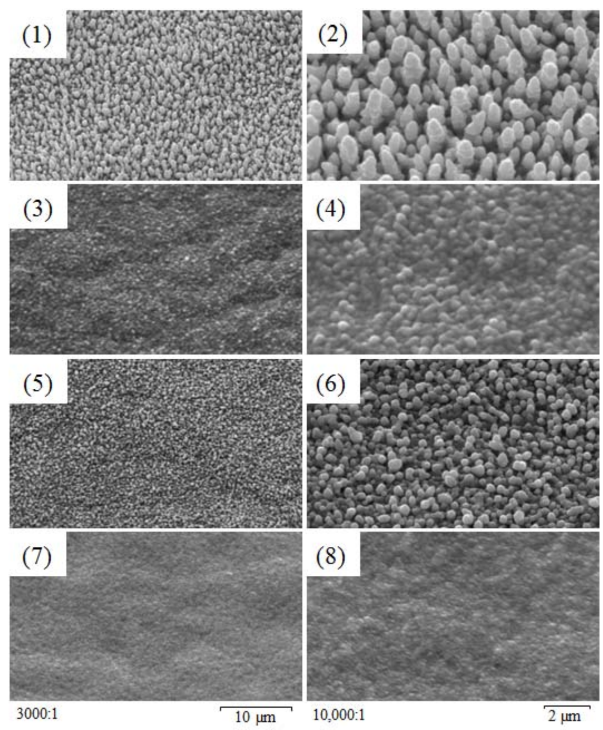

Figure 9. (1,2) Ultra flat profile treatment (3000x and 10,000x), (3,4) first version of almost no profile

treatment, (5,6) final version of almost no profile treatment, (7,8) no profile (untreated) foil.

Despite its extremely low profile (roughness 1.0 µm lower than on ultra-low profile foils), the nodular treatment has a significant impact on the adhesion, and ensures a peel strength above 2.8 pli on low loss materials (Table 5).

Table 5. Roughness and adhesion of low profile copper foils on low loss material (Megtron 6).

Copper foil type (35 µm thickness)	Rz ISO (µm) Contact method	Adhesion on low loss material (pli)
Ultra flat profile foil	2.0	4.3
ANP foil (first version)	1.2	3.0
ANP foil (final version)	1.2	3.8
No profile (untreated)	1.1	0.3

Almost no profile foil passivation

The almost no profile copper foil is passivated with a classical zinc-chromate treatment ensuring high stability at temperatures up to 200°C. For low loss applications, this passivation is expected to exhibit better performances than Nickel-based treatments for example. Indeed, due to its lower conductivity than Copper, a thin layer of Nickel can impact significantly the signal loss at high frequency [10]. This has been verified by applying a Nickel passivation layer on no profile foil and comparing the insertion loss with the one of the regular product (Table 6). The Nickel layer slightly improves the adhesion but also impacts the signal loss.

Table 6. Insertion loss of almost no profile foils with different treatments on low loss material (DS-7409DV) measured with Cisco's S3 test method.

Copper foil	Almost no profile foil	No profile foil	No profile foil
Nodular treatment	Yes	No	No
Passivation	Zinc-chromate	Zinc-chromate	Nickel-based
Rz ISO (µm)	1.19	1.07	1.13
Adhesion (pli)	2.9	0.6	1.1
$\vert S_{21}\vert$ at 10 GHz (dB)	-5.54	-5.37	-5.47
$\vert S_{21}\vert$ at 20 GHz (dB)	-10.18	-9.66	-9.93

ROUGHNESS MEASUREMENT ON ALMOST NO PROFILE FOIL

The roughness of copper foils is usually measured with a contact profilometer consisting of a diamond needle (stylus) sliding on the surface. This method is appropriate for high roughness copper foils, but shows limitations for the almost no profile products. Indeed, it cannot detect the additional roughness caused by the treatment since the nodules size is below 1 µm. The needle is clearly scraping through the treatment, only taking into account the base foil roughness (Figure 10). This is the reason why nearly no difference in roughness could be seen between the base and treated foils.

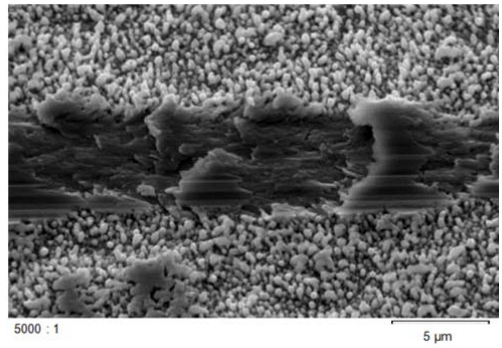

Figure 10. SEM picture of the trace left by the stylus used for roughness measurement on almost no profile foil.

A more appropriate surface roughness measurement for almost no profile foils is the white-light scanning interferometry. The principle is to divide a light beam in two paths, directing one to a reference mirror and the other one to the sample surface. This measurement beam travels different distances depending on the surface profile. The two waveforms are then recombined and create specific interference patterns depending on their phase difference. Those patterns are analysed to calculate the height of the sample at each point (pixel) scanned [11].

Unlike the stylus method, light interferometry does not damage the sample and can measure height differences smaller than 0.1 µm. 3D roughness measurement have been performed on almost no profile (Figure 11) and no profile foils (Figure 12). With this method, clear difference can be seen between the two products.

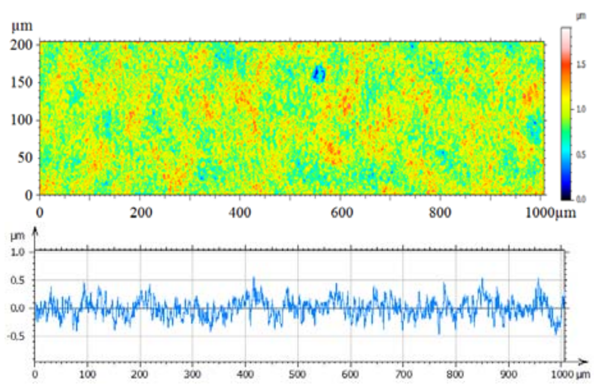

Figure 11. 3D imaging of almost no profile foil (top) and 2D surface profile (bottom) measured with white light scanning interferometry.

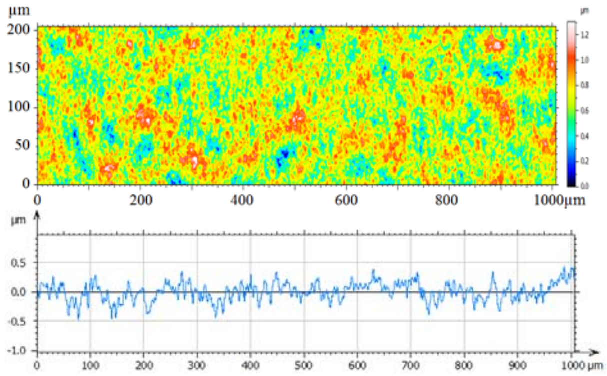

Figure 12. 3D imaging of no profile foil (top) and 2D surface profile (bottom) measured with white light scanning interferometry.

3D profiles give interesting information about the origin of the foils' roughness and their order of magnitude. On no profile foil, some waviness can be seen, inducing a roughness up to 0.8 µm. In addition to this, smaller irregularities appear, with a magnitude of maximum 0.4 µm. Those defects are linked to the additives used for the base foil production. Concerning the almost no profile foil, the treatment nodules appear to have a size similar to the irregularities observed on no profile foil, but with a much higher density. Knowing that the stylus method measure a roughness around 0.9 µm for both foils, we can conclude that only the roughness coming from the waviness of the foil is measured with this method. Roughness values are summarized in Table 7. (Rz on a straight line).

Table 7. Comparison of stylus and light interferometry roughness measurement with different measuring lengths.

Copper foil type (35 µm thickness)	**Rz ISO (µm)**		
	Stylus (8 mm)	Light interferometry (70 µm)	Light interferometry (1000 µm)
Almost no profile	1.19	0.83	0.90
No profile (untreated)	1.11	0.43	0.74

It appears that the roughness can significantly varies depending on the measuring length. On 70 µm distance, only the micro-roughness is measured. The waviness is visible with larger intervals.

CONCLUSION

Almost no profile copper foil has been developed with both plating and treatment improvement. The use of specific additives and low roughness drums for the base foil production resulted in a decrease of 0.3 µm in roughness compared to previous products. Sufficient adhesion (0.5 N/mm) was obtained with a very low profile nodular treatment having little impact on both roughness and insertion loss.

The use of white-light scanning interferometry ensured an accurate measurement of the foil's roughness. Unlike stylus method, this method provided results in good correlation with the insertion loss measurements.

FUTURE WORK

Future development will focus on the reduction of the base foil roughness and the improvement of the adhesion of the no profile copper foil. New approach are being tested regarding the plating conditions of the base foil in order to further reduce the roughness, especially for the low thickness products. The influence of current density, copper concentration and leveler nature are being evaluated. The most challenging yet important project remains nonetheless the adhesion of no profile foil. To further reduce the insertion loss, the nodular treatment must be avoided. New chemical adhesion promoter must be found in order to ensure a peel strength in the range of 0.5 N/mm without roughness increase. Another alternative would be to deposit a rough yet nonconductive layer on the smooth copper surface to ensure adhesion with minimal insertion loss.

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