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REPORT

Flexible solder masks

– Fields of application, performance capabilities and limitations –

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1. Introduction

Flexible **P**rinted **C**ircuits (FPC) are used in many fields. With their primary origin in aerospace applications, they can be found in computer and telecommunication technology, e.g. clamshell cell phones, laptops and hard drives. In recent years, the field has expanded to include automotive applications, sensor technology and medical appliances. The future growth rate of FPC applications is forecast to be 10% and more.

Flexible printed circuits can be coated with a coverlay, in which the openings are punched or lasered, or with flexible solder masks. Besides thermal curing types, flexible solder masks are available as UV curing and photoimageable systems. A number of aspects must be considered when selecting the ideal ink for the application at hand, such as the demands on registration accuracy and resolution as well as the compatibility between the foil substrate and the solder mask process. The processing of flexible photoimageable solder masks requires a slightly different approach to when using "traditional" photoimageable solder masks, one reason being the poor mechanical stability of the foils during processing. With flexible photoimageable solder masks (FLPiSM) in particular, high HDI flex requirements can be achieved using established processes with excellent resistances to the associated surface finishes (ENiG, CSN) and to the heavy environmental loads encountered in aggressive surroundings.

For the various application fields of flexible printed circuits different types of solder mask are available with formulations tailored to the individual requirement profiles. In practice, this enables a good choice of solder mask both with respect to the desired processing properties as well as to the performance capability. Such ink systems are typically divided into:

- UV curing inks
- thermal curing inks
- photoimageable inks (which are thermal cured/crosslinked after the photolithographic imaging process).

The understandable demand for a much higher flexibility of these ink systems compared to "traditional" solder masks used in combination with rigid pcbs is joined by similarly high demands on the thermal, thermomechanical, physical and chemical properties. As a rule, all these inks are formulated as 2-pack systems (resin and hardener component) and applied by horizontal or vertical double-sided screen printing.

2. Formulation

The basic formulations of the three above mentioned ink types vary considerably. The model formulation of a flexible photoimageable solder mask in tables 1a and 1b illustrates the complexity of the type, sychronisation and number of components involved:

Table 1a: Formulation of resin component (A)

Raw Material	Property
Binding agents (photo-reactive and thermal crosslinking resins)	Decisive for adhesion, flexibility, resistances and physical and chemical final properties of the coating
Filling agents	Adhesion, scratch resistance, control of flow behaviour (thixotropy)
Dyes/pigments	Colour-giving substances (soluble/unsoluble)
Additives	Responsible for defoaming during flash-off and drying, wetting of substrate, regulation of flow behaviour, etc.
Solvents	Viscosity adjustment, control of drying behaviour

Table 1b: Formulation of hardener component (B)

Raw Material	Property
Photoinitiators	Initiate photopolymerisation during exposure, influence the required exposure energy and ability to represent fine structures (ink dams between pads)
Solvents	Viscosity adjustment, control of drying behaviour
Hardener (crosslinker for the thermal curing binding agent components)	Decisive for resistances and physical and chemical final properties of the coating

Pure UV curing ink formulations do not contain the thermal crosslinking components or the volatile solvents to adjust the viscosity; the "solvents" used in such products have a UV functionality. They do not evaporate during curing, but as reactive thinners take part in the UV crosslinking reaction and are integrated into the binding agent backbone. Vice versa, the pure thermal crosslinking inks do not contain any UV-reactive substances.

3. Processing

Even if flexible solder masks are processed in the same principle manner as "traditional" solder masks, there are still some peculiarities that need to be observed which can have a considerable effect on the result. The flexible substrate in particular places greater demands on the solder mask application process. Due to the large number of sometimes highly specialised base materials / adhesives it is definitely advisable to assess their individual performance over the whole process. The ink manufacturer specifies the solder mask processing parameters. Figs. 1 – 3 illustrate the process flow for the three types of solder mask used for flexible substrates.

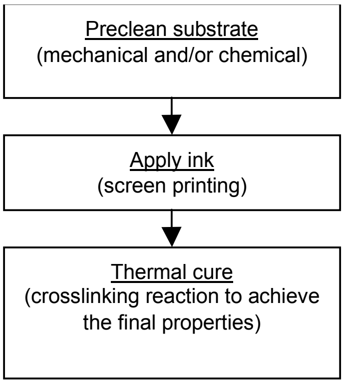

Fig. 1: Process flow for thermal curing solder mask

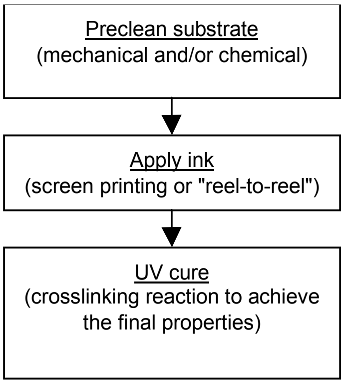

Fig. 2: Process flow for UV curing solder mask

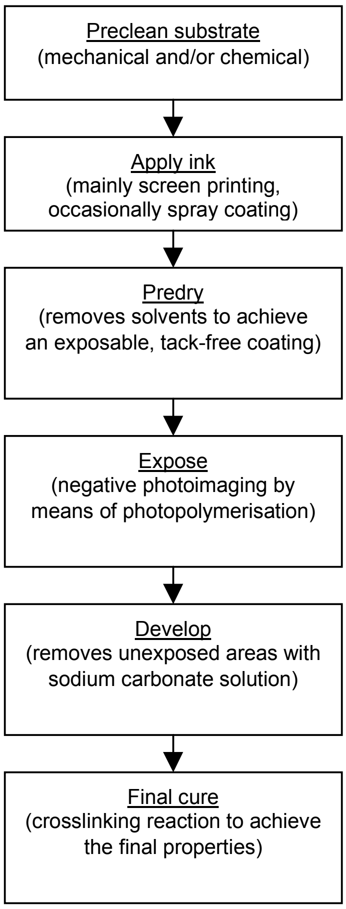

Fig. 3: Process flow for photoimageable solder mask

3.1 Precleaning the substrate

Prerequisites to ensure perfect adhesion of the coating without the risk of dewetting or delamination in subsequent processes as well as to secure the maximum achievable electrical properties are an oxide-free metal layer with a typical average peak-to-valley height of around 0.8 to 1.2 µm and a clean and dry substrate. Polyimide substrates in particular have a tendency to absorb moisture so that it can be advisable to temper them prior to applying the ink to safely avoid problems with the adhesion. Meanwhile, multi-step chemical pretreatments have proven their worth considering the problematic handling of flexible substrates in mechanical pretreatment processes and because of their ability to obtain optimum adhesion of the ink even when exceptionally aggressive finishes (electroless nickel/gold and electroless tin) are used. Especially in application fields for photoimageable solder masks they are valuable in promoting an excellent adhesion, chemical resistance and thermal (shock) resistance.

3.2 Preparing the ink

The resin and hardener components should always be mixed electromechanically to attain a reproducible homogeneous mixture and to avoid "dead zones" in the containers. Devices where the mixing head itself is static and the container is allowed to rotate (Fig. 4) have proven very effective. It is extremely important to avoid trapping air in the mixture as it is difficult to expel and micro-bubbles can be transferred to the substrate even after observing long standing times prior to printing. Typically, the mixture should be stirred for approx. 10-15 minutes. The low revolution speed with this type of mixing equipment keeps the incorporation of air to a minimum. The best way to check whether the components are mixed properly is to decant the mixture into a second container and inspect the emptied container for potential "dead zones". A holding time of at least 30 minutes between mixing and printing is recommended.

Fig. 4: Electromechanical mixer with static mixing head

The use of electromechanical ink shakers should be carefully debated. Although the mixing result is often very good, the amount of air incorporated is considerable. With this method of mixing it is easy to generate enough frictional heat to allow the trapped air to escape (the increased temperature of the mixture reduces the viscosity), but it is imperative to observe long holding times to bring the mixture back down to room temperature prior to application. Another problem is the large influence the high heat generated by the mixing process can have on the pot life, i.e. the maximum possible processing time may be distinctly reduced. At the same time, the predry window of photoimageable inks can become much narrower and negatively affect or even totally prevent unexposed areas from being completely developed free.

3.3 Application

Screen printing is the most popular method for coating flexible printed circuit boards. The main reason for this is that both with the single-sided horizontal and double-sided vertical coating process bend stress during application can be well prevented and coating is practically independent of the substrate thickness. Typically, the processing temperature ranges between around 20 to 23°C, with most inks being tailored to this temperature window. Because the viscosity in particular is closely related to the temperature, larger fluctuations inevitably change the flow behaviour and thus lead to variations in trace coverage.

Overall, flexible solder masks are especially susceptible to static build-up on the substrate which can result in micro-dewettings. This can particularly reduce the reliability in the immediate vicinity of traces due to ultra-low or non-existent coverage. Further, flexible photoimageable solder masks react very sensitively to contaminations (dust, residues from other products on tools, abrasion from gloves, etc.), easily causing wetting problems. In general, it should be assumed that a dry film thickness of at least 10 µm (on edge of trace) is necessary in order to achieve a good resistance in chemical finish processes. The resistance of flexible photoimageable inks basically is much higher than that of pure UV or thermal curing systems for which the higher crosslinking density is primarily responsible.

In the case of higher traces, it is advisable to apply two coats if necessary, instead of one coat with a correspondingly coarse screen fabric (where the large amount of material applied may cause the ink to run off the trace edges). With flexible photoimageable solder masks completely curing the first coat before applying the second one is often not mandatory, but it does reduce the risk of damage/cracking during handling and ensures the first coat is fully stable when the second coat is developed. It may be possible just to initially cure the first coat.

3.4 Drying, exposing and developing photoimageable solder masks

Immediately after application and before the actual drying phase (removal of the solvents to achieve a tack-free coating which can be exposed in a contact process) a holding time or "flash-off" of at least 10 minutes should be observed to allow any marks left by the screen mesh during the printing process to even out and to give any trapped air the opportunity to rise to the ink surface.

Contrary to "traditional" photoimageable solder masks, the types formulated especially for use on flexible substrates may have a slightly greater tendency to stick to the artwork during exposure. This phenomenon is not necessarily to be attributed to insufficient drying, but in general to the specialities of the formulated and flexibilised binding agents.

While the lateral stability of rigid and rigid-flex pcb panels means they can be directly transported through the process line, flexible circuits between 0.1 and 0.2 mm thick can no longer be conveyed without appropriate aids. All kinds of carrier systems have been designed for this purpose.

The problem with several carrier systems is that the flexible circuits are often too wavy to be processed and are then clamped via a lidding system or sucked tight by the vacuum devices of the printer and assembler through holes in the carrier. These carrier systems can be used for the printing process, but not for the wet chemical processes required for photoimageable solder masks.

In this case, sandwich components are more appropriate – optionally with an eloxised aluminium base plate or an ESD[1]-approved epoxy base plate – where the surface is covered with a fully polymerised, adhesive modified silicone which attracts the flexible circuits depending on their surface quality.

A key speciality of flexible photoimageable solder masks is that they only exhibit the required/desired degree of flexibility after thermal cure, because it is only then that a complete and stable three-dimensional network is created. This demands great care in avoiding bend stress and crazing in the uncured ink film (Fig. 5) during all prior processing and handling steps. Single-sided processing has proven very beneficial in this respect, but is coupled with a higher effort and lower capacity.

Fig. 5: Crazing in solder mask following bend stress prior to curing

Occasional staining (moisture trapped under the surface) in the electroless nickel/gold process is frequently a consequence of poor polymerisation during exposure. With flexible photoimageable solder masks in general it is extremely important to keep to the exposure energy specified by the manufacturer to achieve optimum results. Because the trapped moisture is usually superficial, brief tempering often helps to remove it.

3.5 Curing / Crosslinking

When using flexible photoimageable solder masks it should be carefully considered whether to perform a "UV bump" before or after thermal cure. Ideally, a UV bump vitrifies the ink surface thus, for example, promoting ultra-low ionic contamination readings with various surface finishes, however it often leads to embrittlement and reduced flexibility.

The common rule is that the manufacturers' curing instructions must be followed very precisely. Excessive UV and thermal crosslinking can be detrimental to the flexibility.

[1] ESD – electro-static discharge

4. Performance and limitations

Table 2 lists an estimated ranking of some characteristic properties of the three principle types of ink available.

Table 2: Estimated comparison of selected characteristics of flexible solder masks

Property	UV curing	Thermal curing	Photoimageable
Process complexity	low	low	very high
Suitability for "static-flex"	very high	very high	very high
Suitability for "dynamic-flex"	high	high to very high	medium to high
Achievable resolution	very low (approx. 150–200 µm)	very low (approx. 150–200 µm)	very high (up to 30 µm)
Thermal stress on substrate during cure	very low (depends on equip-ment used)	low to very low (cure from 80°C)	very high (as a rule 1 h at 150°C)
Suitability for "reel-to-reel" processing	very high	low	low
Soldering resistance	low to medium	low to high (depends on curing parameters)	very high
Chemical resistance	low	low to high (depends on curing parameters)	very high
TCT resistance	low	medium	very high
Permanent temperature resistance	low	medium	very high
UL 94 approval	depends on manufacturer	depends on manufacturer	depends on manufacturer

4.1 Selecting a suitable ink system and resolution

Traditionally, flexible circuit boards are used in combination with so-called coverlays (foils) based on epoxy or acrylate polymers into which a pattern is drilled or punched before they are applied. Their precision is similar to that of screen printed solder masks. Line/space requirements of 50 µm cannot be met that way. Photoimageable solder masks are one solution in achieving this increasingly important requirement for flexible circuit boards. A combination of classic application processes – such as lamination or screen printing – and laser ablation to open the holes is also possible and has already partly established itself as a further option. Laser ablation is particularly beneficial in achieving an exact registration.

One restriction to be remembered, especially with BGA applications, is the film thickness. In this case, 50 µm foils are not unproblematic, and while 25 µm foils are more suitable they are much more difficult to handle. Photoimageable solder masks have a significant processing advantage in this respect.

Table 3: Estimated comparison of selected characteristics of coverlays and flexible solder masks

	Dry film (Coverlay)	**Liquid solder masks (SM)**		
Application	**Vacuum laminator**	**Screen printing**		
		2-pack SM	UV-SM	FLPiSM
Film thickness	25–50 µm	10–20 µm	10–20 µm	10–20 µm
Resolution	approx. 200 µm	150–200 µm	150–200 µm	approx. 30 µm
Electrical properties	good	good	good	very good
Flexibility	very good	very good	good	good
Processing	complex	simple	simple	complex
Costs	high	low	low	medium

4.2 Selecting a suitable ink system and flexibility

When selecting a suitable ink system for a specific application, a number of partly contradictory factors must be taken into consideration. Naturally with flex applications the focus is on the bend stress capability which, besides the choice of product, is primarily influenced by the applied film thickness (thicker films usually behave far less favourably in this regard than thin films). As a rule, the bend stress capability specified by the ink manufacturers refers to a certain bend radius with a defined substrate and a defined ink film thickness. Often the maximum possible number of bend cycles without cracking is specified. Generally, with "static-flex" or "flex-to-install" applications the number of bend stress cycles is limited; photoimageable solder masks are particularly suitable for such scenarios, especially where the demands on the resolution (e.g. ink dams between pads) are high. When pure thermal or pure UV curing ink systems are used it must be accepted that the resolution will not be nearly as good, although the bend stress capability of such inks is much higher.

Table 4 shows a typical method to test the adhesion of a coating after long-term thermal stress. The evaluation of potential cracks is performed under a light microscope at 16x magnification. The solder mask is ranked as delaminated from the substrate if lifting is visible under the light microscope.

Table 4: Results of adhesion after thermal storage – flexible photoimageable solder mask

Test	**After 500 h storage at 120°C**	**After 1000 h storage at 120°C**
Adhesion IPC-TM-650, 2.4.29B, 10 cycles, 20 bends, 2 mm mandrel, 180° (PI foil, 25 µm film thickness)	no cracking, no delamination	no cracking, no delamination

4.3 Resistances

Table 5 illustrates the thermal resistances of different flexible solder mask types. The maximum resistance (based on the criteria delamination and chalking) is achieved by a photoimageable solder mask. With thermal curing inks it should be noted that the curing parameters can be varied over a relatively wide range so as to accommodate the thermal stress capabilities of the substrate. The curing temperature of some thermal curing inks can be varied over a range from approx. 80 to 130°C although the curing time must be adapted accordingly. In general, the different degrees of crosslinking that result affect the soldering resistance, i.e. the resistance is lower at a lower curing temperature than at a higher curing temperature.

Table 5: Comparison of the soldering resistances of
UV curing, thermal curing and photoimageable solder masks

Test	UV curing	Thermal curing	Photoimageable
IPC-SM-840D, 3.7.2, 10 s / 260°C	passed	passed	passed
IPC-SM-840D, 3.7.3, 10 s / 260°C (Pb-free)	passed	passed	passed
IPC-T-650, 2.6.8, 20 s / 288°C	10 s passed	10 s passed	20 s passed
UL 94 (20 s / 288°C)	10 s passed	10 s passed	20 s passed
IPC-SM-840D, 3.7.3.1, sim. reflow Pb-free (5 x 10 s/260°C)	failed	failed	passed

As can be seen from a comparative thermogravimetric analysis based on a 5% mass loss (Fig. 6), the thermal resistance level of photoimageable flexible solder masks is similarly high to that of solder masks for rigid applications. The thermal resistance with a TG_5 value of around 350°C is comparable to high-Tg base materials. While this means that the thermal resistances of the polyimide carrier cannot be utilised to the full, applications projecting into a temperature range of 150°C are possible.

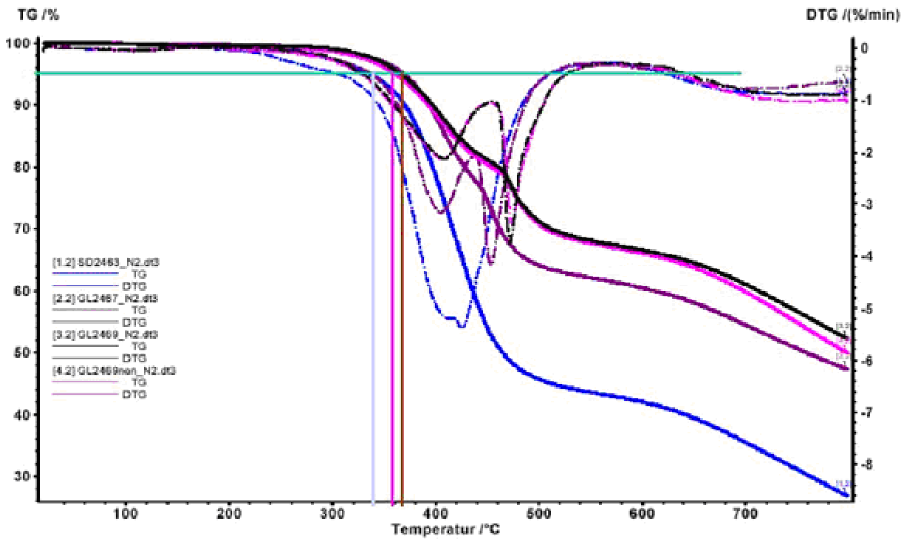

Fig. 6: Thermogravimetric analysis (5% mass loss method)
of photoimageable solder masks

A comparison of the maximum possible bend radius (Table 6) when using a 50 µm thick polyimide foil coated with different ink types at a film thickness of 25 µm shows that the appropriate thermal curing ink performs best, exhibiting folding resistance without cracking. However, the prerequisite for this maximum flexibility are ultra-low curing temperatures which, as mentioned above, have a detrimental effect on the soldering resistance. When describing the flexibility, the method to determine the "bend strength" has a great influence on the specified minimum radii and number of bend cycles. The substrate and trace geometry equally have an important effect. To differentiate, amongst others the so-called bar code test has proven a practical tool where the bend cycles are performed at right-angles to the copper traces and the bend strength can be determined depending on the lines and spaces.

Table 6: Possible maximum bend radii

Test	UV curing	Thermal curing	Photoimageable
maximum bend strength around mandrel (20 bend cycles/180°)	1.5 mm radius	< 1.0 mm radius (resistant to folding)	2 mm radius

Fig. 7 shows the moisture and insulation resistance results of a flexible, photoimageable solder mask which was tested based on TM 2.6.3.1 of IPC-TM-650 at various moisture and temperature conditions. The test was performed over a range from 40°C and 90% r.h. up to 85°C and 85% r.h. at 50 V BIAS.

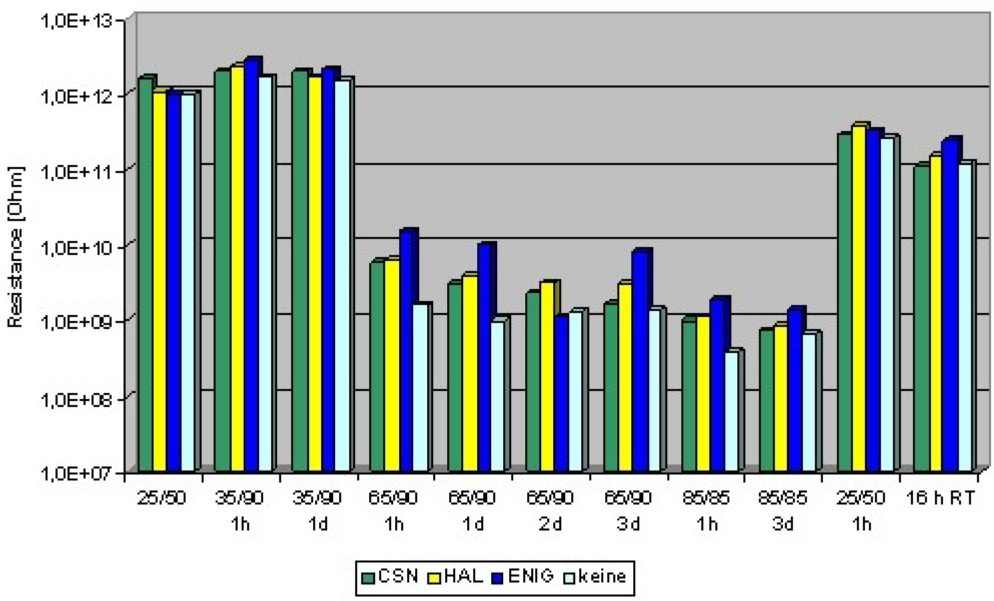

Fig. 7: Insulation resistances of a flexible photoimageable solder mask with various finishes after thermal cycling [1000 cycles, -40°C (30 min) / +150°C (45 min)]

The measured resistance values are all > 500 MOhm and thus exceed the "IPC threshold" of the IPC-SM-840 specification. The resistance values at 85°C/85% r.h. are equally above the lower threshold value of 100 MOhm per IPC despite the high humidity/thermal stress. There was no evidence of a significant influence of the type of finish. The results are comparable to those from tests performed on photoimageable solder masks for rigid applications.

With flexible substrates, special attention must be paid to the adhesive film. It can have a considerable effect on the electrical moisture and insulation performance. Fig. 8 shows an identical photoimageable solder mask on foils with different adhesives which has been characterised by means of an 85/85 cycle test. Depending on the level of humidity and thermal stress the insulation resistance fluctuates immensely. The environmental conditions 35°C and 90% r.h., 65°C and 90% r.h. and 85°C and 85%

r.h. were continually applied and the insulation value recorded after one hour and after three days. The two end values at 25°C and 50% r.h. (RT – room temperature) represent the regeneration capability. The best results were achieved with an adhesive-free substrate.

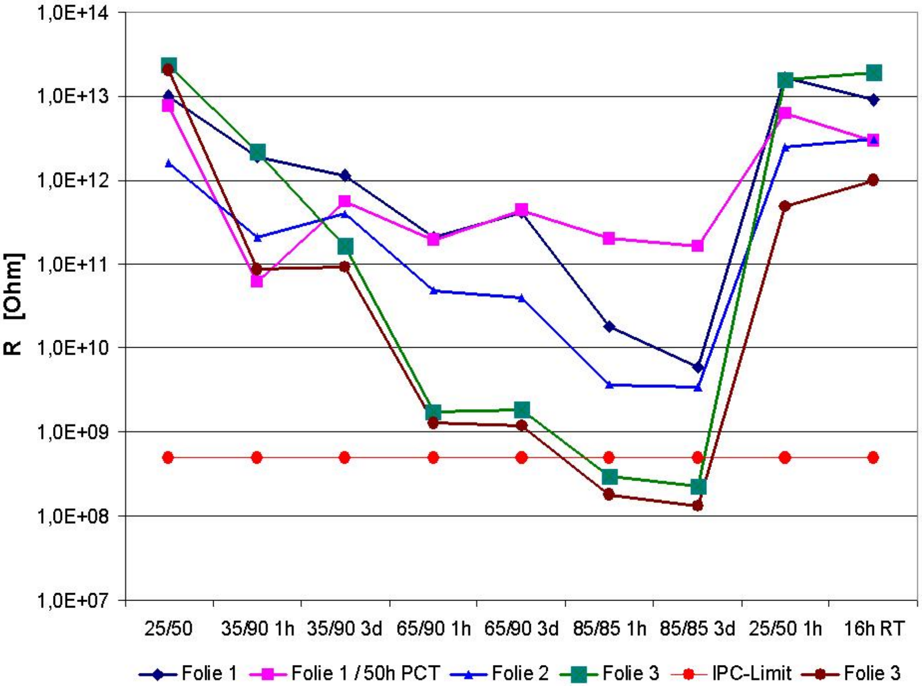

Fig. 8: Moisture/insulation resistances of a flexible photoimageable solder mask in an 85/85 cycle with various adhesive substrates

5. Summary

The use of solder masks on flexible substrates is gaining in importance. UV curing, thermal curing and photoimageable materials are available that differ considerably in their application and final properties. The most significant differences are the degree of flexibility that can be achieved, the maximum possible image resolution and the potential resistance during soldering. These solder masks are processed by means of familiar and established methods which can be reliably mastered after taking into consideration a few specialities related to flexible solder masks.

The majority of flexible circuits will certainly be produced in Asia, however it is evident that German printed circuit board manufacturers can also handle this technology at a high level and a lot can be expected here in the future.

6. Literature

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