

Solder Balls

on

Photoimageable Solder Masks

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Abstract

Solderballing during reflow and wave soldering has been on the agenda for many years. The demand of pcb manufacturers for an elimination of solder balls is becoming more and more insistent. A multitude of mechanisms behind and causes of solder balls and their adhesion to solder masks is discussed, but the problem still exists and is obviously becoming more disturbing with growing miniaturisation. This paper focuses on what is known about solderballing and solder ball adhesion to solder masks today and summarises what measures have proven to eliminate or largely reduce this phenomenon from a solder mask manufacturer perspective.

1. Introduction

In the past years, numerous publications have dealt with the problem of the origin and adhesion of solder balls to solder masks. Solder balls, however, are not a new phenomenon; studies on the subject were published back in the early eighties. Essentially, there are three reasons why the solder ball phenomenon is topical today:

- So far, the adherent solder balls have been largely removed when cleaning the printed circuit boards of residues of conventional flux agents rich in solids by means of CFC-containing cleaning agents and brushing equipment. Since legislation today prohibits the use of ozone-damaging CFC in most countries, the manufacturers of printed circuit boards are forced to employ alternative cleaning procedures or to apply methods that enable the complete elimination of cleaning. In order to be able to do without cleaning, so-called no-clean flux agents, low in solids, were developed. These flux agents render a cleaning of the printed circuit boards after the soldering process unnecessary, because only a very small amount of flux agent residues remains on the printed circuit board. Nevertheless, depending on the quality requirement, the printed circuit boards have to be brushed after the soldering process in order to remove the adherent solder balls. In case of particularly stringent quality requirements regarding freedom from solder balls, a manual elimination of the balls is still indispensable.
- The increasing insertion and interconnection density of printed circuit board assemblies result in the fact that even smallest solder particles that adhere to the surface of the printed circuit board (thin component branches and mainly on the mask after the soldering process) have to be regarded as metallic contamination because they represent a potential danger for uncontrollable disturbances, such as short circuits, for the printed circuits owing to their electric conductivity.
- The proportion of photoimageable solder masks has gone up considerably. Available investigations have proved that photoimageable solder masks - with substantial variations as far as the individual resist systems are concerned - are much more sensitive regarding the formation of solder balls than conventional 2-pack solder masks. This particularly applies to purely alkaline developable systems, both for liquid and dry masks.

Increasing cost pressure compels the manufacturers of printed circuit boards to solve the solder ball problem because substantial savings can be achieved by eliminating the brushing process and, above all, the manual removal of the solder balls.

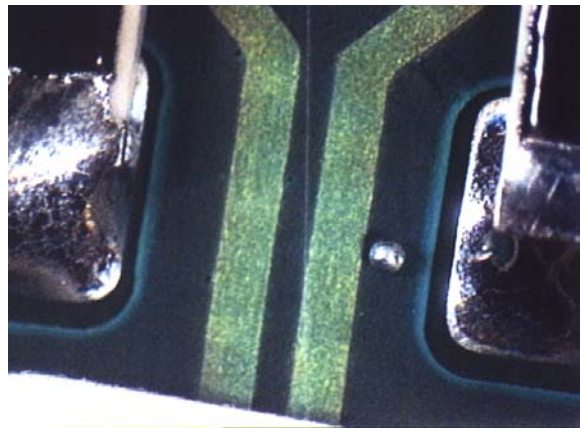


Fig. 1: Solder ball adhering to photoimageable solder mask

2. Demands for non-occurrence of solder balls on PCB assemblies

The diameter of the solder balls observed on the printed circuit board assemblies varies greatly and ranges from several hundred microns to less than one micron. Since solder balls very often are not visible to the naked eye, many printed circuit board users, even today, are not aware of the fact that they have a solder ball problem. The following requirement parameters are currently regarded as a guideline for the freedom from solder balls on printed circuit board assemblies:

2.1 MIL-STD-2000A

The US-American military standard MIL-STD-2000A does not permit any solder ball adhesion. However, this cannot be achieved currently without a corresponding cleaning effort.

2.2 ANSI-IPC-S-815B

The requirements of ANSI-IPC-S-815B (general demands for the soldering of electrically conducting connections) are of a lower standard and stipulate the following:

- no solder balls with a diameter of > 0.13 mm

- less than 5 solder balls with a diameter of < 0.13 mm/sq. in.

With regard to the solder masks currently on the market, even those requirements can only be met by means of a corresponding cleaning effort and/or high-wage follow-up treatment, keeping in mind, however, that considerable differences exist among the various photo-sensitive solder masks as far as the susceptibility to solder ball adhesion is concerned.

2.3 Modified ANSI-IPC-S-815B

Some manufacturers of printed circuit board assemblies have modified ANSI-IPC-S-815B as follows:

Fixed adhering solder residues are permitted up to an extension of 0.2 mm if the number of 5 is not exceeded on an area of 25 x 25 mm, provided insulation resistance as specified is not impaired.

Some assemblers state that solder balls are acceptable if they adhere to the pcb/to the solder mask and cannot be removed without applying a defined force. However, these specifications are rare and obviously not applied in sensitive fields of electronics.

3. Accidental and systematic solder balls during wave soldering

While the term "occurring solder balls" was generally employed, the differentiation today is between accidental and systematic solder balls, depending on their distribution on the printed circuit board:

Accidental solder balls are accidentally spread over the printed circuit board, mainly on the component side, less frequently on the solder side, in the case of wave-soldering.

As a rule, they originate in association with the soldering unit on account of the run-off attitude of the solder. The solder rushing back into the solder reservoir causes splashes which are deposited on the surface of the printed circuit board in a random or accidental pattern. However, also blow-out effects caused by flux agent or water residues in plated-through holes lead to the formation of such accidental solder balls.

Systematic solder balls are located on the solder side in a systematic distribution pattern. Their distribution is in direct relation to the pcb layout. Systematic solder balls occur in certain areas only, for instance between component connections. Systematic solder balls are regarded as the real solder ball problem.

3.1 Origin of systematic solder balls

A variety of different theories have been set up and rejected again as far as the origin and, particularly, the adhesion of solder balls to solder

masks are concerned. The currently generally accepted theory formulated by H. Bell regarding the origin and adhesion of systematic solder balls says that the balls originate while the printed circuit board leaves the main soldering wave, and the remaining solder deposit, for instance between two component connections, cannot flow off completely onto the component connections or into the solder reservoir as a consequence of the interfacial energy solder/solder mask and develops into a solder globule or solder ball owing to the surface tension of the solder. Thus, the amount of interfacial energy solder/solder mask, at least in those areas where solder balls separate, is higher than the cohesion of the solder and leads to the development of solder balls.

4. Influence in the development of solder balls

The following factors indisputably contribute to the development of solder balls:

- solder mask
- printed circuit board layout
- solder / printing of solder paste
- flux agent
- soldering unit
- environment (e.g. humidity)

The solder, flux agent and soldering unit employed obviously exert an influence on the formation of solder balls; this influence, however, is comparatively small. Special solder alloys, optimised flux agents and modifications to soldering units as well as optimised printing parameters (e.g. precision/definition during solder paste printing) lead to a reduction in the adherent solder balls, but it is practically unanimously agreed today that the main influence on the development of solder balls originates from the solder masks and that the decisive breakthrough in the solution of the solder ball problem can only be achieved by modifying the formulation of the solder masks employed.

4.1 Formulation of solder masks

The basic formulation of solder masks is quite similar, no matter what brand is used. Most common are two-pack formulations in the field of photoimageable solder masks, consisting of a resin component (A component) and a hardener component (B component). The principle build up might look as follows:

Table 1: Composition of resin component (A)

Raw material	Property
Binders	Photoreactive and thermally cross-linking resins, decisive for adhesion, dielectricity and resistance
Fillers	Adhesion, scratch resistance, control of flow behaviour (thixotropy)
Dyes/Pigments	Colouring substances
Additives	Defoaming in air exhaustion and drying, wetting of substrate, influence on flow behaviour, etc.
Solvents	Viscosity adjustment, control of drying behaviour

Table 2: Composition of hardener component (B)

Raw material	Property
Photoinitiators	Initiate photopolymerisation in exposure, influence on exposure time and representability of very fine details
Solvents	Viscosity adjustment, control of drying behaviour
Hardener	Cross-linking medium of the thermally curing binder components, decisive for resistance and physical and chemical final properties of the coating

Despite the similarity in the fundamental formulation setup of photoimageable solder masks, some enormous differences exist regarding processibility and efficiency of individual lacquers. On the one hand, this is due to the quality and clarity, respectively, of the raw materials employed that may only fluctuate very slightly from batch to batch, and, on the other hand, to the correlation of the individual raw material components of a lacquer formulation. Examples of this are the partly big differences with regard to solderballing. Therefore every single ingredient of a solder mask formulation has to be checked very thoroughly with regard to its impact on solder ball formation.

5. Methods for the evaluation of the solder ball-repellent characteristics of solder masks

The methods for testing and classifying the solder ball susceptibility of a solder mask proposed to date had the disadvantage that merely isolated, partly contentious influence parameters were quoted as a standard for the solder ball numbers to be expected in practical production.

The determination of the Knoop-hardness of solder masks shall serve as an example for this. This hardness measuring method is employed in electro-plating technology for measuring the hardness of deposited metal layers and also as a suitable method for the interpretation of the solder-repellent characteristics of solder masks in research and practice. This method is based on the assumption that a connection exists between the Knoop-hardness of a solder mask and the number of adherent solder balls. According to this method, solder masks with a high degree of hardness consequently have a lower number of solder balls than softer solder masks.

It must be mentioned, however, that the hardness of a solder mask measured at room temperature, not least owing to the influence of the prescribed fillers, may definitely be high, but that the hardness measured is not indicative of the hardness of a resist system at soldering temperatures. The thermo-plasticity of solder masks at soldering temperature is therefore ignored. Furthermore, it is proved that some conventional 2-pack solder masks that have a lower hardness compared with photo-sensitive solder masks show a much lower number of solder balls. Statements with regard to high solder mask hardnesses leading to low or no solderballing at all therefore seem to be in contradiction to both theory and practical experiences so far.

The only possibility of reliably recording the solder ball-repellent characteristics of solder masks and safely assessing resist modifications had for a long period of time consisted of soldering tests in the pcb production and the subsequent counting of the adhering solder balls.

Parallel to this method, however, one has gone over to describing this assessment and classification of the interfacial attitude solder mask/solder by the dewetting characteristics of the solder mask towards the solder, using wetting scales.

This process ensures that even minute solder adhesions occurring in practical pcb assembly production are reliably forecast. The complicated and time-consuming counting of the solder

balls in soldering tests is eliminated because only small, extensively solder mask-coated test specimens, consisting of prepreg material, are required and tested for the measurement. Regarding the processing stresses, the coated prepreg material corresponds to the operating phases of a printed circuit board (for instance hot-air levelling).

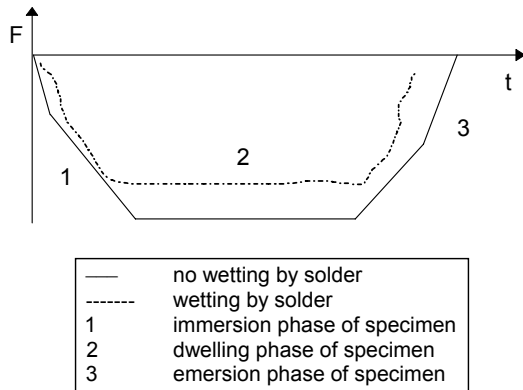


Fig. 2: Principle diagram of graphs recorded in tests with the wetting scales

In principle, these flux-treated specimens are hung from a sensitive balance (mostly a spring balance) and vertically immersed in liquid solder to a pre-set depth. A vertical force results from buoyancy and surface tension that acts on the immersed specimen. This force is continuously recorded as a function of time. From the measuring curves thus obtained (fig. 2), the interfacial attitude solder mask/solder can be inferred.

In the case of an axial symmetry of the immersion and emersion phases of the measuring curves obtained, a dewetting effect of the solder mask towards the solder exists and no solder ball adhesion or only a very small amount of solder ball adhesion is expected in practical tests. Deviations from this ideal course of the curve indicate wetting of the solder mask with solder and thus an increased solder ball susceptibility of the corresponding resist system.

6. Considerations and tests to avoid solder balls

As initially mentioned, the solder masks employed in the production of printed circuit boards obviously exert the main influence on the development of solder balls that adhere to the printed circuit board assemblies. Therefore, the solder mask manufacturers were, and still are, under the obligation to eliminate or to substantially reduce solder ball adhesion step-by-step by means of adequate formula modifications. The measures described below give an overall view of some of the methods used to eliminate solder balls. The modifications of the solder mask formulations were effected on a polyalcohol developable, photoimageable sol-

der mask. However, in the mean time, these modifications have also been implemented to aqueous-alkaline developable solder masks with excellent results.

The tests concerning the solder ball elimination were carried out in the following sequence:

1. Establishment of the solder mask modification by employing selected raw materials.
2. To begin with, application of the solder masks to copper-clad base material.
3. Examination of technological minimum requirements of solder masks, among others perfect developability, definition, solder bath resistance, adhesion as well as the most important electrical characteristics.
4. Solder masks meeting these minimum requirements were applied to prepreg material by means of a casting unit in order to perform the wetting tests with the wetting balance. In addition, printed circuit boards with a particularly solder ball-susceptible layout were coated in order to assess the practical solder ball adhesions. Ten each of these coated printed circuit boards were subjected to the practical soldering test. In the case of especially positive results, the relevant solder mask setting was produced again and tested in order to verify the results.

In the evaluation of the practical soldering tests using a stereo magnifier, a general differentiation was initially made between solder leads > 0.2 mm and < 0.2 mm at 4-fold magnification.

In the course of the tests it became obvious, however, that, with progressive optimisation of the resist modifications, differences regarding the number of adhering solder balls - particularly in the < 0.2 mm solder ball range - were very difficult to determine at 4-fold magnification. The magnifying factor was therefore increased to 10.

The tests were performed on the premise that it cannot be the target to develop an entirely solder ball-free solder mask with deficiencies regarding, for instance, processibility or final electrical properties, thus the practicality of the developed solder mask modifications was always a prominent consideration.

6.1 Microroughness of the solder mask surface

One of numerous examinations on solderballing shows that solder masks that were roughened prior to soldering by pumice brushing or a treatment with potassium permanganate solution have clearly less solder balls than untreated solder masks. The roughening process means an extension of the sol-

der mask surface and thus a change in both the surface energy and surface topography of the solder mask which effects a reduction in solder ball adhesion as a consequence of the modified interfacial relations solder/solder mask.

This resulted in the following considerations:

- A roughening or extension of the solder mask surface, respectively, by means of the methods described above is not practical because this might damage the coating. Exposed conductors would oxidise and reduce the reliability of the pcb assembly. In addition, this kind of surface extension represents an undesirable additional operating step causing extra costs.

A rougher surface and extension of the solder mask surface, respectively, however, can also be achieved by the formulation of special filling agents. The subsequent treatment of the solder mask surface could thus be eliminated.

The use of coarse fillers would be a superficial method for reaching a maximum roughness of the solder mask surface. However, since current pcb production calls for the representation of ≤ 75 micron solder dams between SMD pads that can be realised with various resist systems, only very fine-grained fillers can be used. Coarse ingredients eliminated from the finely graduated solder dams in the development process would weaken the stability of these dams to such an extent that they would lose their stability and break in the subsequent HAL process or other processes (e.g. electroless Ni/Au) that mean a great amount of stress for the solder mask.

For this reason, it was only possible to achieve a microroughness of the solder mask surface by using very fine-grain fillers and thus minimise the adherent solder balls by means of a modified surface topography.

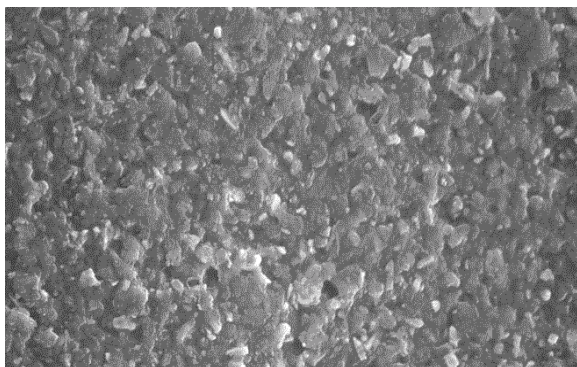


Fig. 3: SEM photograph of a microrough solder mask at 700x magnification

Besides, there were other theories in the air saying the certain filler points that emerge from the binder matrix effect or favour the adhesion

of solder balls on account of their polarity. In order to create a basis for further investigations in this respect, a solder mask formulation was developed that is entirely free from fillers as well as containing non-soluble colour giving substances (pigments). This solder mask was subjected to a practical soldering test.

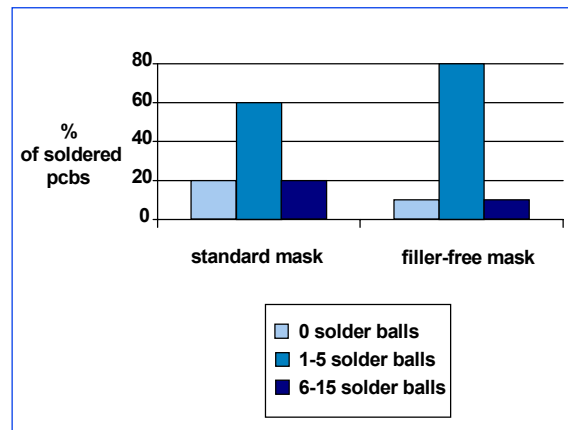


Fig. 4: Change in > 0.2 mm solder ball adhesions renouncing the use of fillers compared to the standard solder mask

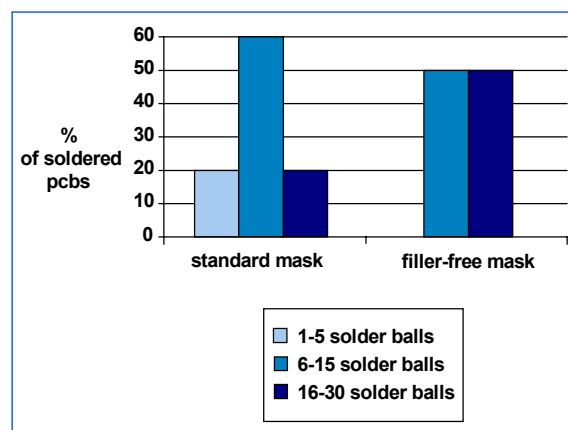


Fig. 5: Change in < 0.2 mm solder ball adhesions renouncing the use of fillers compared to the standard mask

The counting of the solder balls resulted in a clearly increased adhesion of solder balls compared to the reference solder mask (standard mask) (figs. 4 and 5). It could therefore be concluded that solder balls can be minimised by means of the formulated fillers (type, shape, follow-up treatment).

After the testing of a variety of different fillers and filler combinations, this method has turned out to be basically correct. Compared to the standard solder mask systems, an effective reduction in solder balls could be observed (figs. 6 and 7). The > 0.2 mm solder balls could be eliminated completely by means of the formulation of special fillers.

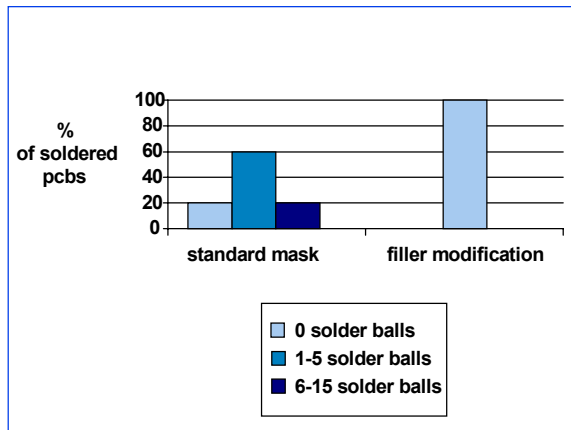


Fig. 6: Change in > 0.2 mm solder ball adhesions by using fine-grained, retreated fillers compared to the standard mask

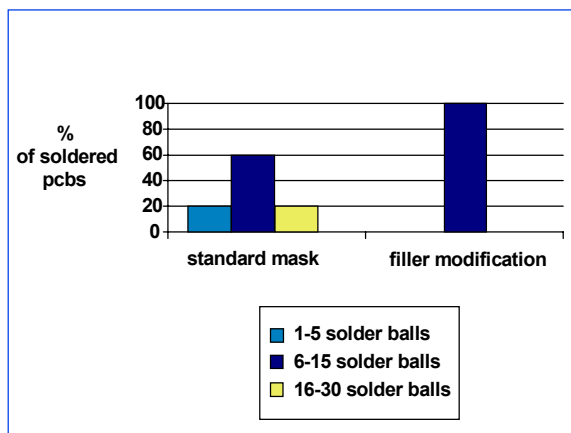


Fig. 7: Change in < 0.2 mm solder ball adhesions by using fine-grained, retreated fillers compared to the standard solder mask

In order to further improve the practicability of these solder mask settings, it was also attempted to arrive at an improvement of the thixotropic properties of these solder mask modifications by using special wetting and dispersing additives. It was found, however, that even extremely small quantities of these additives reduce the solder ball-repellent properties of the solder masks.

This example proves that the attitude of the solder masks regarding solder balls can be influenced by even one formula constituent at very low additive quantities. The substitution of fillers differing from each other regarding type, shape and, if applicable, a retreatment can therefore constitute only one step towards an entirely solder ball-free coating; the other formula components, too, were examined regarding their solder ball-repellent attitude, particularly the binding agents included.

6.2 Use of modified binders

The comparison of the polyalcohol developable, photoimageable solder mask system and a system developable both in aqueous-alkaline (soda) solution and polyalcohols proved that the aqueous-alkaline and polyalcohol develop-

able system shows better results regarding the non-adhesion of solder balls than the purely polyalcohol developable resist. The main difference in the formulated binders is that the aqueous-alkaline and polyalcohol developable resist system contains carboxyl, i.e. acid, functional groups which effect the solubility of the unexposed resist areas in the soda developer solution.

This results in the following consideration:

- On account of their polarity, the carboxyl groups obviously influence the adhesion of the solder mask surface. The incorporation of these groups in a solvent developable resist system could reduce the solder balls in this system.

Such resist binders were synthesized and tested in wide-range test series' in cooperation with manufacturers of resist raw materials.

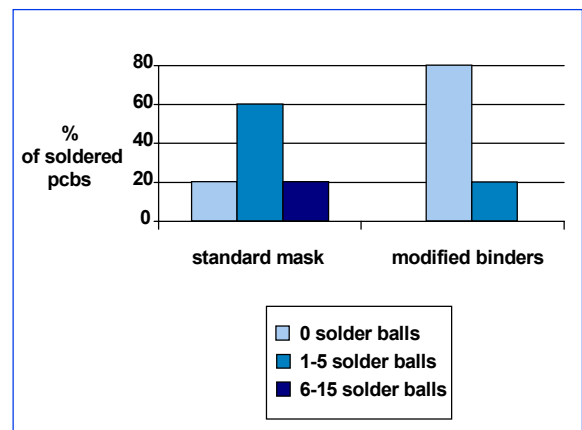


Fig. 8: Change in > 0.2 mm solder ball adhesions owing to the use of modified, carboxyl group-containing binders compared to the standard solder mask

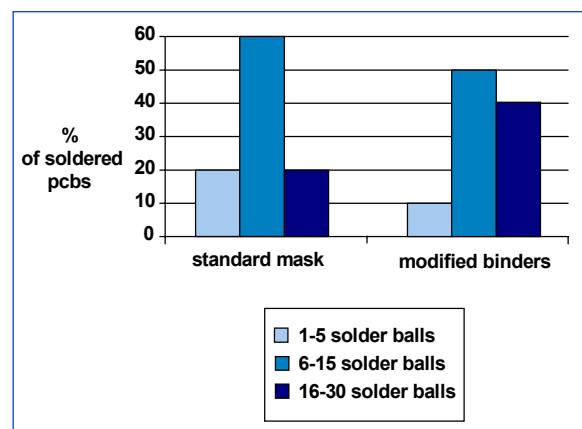


Fig. 9: Change in < 0.2 mm solder ball adhesions owing to the use of modified, carboxyl group-containing binders compared to the standard solder mask

It was found in this respect that those solder masks at least have a definite influence on > 0.2 mm solder balls (fig. 8). Those could be reduced drastically. The < 0.2 mm solder ball adhesions increased, however, (fig. 9) so that

the total number of solder balls established thus decreased only slightly compared to the reference resist. Generally, it must be stated, however, that the interaction between solder and solder mask can be influenced by the incorporation of carboxyl groups.

6.3 Use of surface additive substances

Practical production proves that when wave-soldering with flux agents rich in solids generally less solder ball adhesions occur than with flux agents low in solids. This is generally attributed to the higher coating thickness that remains on the printed circuit board after the application of the flux agent. This thicker coat obviously influences the solder/solder mask interface and largely prevents a wetting of the solder mask with solder.

This resulted in the following consideration:

- On account of their low density, certain additives rise to the surface of the applied solder mask where they form a protective film which generally improves the scratch resistance of the resist.

It is conceivable that this protective film as well as the relatively thick flux agent coats eliminate or minimise an interaction between solder and solder mask.

A decisive factor for the selection of those additives - as a rule, high temperature-resistant waxes - is the temperature resistance that should be $> 280\text{ }^{\circ}\text{C}$, because otherwise a decomposition of these materials at HAL or soldering temperatures, respectively, must be expected.

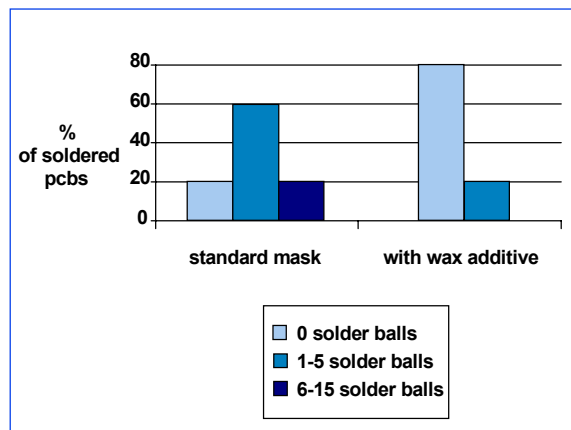


Fig. 10: Change in $> 0.2\text{ mm}$ solder ball adhesions owing to the use of high temperature-resistant wax compared to the standard solder mask

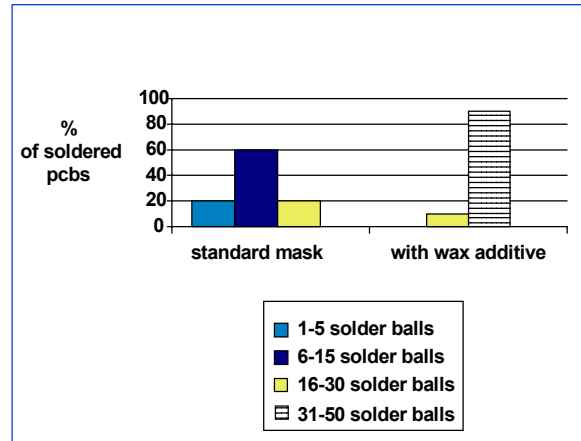


Fig. 11: Change in $< 0.2\text{ mm}$ solder ball adhesions owing to the use of high temperature-resistant wax compared to the standard solder mask

The formulation of a high temperature-resistant wax results in a distinct reduction in the $> 0.2\text{ mm}$ solder ball adhesions (fig. 10). The $< 0.2\text{ mm}$ solder ball adhesions (fig. 11), however, increased considerably. The total number of adherent solder balls was thus clearly above the numbers for the reference solder mask. A reduction in the interfacial strength solder/solder mask by means of using this additive can therefore be excluded. It must be considered, however, that in the preliminary tests only few substances proved suitable for use in the resist system applied. Another, untested additive might have yielded better results.

This example of a deterioration in the solder ball numbers encountered compared to the reference resist explains the problems in the optimisation of existing solder mask formulations as far as solder ball adhesions are concerned.

On account of the enormous variety of raw materials available - this applies to both fillers and additives - solder mask manufacturers find it very difficult to select suitable raw materials for testing. Even though the determination of the wetting characteristics of solder masks with solder by means of wetting balance statements regarding the solder-repellent properties of a solder mask can be made relatively quickly and easily without expensive and time-consuming production tests, lengthy test series are certainly not eliminated. Each and every theoretically suited raw material intended for solder ball elimination still has to be tested with respect to its general compatibility with the remaining system and an optimum additive quantity has to be determined. Furthermore, it must be excluded that this substance will have a negative influence on the remaining property spectrum of the solder mask system before the attitude regarding solder balls can finally be tested.

7. Influence of the photoimageable solder mask processing on solder balling

The processing of solder masks is prescribed by the ink manufacturer within more or less tight specifications with regard to the processing parameters. The general process flow is as follows:

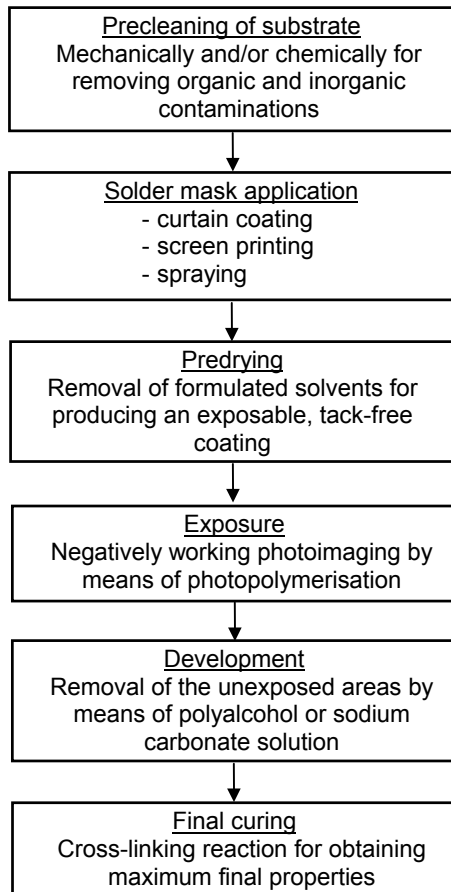


Fig. 12: Solder mask processing steps

With the variety of processing steps during the processing of photoimageable solder masks and the resulting multitude of processing parameters, it is likely that these parameters can have an impact on the performance of solder masks with regard to solderballing.

An example for this might be the case where two different pcb manufacturers were using the same solder mask and supplied an identical type of board to the same assembly. The results with regard to solder ball occurrence however differed largely. Besides using different equipment, but applying the same parameters for coating, exposure and developing, the difference in processing were the methods of predrying and final curing the boards. In case of the pcbs showing good results convection was used for both predrying and curing, whereas in case of the poor results IR was used for both processes. The processing step predrying can be excluded to a large

extent from influencing solderballing, because during this stage no chemical reaction of the solder mask takes place but only the solvents are removed to enable exposure.

A determination of the degree of cross-linking (determined by a solvent resistance test of the cured solder mask) showed that the IR-cured solder mask (6 min/180°C object holding time) showed a considerably lower solvent resistance than the convection-cured one (60 min/150 °C object holding time). This phenomenon shows that the degree of cross-linking/the way of final curing has obviously a big impact on the occurrence of solder balls, should be observed very carefully and that it is definitely worth conducting larger scale tests.

Other theories with regard to the influence of final cure state that the solder ball occurrence in the above mentioned cases might be related to differences in surface tension.

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