Vitronics Soltec

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Matt solderjoints after lead-free wave soldering

Introduction

Most joints soldered with lead-free solders get a less shiny appearance.
While tin-lead surfaces are smooth and bright, SAC joints look dull and rougher.
(SAC = tin-silver-copper solder alloy)

The reason for this can be of different origins. One of them is the fact that these lead-free alloys contain often three elements that can give three eutectics during solidification of the solder. These eutectics have each their own melting point and solidification behaviour.

After wave soldering, especially when using lead-free solders, joints on the same PCB may not have the same glossy appearance, although they are soldered under the same conditions.

Next, the reasons for these effects will be explained.

The reasons for solderjoints with matt appearance

1 Formation of different eutectic nuclei:

Solder consists of an alloy that is a mix of two or more metals. The melting and solidification behaviour will be very much depending on the formation of areas in the solder where finally different eutectics might solidify. This can be the case when solder contains elements like copper and silver. In that case copper-tin and silver-tin eutectic-parts or eutectic-traces can be formed, next to the tin-silver-copper eutectic, during the solidification of the solder in the joint.

The different eutectics that can be formed in SAC-alloys are Sn_5Cu_6 - 227°C, $SnAg_3$ - 221°C and $Sn+SnAg_3+Sn5Cu_6$ - 217°C. This is however only true if the total process contains only lead-free elements.
In case of a tin rich alloy also tin crystals can precipitate out from the alloy during cooling of the joint at 232°C.
If component leads are used with a tin-lead plating, also the lead dissolved from the plating can introduce eutectic traces.
This will lower the melting point for some parts of the solder in the joint to 183°C for SnPb eutectic, or even to 178°C for the SnPbAg eutectic.

2 Effect of soldercontraction during shrinkage of the solidifying solder:

As the solder solidifies it will shrink about 4%. Most of this volume reduction will be found on those areas where the solder solidifies last. These are commonly the areas where traces of the lowest melting eutectic solderparts are found. If these traces are at the joint surface area this mechanism can create a dull appearance.

The 4% volume reduction can often also be held responsible for the formation of so called microcracks in the solderjoint.
In case the solder fillet is moving during this process, e.g. due to pads that lift during soldering and move back during cooling, these microcracks can introduce even larger cracks due to the combination of volume reduction and movement.

These cracks will however normally only be found at the fillet surface of the solderjoints. The solder in-between the copperbarrel and the lead will in general make a sound connection that will give the joint its strength.

3 Moving soldered parts or solder when solder is in its pasty stage:

Another reason that might even create cracks in solderjoints, but for sure will give a matt appearance on the joint surface, is the movement of the soldered parts, or the solder at the surface during solidification of the solder.
This movement can be caused by the natural movement of the solderpad during the formation of a solderjoint.

Especially when more joints are closely spaced together, such as with a connector, this solderpad movement can be quit considerably. This even may give fillet tearing, pad lifting or fillet lifting.
The basics for this pad movement lies in the differences of thermal expansion between the copperbarrel that forms the plated through hole and the epoxy basis material that is situated in-between these joints. As a result of that, the solderpad will be lifted in a wedge shape from the edges of the copperbarrel, during contact with the solderwave and the filling of the joints with liquid solder.

As soon as the soldered joint has left the solderwave, the solder starts to solidify. During this process at first more heat is transferred inside the epoxy basis material until the solidification heat/energy is fully dissipated. After that the board cools also down, bringing the basis material back to its original dimensions.

As the basis material is coming back to its original dimensions, the wedge shape of the solderpad returns to a flat shape again. When this occurs the solder is often still not completely solidified and has a pasty behaviour. It is this movement that can disturb the joint surface during the solidification of the solderjoints and can create even cracks as a combination of shrink and fillet tearing. These cracks are commonly positioned parallel with the PCB surface. They can in some cases even form a complete crack circle.

Solderjoint appearance

During solidification the eutectic with the lowest melting point is often surrounded with already solidified parts from the eutectics with the higher melting points. This means that during the final solidification of the solderjoint a mix of already fixed solderparts and liquid solder is solidifying, where these fixed parts have another grain structure than the last solidifying alloy elements.
During this solidification process the solder volume will shrink by about 4%. The main part of this volume reduction and contraction will be found on those alloy parts in the joint that solidify last.

This mixture of parts in the solidifying solder at different stages during the cooling to solid solder, combined with the volume reduction, finally gives the joint a dull appearance; since these different eutectic pieces will each have their own surface structure.

Often the combination of all three described mechanisms will act at the same time, but not on every group of joints at the same rate. This explains the differences in surface appearance after soldering.

Since the source of the dull solderjoint appearance lies in the combination of the process and the alloy that is used, the outcome should be judged as normal. That is why the dull or matt appearance of such solderjoints should be judged as an effect and not as a defect.

The effect of forced cooling

Forced cooling will help to reduce the temperature of the PCB at a somewhat faster rate, but has no real effect on one of these mechanisms. It can however prevent further heat build-up in components, from the dissipated solidification heat coming from the solderjoint directly after soldering, if cooling takes place at the component side during this stage.

Temperature measurements on the solidification behaviour on soldered joints have taught us that the solder solidification is for most joints completed within 3 seconds after wave departure time. Any cooling that is positioned after this has no major effect on the already solidified joint. Forced air cooling within this 3 seconds area will also cool the solderwave, which is an undesired effect and is therefore not recommended.

Typical values for reaching the solidification temperature using SAC-alloys are 1.4 seconds, while the joint is completely solidified in 3.2 seconds after wave exit.

Conclusion

In lead-free soldering matt or dull joints are normal and should be judged as an effect and not as a defect.
Differences in dullness or gloss on soldered joints are caused by differences in cooling behaviour. This again is due to differences in the thermal layout of the individual solderjoints. In a process equal joints will normally behave equal and will therefore have the same appearance after soldering.

However joints with another layout, such as larger or smaller holes, different padsizes, other component leads or components, might give another cooling behaviour, resulting in another joint appearance.
Finally also the soldercomposition plays a major part in this respect.
Forced cooling after soldering is not a solution for avoiding dull joints.

Appendix

Subject: Explanation of shrink structure formation

If the solder alloy contains elements that can form more than one eutectic alloy, different shrink patterns can be formed that finally give the solderjoints a rough appearance. Since the cooling of a soldered joint after leaving the solderwave is affected by many factors, such as solder volume in the joint, heatsink effect of the parts involved, alloy composition, lead plating etc., the solder solidification will not be the same for all joints. This means that joints can have a different appearance at the end of the soldering process.

Basically the reasons for that can be elucidated as follows:

Assume that a given SAC solder volume does exactly has the ternary eutectic composition Sn3.5Ag0.9Cu. This alloy will have a melting point of 217°C. In fact under ideal conditions it has only that melting point and no other melting points from the binary eutectics that also could be present in this solder volume.
So this melt will during cooling solidify as one homogeneous alloy that is in full equilibrium due to its exact ternary eutectic composition and equal temperature. Normally such an alloy will solidify with a smooth surface under these conditions, since the solder shrinkage will be equally divided over this solder volume.

Next assume that extra tin is deliberately added to this perfect ternary solder mixture. The extra tin that is added can not be part of the ternary eutectic, because the alloy now contains too much tin. This 'excess' tin having a melting point of 232°C will during cooling of the liquid solder first precipitate as solidified crystals (dendrites), until the remaining liquid mix has its perfect ternary eutectic composition.
As this remaining liquid mix, after the precipitation of the tin dendrites, solidifies at 217°C, the solder shrinks by about 4%. This shrink comes fully from the remaining liquid and not from the already solidified tin dendrites. The final shrink will take place at the point where the joint will at last get a temperature below 217°C. In most cases this will be the part that was in contact with the solderwave for the longest time, which is commonly the joint fillet at the solderside. As a result the tin dendrite profile is prominent present at the surface of the solidified solder.

In the real solderjoints the ideal ternary mix, assuming one starts with such an alloy, will be mixed with metallic parts from the PCB and lead metallisation. Parts of these elements will be dissolved in the limited amount of solder that forms the joint. These extra elements will now disturb the ideal ternary eutectic. This means that the solidification of that solder mix will not be at one temperature of 217°C, but that parts of this mix may already solidify at 232°C, or at 227°C or at 221°C. In case the component leads are tin-lead plated, also tin-lead eutectic traces or tin-lead-silver eutectic traces can possibly be found in the joint, having melting points of 183°C and 178°C respectively.
In most cases SAC-alloys are used with a composition that deviates from the ideal eutectic composition. This might create the different eutectics that give a rough joint surface.