Mechanical Reliability – A New Method to Forecast Drop Shock Performance

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Abstract
In light of the recent technological trends within PCB manufacturing industry, there is an increasing degree of interest in understanding the influence factors of mechanical stress on the durability of mobile devices.
In the past, many papers focused on PCB reliability and the influence factors during drop shock test. In most cases, the potential influence factors in regards to underfill have not been fully investigated. Additionally, there is no clear direction on the influence of the interaction between solder mask inks and underfill systems.
The intent of this paper is to identify an accurate method to predict drop test behavior by understanding the surface tension of both, the solder mask ink and the underfill material. This could become a significant advantage for improving the reliability of the entire electronic construct. In this paper a method has been examined that can be used to subsequently analyze the reliability of the latest mobile device related materials and design.
The prescribed test has been constructed using a cross comparison of pad design, surface finish, solder mask and underfill, measured by drop testing. Based on the resulting data, a method was evaluated to predict and optimize drop test reliability by understanding the surface tension of solder mask and underfill (adhesion).
We are now able to identify specific advantages and limitations for different material combinations, without the need of expensive and time intensive drop tests.
In an effort to achieve a broader understanding of the entire process and product scope, the participants in these trials were an HDI PCB manufacturer (AT&S) and it´s material suppliers.

Introduction
Continual miniaturization and RoHS (Restriction of Hazardous Substances) requirements have significantly aggravated the endeavor to achieve customer expectations in terms of reliable electronic devices. Drop-shock performance has especially become an important factor in the past several years, due to the increasing number of portable electronics, such as mobile devices, MP3 players and tablet computers.

Many investigations have shown that the interaction of solder paste and surface finish, material selection and the rigidity of the whole electronic construct all have an impact on the final drop shock performance. Even an optimum combination of the before mentioned factors might not be enough to ensure a satisfying quality of drop shock resistance, without factoring in critical design features and component selection. It is common to lower such risks with an under filling step between surface mount components and the printed circuit board. The efficiency of such an additional step strongly depends on the adhesion between solder mask and underfill material.

The investigations for this paper includes a full factorial drop test DOE (design of experiments) and a new method to predict drop shock performance based on the knowledge of the surface energy of solder mask and underfill material.

Test equipment & method
The drop test was performed based on an AT&S internal standard (mobile devices), which was evaluated and developed in conjunction with mobile device customers to meet their specific requirements. A correlation between JEDEC JESD22-B111[i] and our mobile device standard might be difficult in terms of absolute number of drops, but it can be compared to determine basic trends, (failure mode and time to failure results are similar). For the intent of this paper the material was the major focus, not the overall design.

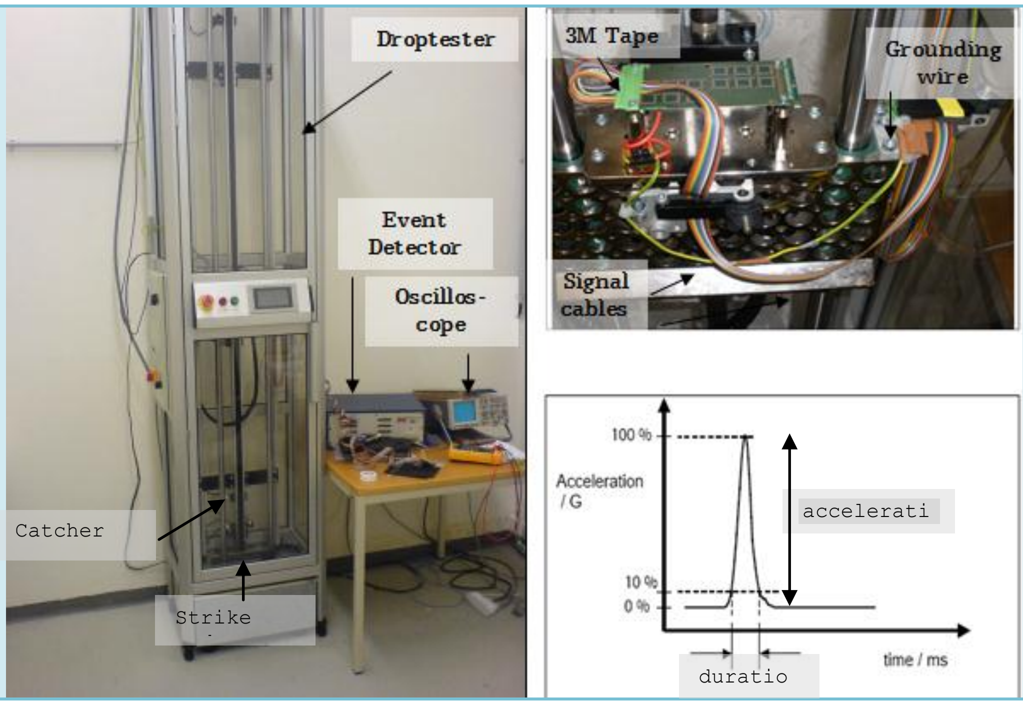
The PWB Level Drop Tester was calibrated daily before starting any actual DOE measurements. **Error! Reference source not found.**The test vehicles were assembled with 12 dummy components and flat ribbon cables[1] soldered to the PTH terminals. To minimize the risk of solder joint failure of the signal cables during drop shock stress, the joints have been additionally fixed with a common available 3M tape. Furthermore the cables were fixed to the test equipment in such a way that the stress during test was reduced to a minimum (

Table 1).

[1] Signal cables for event detection

Table 1: Basic test setting of mobile devices standard & JEDEC JESD22-B111

Parameter	Mobile Devices	JEDEC JESD22-B111
Peak acceleration[2]	1500g ±10%, Cpk≥1.3	1500g ±30%, Cpk≥1.3
Pulse duration[3]	1.0ms ±10%, Cpk≥1.3	0.5ms ±30%, Cpk≥1.3
Pulse shape[4]	Half-sine wave form	Half-sine wave form
Catcher[5]	off	on
Strike Pad[6]	5-6mm	2-3mm
Current	1.1mA	1.0mA
Voltage	1.65V	1.0V
Resistance	1.5 kΩ	1.0 kΩ



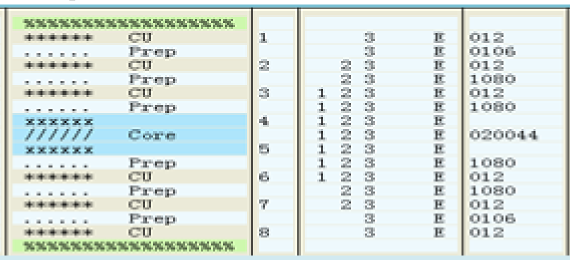
Test vehicles

The PCB build up for the 30.7mil thick DOE samples was an 8 layer multi-layer with a common available halogen-free 150TG FR4 material. The soldering was performed with a 4mil thick electro-polished stainless steel stencil, glued into polyester mesh and tensioned in an aluminum frame. The outer stencil dimensions were 736 x 736 x 40mm. A commonly available SAC type 3 solder was used for assembly. The under-filling material was based on a single-component epoxy system with fast curing, low CTE and Pb-free compatible behavior. In the table below, the three steps of sample production (multi-layer, assembled multilayer & assembled multilayer after underfilling) is shown.

[2] Maximum de-acceleration
[3] Peak at 10% of maximum acceleration
[4] Shape of acceleration curve
[5] Mechanical part which caches sledge to prevent double bounces
[6] Surface on which the sledge drops

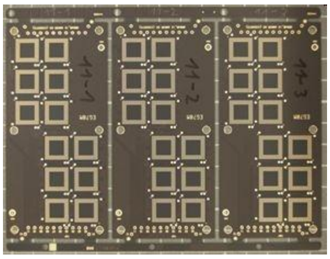
Table 2: Test vehicle build-up

Basic Design	
Structure	1-1-1-2-1-1-1
Nominal board thickness	30.7mil +/-3mil
Cu thickness	1/3 oz
Glass fibers	1080 & 106
Dielectrical material	FR4, halogen free 150TG
Glass Transition Temperature (Tg)	150°C
Surface finish	ENIG (Ni – 3µm & Au – 0,05µm)
Pad size	Ø 20mil (via in pad)
Solder paste	SAC type 3
Flux system	low sputter application
Reflow profile	lead free
max. reflow temperature	247°C +/- 1°C

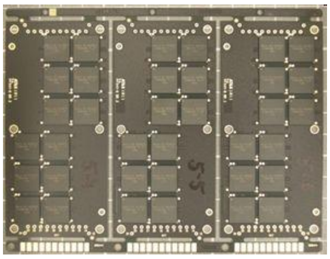


%%%%%%%%%%%%%%%%%%							
******	CU	1			3	E	012
......	Prep				3	E	0106
******	CU	2		2	3	E	012
......	Prep			2	3	E	1080
******	CU	3	1	2	3	E	012
......	Prep		1	2	3	E	1080
xxxxxx		4	1	2	3	E	
//////	Core		1	2	3	E	020044
xxxxxx		5	1	2	3	E	
......	Prep		1	2	3	E	1080
******	CU	6	1	2	3	E	012
......	Prep			2	3	E	1080
******	CU	7		2	3	E	012
......	Prep				3	E	0106
******	CU	8			3	E	012
%%%%%%%%%%%%%%%%%%							

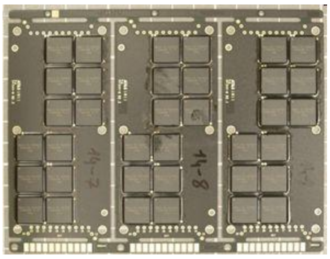
(from left to right: schematic build-up, layer number, lamination process number)



Bare board



Assembled board



Assembled board with underfill

The DOE layout was full factorial with four factors, each with two sub groups (see Table 3). Besides the main focus on solder mask type and underfill, the influence of pad design and surface finish (phosphorus content of nickel phosphorous layer: MP = 6-9wt% P; HP = 9-12wt% P) was observed. For each DOE group nine cards were dropped and the response was statistically analyzed by Weibull method. The failure mode was optically determined by cross sectioning and optical microscopy.

Table 3: Full factorial drop test DOE

Design	Surface Finish	Pad Design	Solder Mask	Underfill	No. of cards
01	ENIG - MP	SM defined	Type A	without	9
02	ENIG - MP	SM defined	Type A	with	9
03	ENIG - MP	SM defined	Type B	without	9
04	ENIG - MP	SM defined	Type B	with	9
05	ENIG - MP	Cu defined	Type A	without	9
06	ENIG - MP	Cu defined	Type A	with	9
07	ENIG - MP	Cu defined	Type B	without	9
08	ENIG - MP	Cu defined	Type B	with	9
09	ENIG - HP	SM defined	Type A	without	9
10	ENIG - HP	SM defined	Type A	with	9
11	ENIG - HP	SM defined	Type B	without	9
12	ENIG - HP	SM defined	Type B	with	9
13	ENIG - HP	Cu defined	Type A	without	9
14	ENIG - HP	Cu defined	Type A	with	9
15	ENIG - HP	Cu defined	Type B	without	9
16	ENIG - HP	Cu defined	Type B	with	9

The drop events were continually monitored (online) until an event detector recorded electrical failures of any of the four middle components or until 5000 drops were exceeded. The four middle components were chosen because electrical defects happen first at the center positions of the board due to the highest tension/compression in this area (see Figure 1 & Figure 2).

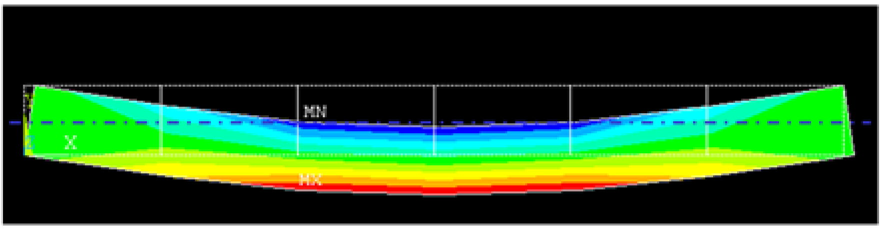


Figure 1: red = area of tension; green = strain less area; blue = area of compression;

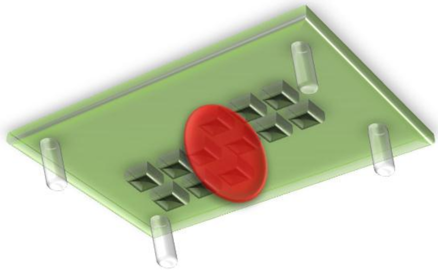


Figure 2: schematically view of drop test boards - the four critical components are marked in red.

Test results

The influence of drop shock performance caused by the phosphorus content in the nickel layer was in both cases, with and without underfill, slightly better for HP in compare to MP samples. But as it can be seen in the interval chart of Figure 3, the statistical significance was not convincing. Summarized can be concluded that HP-ENIG surfaces have at least no negative impact to the drop shock resistance.

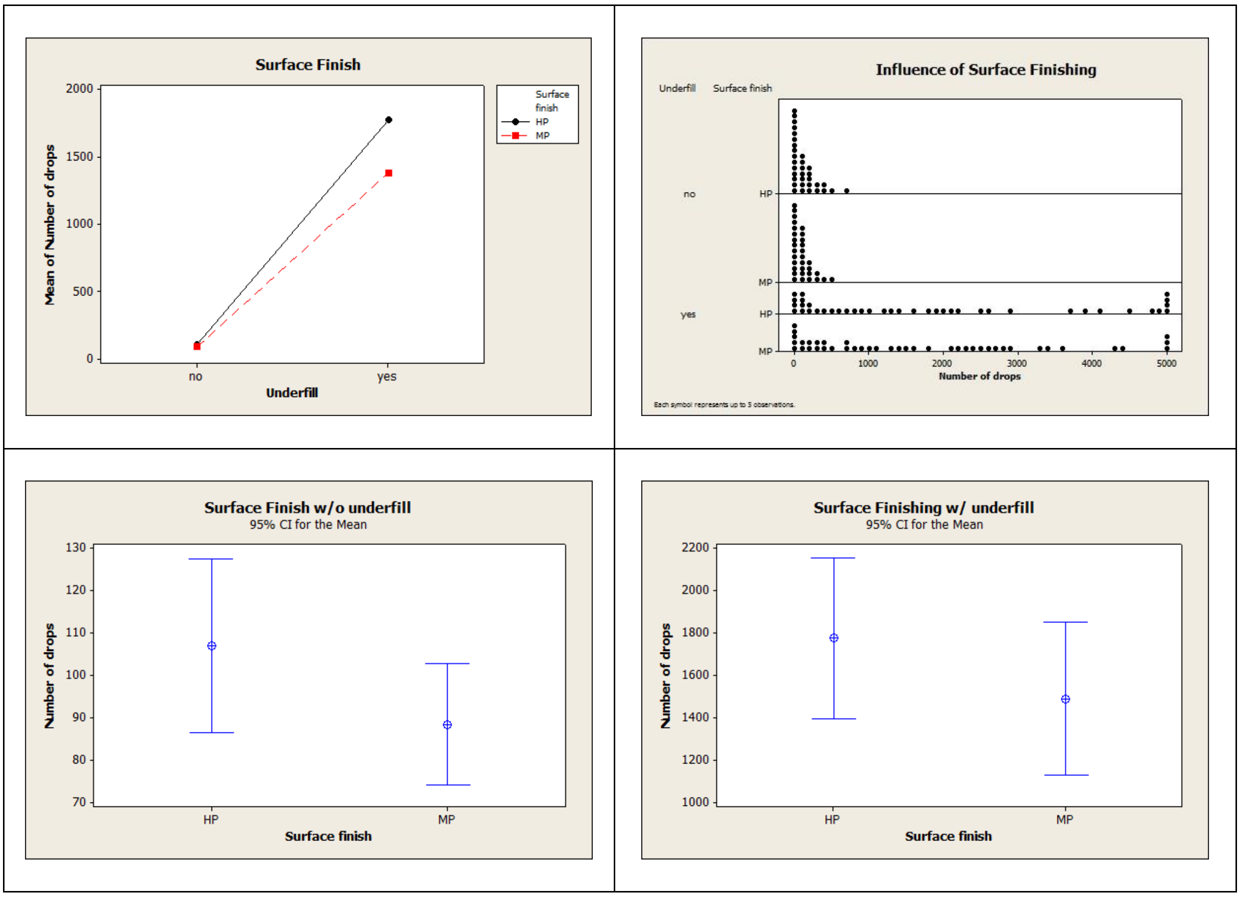


Figure 3: DOE output for ENIG surface finish (high phosphorous (9% - 12%) vs middle phosphorous 6% - 9%)

Well known from previous studies is the positive effect of Cu defined (CuD) pads in comparison to Solder Mask defined (SMD) pads. Due the fact that the influence of solder mask / underfill interaction surpasses the influence of the pad design (see Figure 5), the difference between CuD and SMD pads is statistically not so obvious in the case of underfill, but is the major impact for samples w/o underfill (Figure 4).

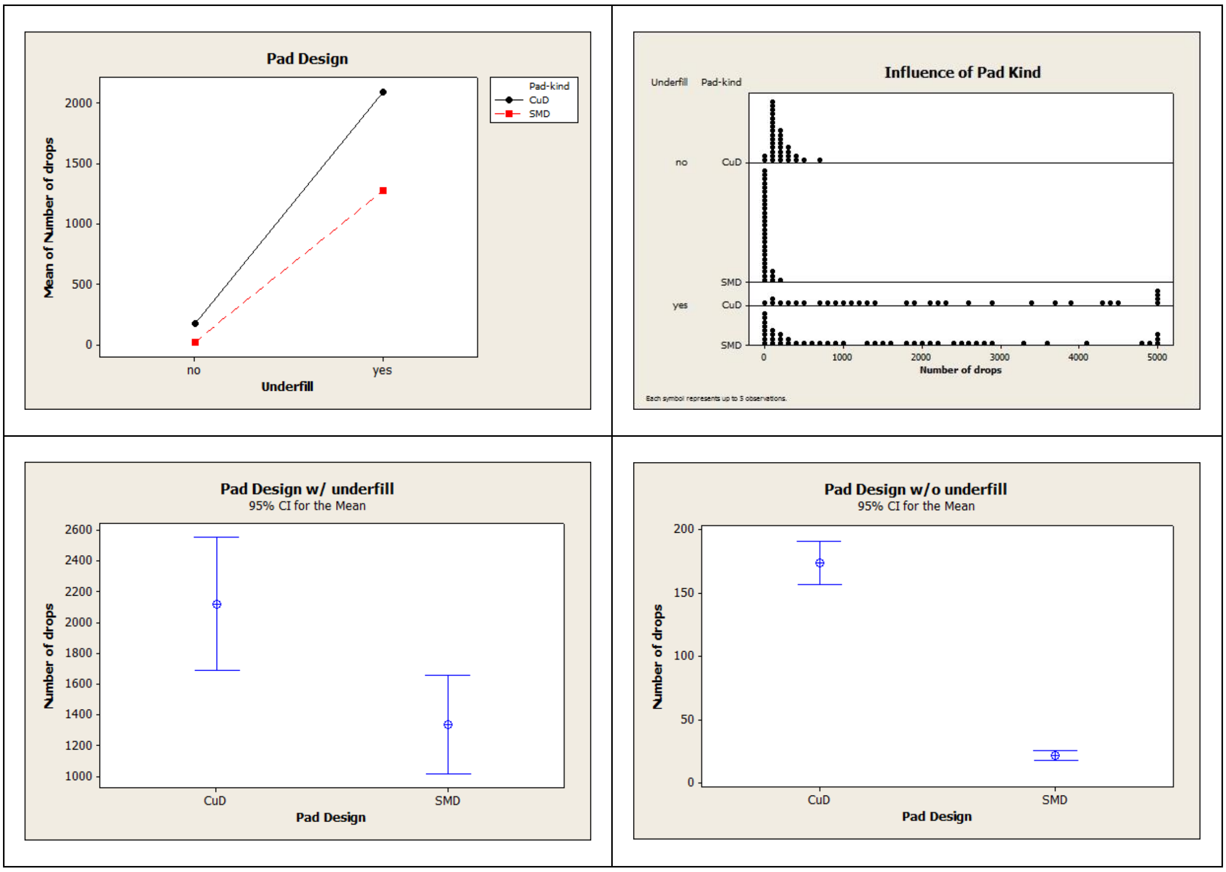


Figure 4: DOE output for copper defined (CuD) and solder mask defined (SMD) pads.

As mentioned above, the major impact for this DOE was the use of underfill and the interaction with solder mask. Two types of solder mask inks have been compared - both are commonly available and released for mass production. As it can be seen in Figure 5, the difference between the inks for samples without underfill is negligible. However, in drop testing performed on underfilled parts, there was a notable difference in the drop test results between the solder mask inks.

Considering that the performance of solder mask type A & B without underfill was similar, we concluded that the interaction of underfill and solder mask is the main impact to the overall drop performance.

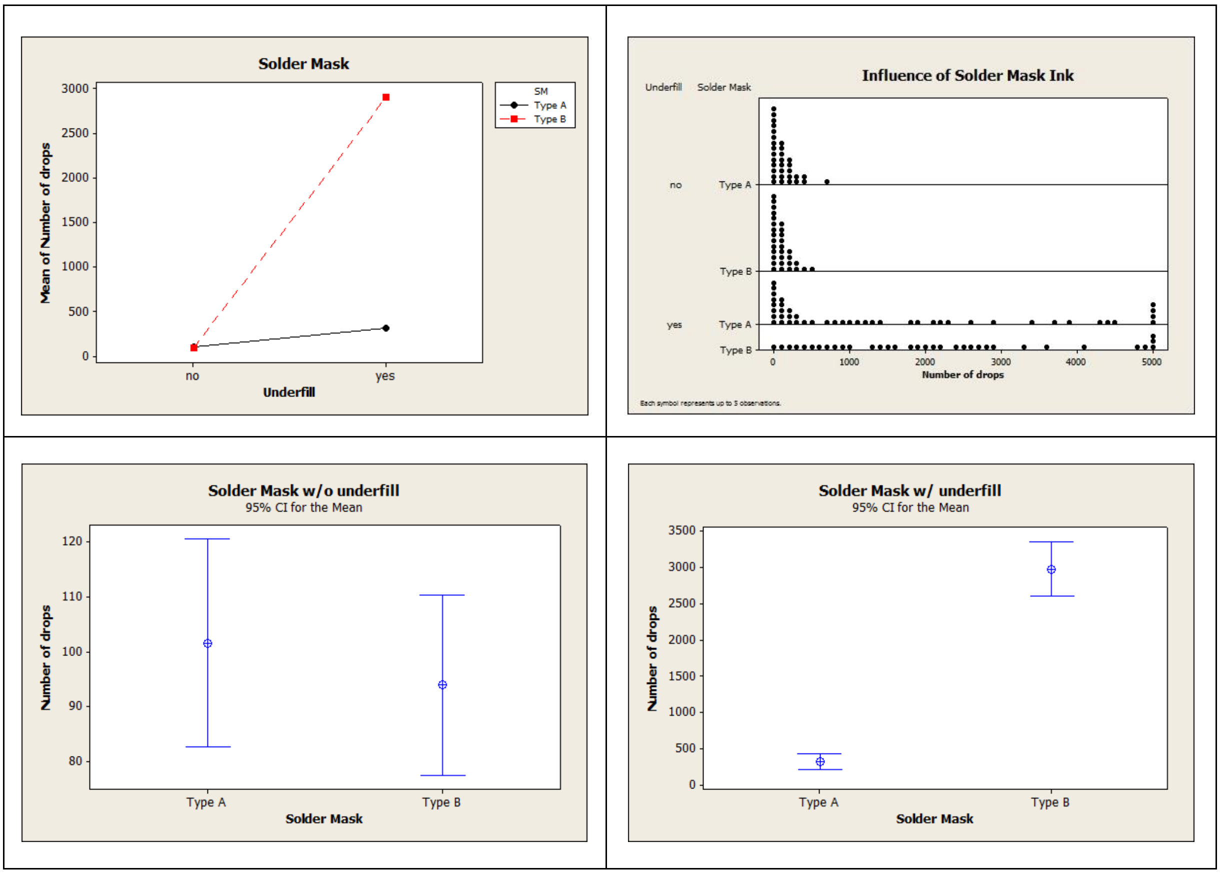


Figure 5: DOE output for solder mask type A & B.

As it was shown in the analysis above, the main influence factor for this DOE was the underfill (w/ or w/o), which caused performance changes up to 100 times. Surprising was the prevalent failure mode which was independent of underfill, solder mask or surface finish. Differences in the pad design seemed to create the only impact, resulting in either “solder crack close to PCB” in the case of solder mask defined pads, or “via / prepreg crack” in the case of copper defined pads (see Figure 6).

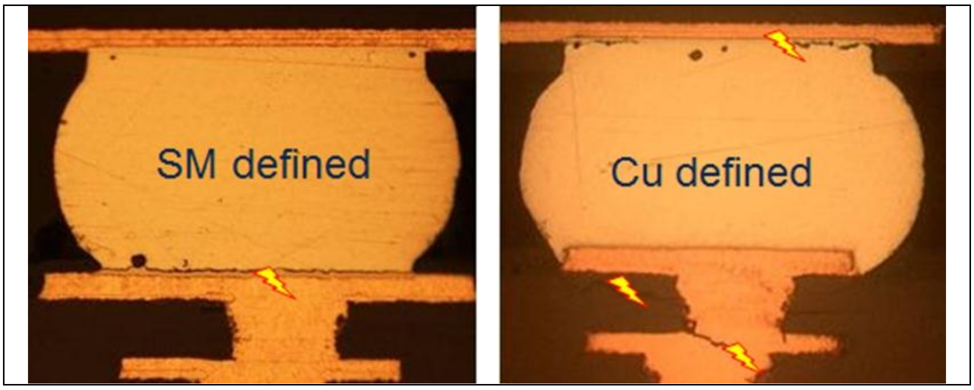


Figure 6: Drop test failure mode

The different DOE parameters have been compared by two-parameter weibull analysis. For below comparison of the different DOE factors, an improvement factor was calculated by using the same slope parameter (β) for all Weibull curves (see Table 4). It should be mentioned that due to the complexity of the interaction of all parameters, these test results are only valid for this specific DOE, but the order of magnitude of the impact of the given parameter should allow for reasonable estimates to be made.

Table 4: Impact of DOE factors

DOE factor	Factor (based on weibull analysis)
Underfill (w/ vs. w/o)	106
Solder Mask (type B vs. type A, both w/ underfill)	14
Pad Design (CuD vs. SMD)	7
Surface Finish (HP vs. MP)	1,5

Summarized can be said that the interactions of solder mask and underfill, or their adhesion properties, have a major impact to the final drop-shock reliability performance.

Contact Angle, Surface Energy & Adhesion

A common method to predict the interaction between two materials are contact angle measurements which enable the determination of surface energy. Knowing the surface energy of two materials allows the calculation of WoA (Work of Adhesion) and IFT (InterFacial Tension), which are indicators for adhesion quality. It has to be mentioned that both, WoA as well as IFT, are important indicators for strong and lasting adhesion. In simplified terms, WoA represents the initial adhesion strength while IFT represents the force which works against it (long term). Therefore, the higher the work-of-adhesion and the lower the interfacial-tension, the better the adhesion. Depending on the application, it has to be decided which of both behaviors have to be rated higher.

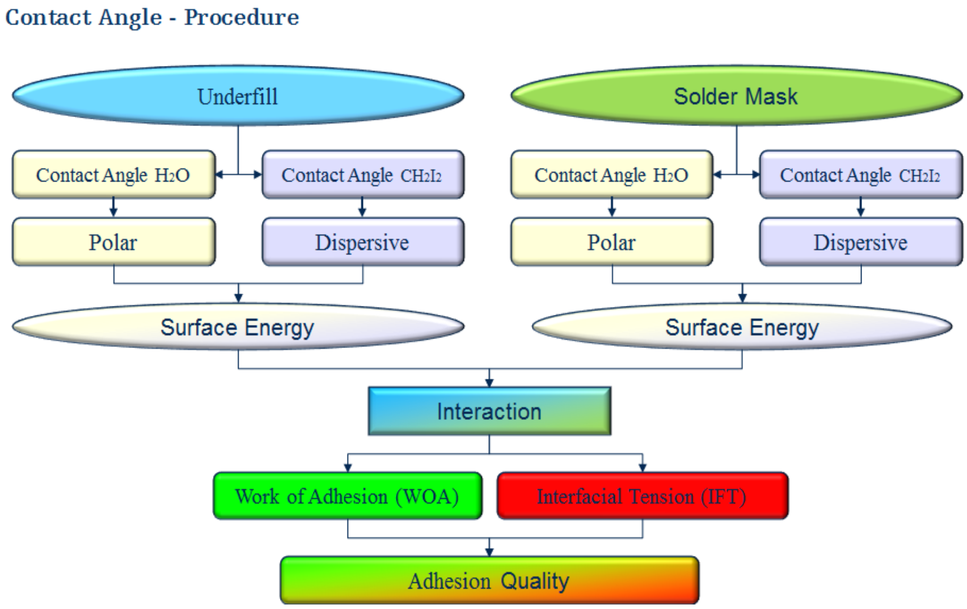


Figure 7: schematic overview of adhesion determination

The measurements were carried out with a fully automatic Kruess DSA100 drop shape measurement analysis system following ASTM D7334[ii] and ASTM D7490[iii] (

Table 5). The calculation of surface energy followed Fowkes Theory[iv] (see Figure 8).

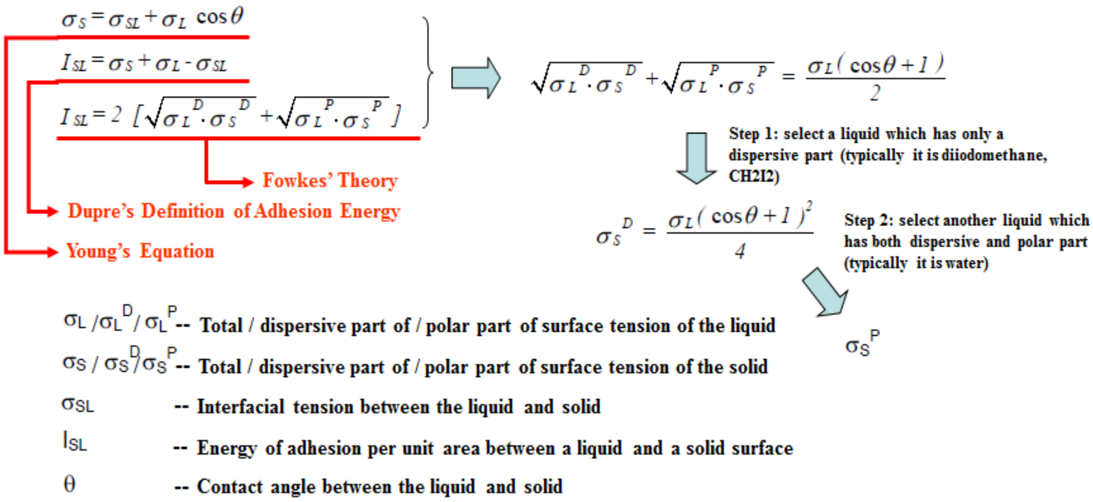


Figure 8: Fowkes Theory

Table 5: Parameter setting

Contact Angle Parameter	
Standard	ASTM D7334 & ASTM 7490
Equipment Type	Kruess, DSA100
Droplet Volume	1,5µl +/- 0,1µl
Measurement Time	< 5sec after drop applying
Liquids	Water & Diiodmethane
Sample Condition	1 x lead free reflow
Solder Mask	11 solder mask types 2 types of underfill

Several types of solder mask (A - K) and two types of underfill systems (UF A & UF B) have been compared (see Figure 9). The solder mask types are commonly available and there was no special focus on color, supplier or process. Solder Mask A and B, as well as Underfill B, are the same like in the drop test DOE, all other solder mask inks have not been cross compared by drop shock test.

The chart below shows that the total surface energy (= sum of polar (blue) and dispersive part (red)), has notable differences between the solder mask inks, and likewise for the underfill. It can be assumed that two materials with similar polarity will also have lower interfacial-tension. The reverse should be true for the total surface energy – the higher, the higher the work of adhesion.

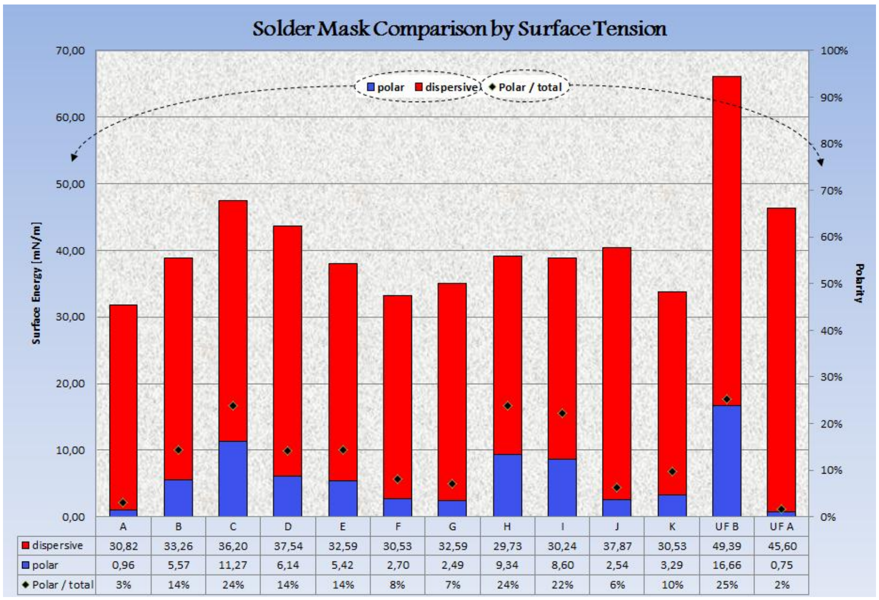


Figure 9: Surface energy comparison of different solder mask and underfill inks.

Figure 10 was created using the Kruess adhesion tool, which enables the calculation of WoA as well as IFT based on the knowledge of the polar and dispersive part of two materials. The interaction between underfill A and the different types of solder mask inks is shown in blue, likewise the interaction of underfill B in red. The bar reflects WoA (left axis) and the point the interfacial tension (right axis).

Comparing the interaction of solder mask A & B with underfill B (red) it can be assumed that the adhesion of solder mask B will be significant better due to higher WoA and lower IFT – which coincides with drop test results. Comparing the same solder mask inks and their interaction with underfill A (blue), a clear statement of a preferable solder mask would get difficult due to reverse behavior of WoA and IFT. Furthermore can be assumed that solder mask C and the interaction with underfill B causes remarkable adhesion, supported by excellent drop shock reliability.

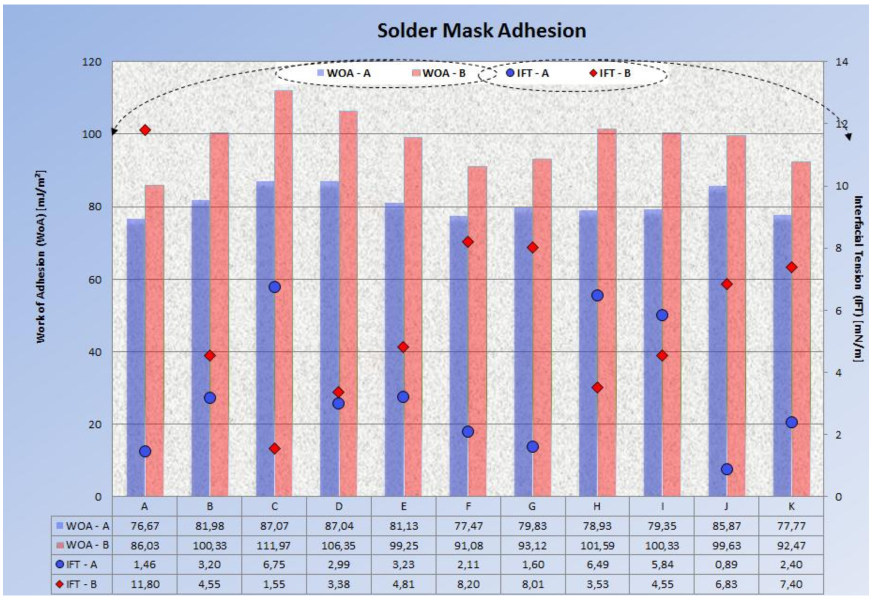


Figure 10: Work-of-adhesion & Interfacial Tension of solder mask and underfill

Conclusion/ Summary

The first part of this paper was a drop test DOE focusing on four factors and their influence to the drop shock reliability of assembled PCBs. The second part has focused on the main influence factor, the interaction between solder mask and underfilling system, including a method to predict the efficiency of such additional production step without the need of time & cost intensive drop tests.

It was proven that the drop shock performance of two different solder mask inks without an underfilling step are quite comparable, independent of pad type or surface finishing. The use of underfill provided a reliability improvement for both solder mask types, but the efficiency strongly depended on the specific solder mask. Consequently, underfill / solder mask interaction (adhesion) has a major impact to the final drop shock reliability.

The different ink and underfill types were measured by contact angle. Based on these results, surface energy, work of adhesion and the interfacial tension of each sample was calculated. The calculated adhesion fits quite well with the drop test results - the better the adhesion, the better the shock resistance.

Finally, it should be mentioned that contact angle measurements strongly depend on factors like contamination, pre-treatment or environment, therefore, comparison tests should only be carried out by knowing exact experimental setup.

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[i] Board Level Drop Test Method of Components for Handheld Electronic Products, Jedec Standard 2003
[ii] Standard Practice for Surface Wettability of Coatings, Substrates and Pigments by Advancing Contact Angle Measurements
[iii] Standard Test Method for Measurement of the Surface Tension of Solid Coatings, Substrates and Pigments using Contact Angle Measurements
[iv] http://www.kruss.de/en/theory/measurements/contact-angle/models/fowkes.html

Mechanical Reliability

A New Method to Forecast Drop Shock Performance

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Agenda

- Background
- Drop Test DOE
- Contact Angle, Surface Energy & Adhesion
- Summary / Conclusion

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Background

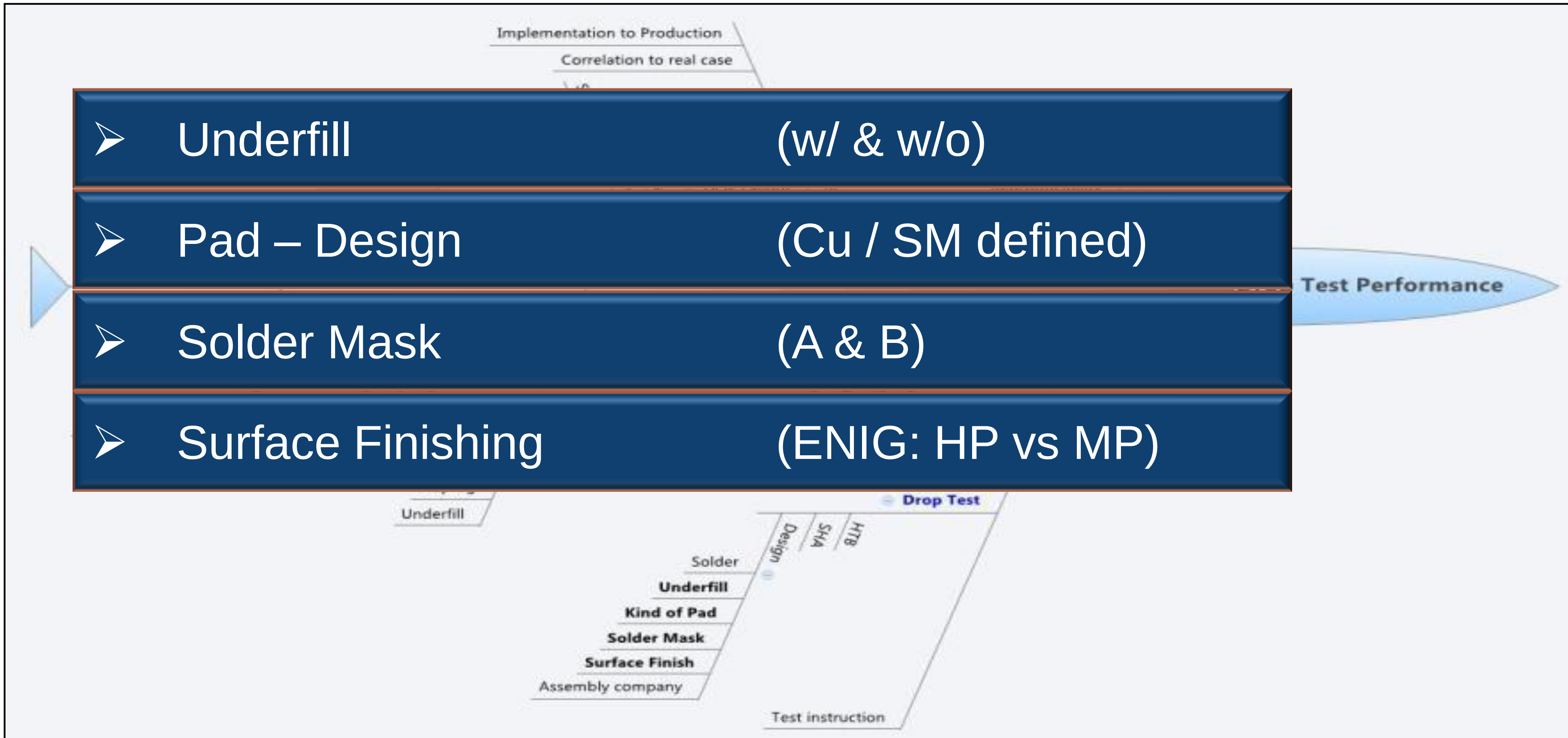
Project Consideration

Business Case:
Miniaturization and lead free soldering requirements aggravate the endeavor to fulfill customer expectations in terms of high end quality. Especially for portable electronic the importance of drop shock reliability for printed circuit boards has increased in the last years.

Target of investigations:
The purpose of these investigations was to determine main influence factors to drop shock performance as well as to prove a method capable to predict the effects of different PCB material combinations without time & cost expensive drop test.

Background

Fishbone



The shock reliability of PCB´s is influenced by many factors, many of them well known. These investigations focused on the influence of underfill, pad design, solder mask and surface finishing.

Background

Contribution

Supplier → Input → Process → Output → Customer

Supplier

- PE/CAM
- Imaging
- Engineering
- Customer Quality
- Laboratory
- External Support
  - Assembly
  - Underfill
  - University
  - Equipment companies

Input

- Samples
  - Design
  - Production
- Know How
  - Underfill
  - Methods
  - Risks
- Measurements
  - Drop Test
  - Surface T.
  - Lap Shear
  - Ball Shear

Process

Information
⇩
Measurements
⇩
Analysis
⇩
Implementation
⇩
Standardization

Output

- Drop Test
  - Influences
  - DOE
- Surface Finishing
  - Influences
  - Method implementation
  - DOE
- Solder Mask
  - UF interaction
  - Method implementation
  - DOE

Customer

- All AT&S customer
- Internal
  - Quality
  - Production

Agenda

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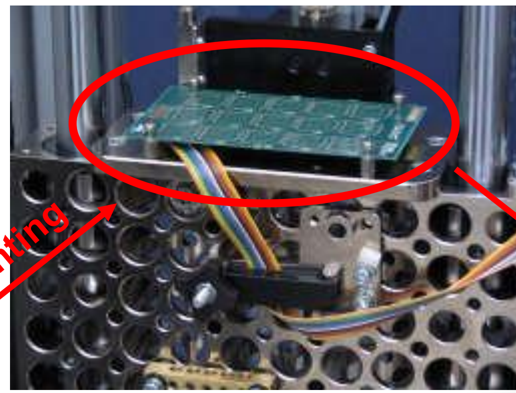
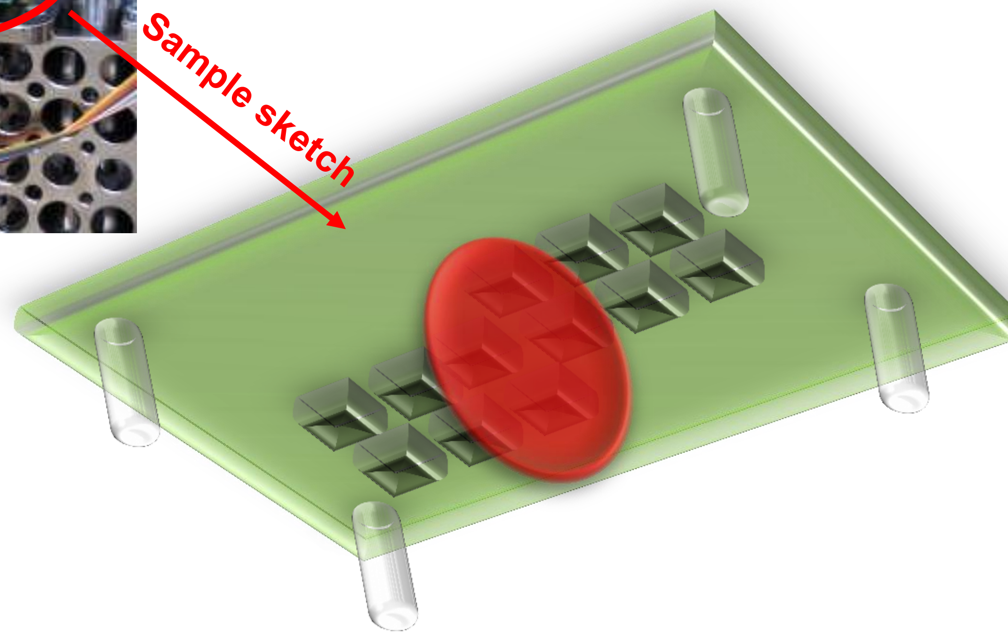
Drop Test

Procedure

Drop Tester

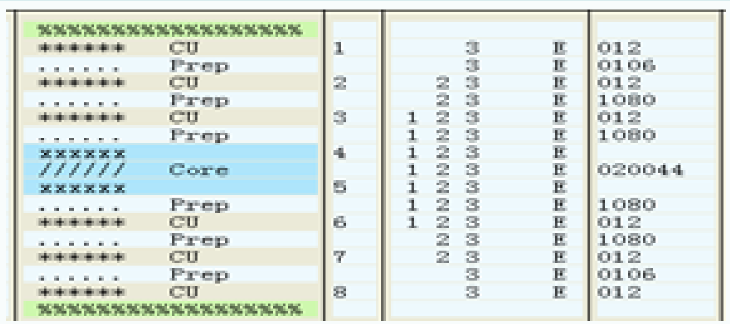




The drop tests were performed until the middle 4 components lost electrical contact (max. 5000 drops). Online resistance measurements by event detector ensured accurate data collection.

Drop Test

Basic Design	
Structure	1-1-1-2-1-1-1
Nominal board thickness	0,78mm +/-0,08mm
Cu thickness	12µm
Glass fibers	1080 & 106
Dielectrical	FR4, halogen free
Glass Transition Temperature (Tg)	150° C
Surface finish	ENIG (Ni – 3µm & Au – 0,05µm)
Pad size	Ø500µm (via in pad)
Solder paste	SAC type 3
Flux system	low sputter application
Reflow profile	lead free
Reflow max. temperature	247° C +/- 1° C

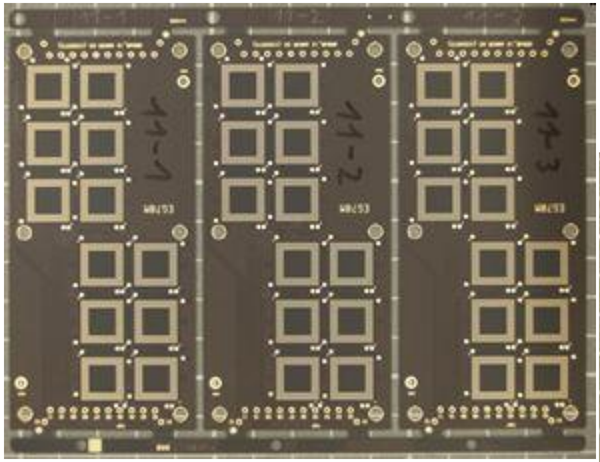


Basic design for drop test DOE.

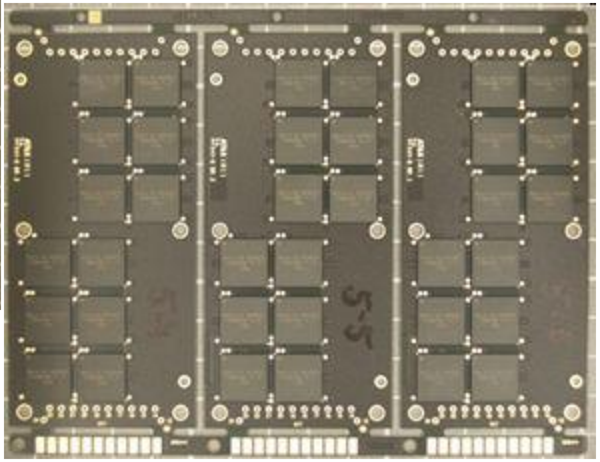
Drop Test

Samples

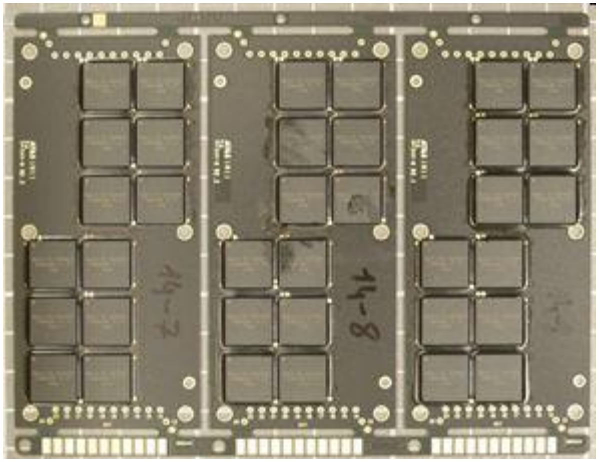
After production



After assembly



After underfilling



Drop Test

DOE Lay-out

Design	Surface Finish	Pad Design	Solder Mask	Underfill	No. of cards
01	ENIG - MP	SM defined	Type A	without	9
02				with	9
03			Type B	without	9
04				with	9
05		Cu defined	Type A	without	9
06				with	9
07			Type B	without	9
08				with	9
09	ENIG - HP	SM defined	Type A	without	9
10				with	9
11			Type B	without	9
12				with	9
13		Cu defined	Type A	without	9
14				with	9
15			Type B	without	9
16				with	9

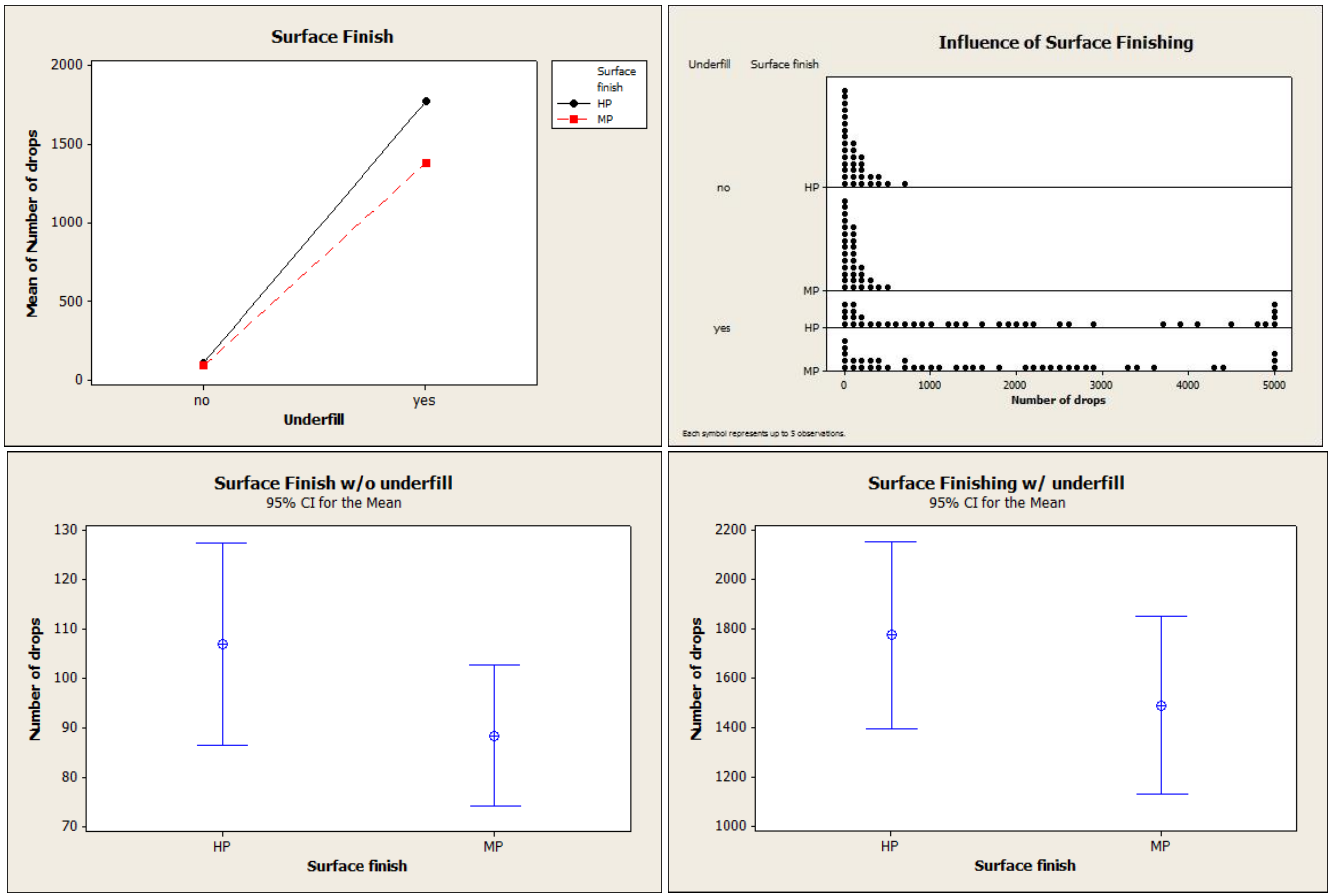
Drop Test

Surface Finishing

- ENIG-HP = high Phosphorus = 9 – 12 wt% P-content
- ENIG-MP = mid. Phosphorus = 6 – 9 wt% P-content

Drop Test

Surface Finishing

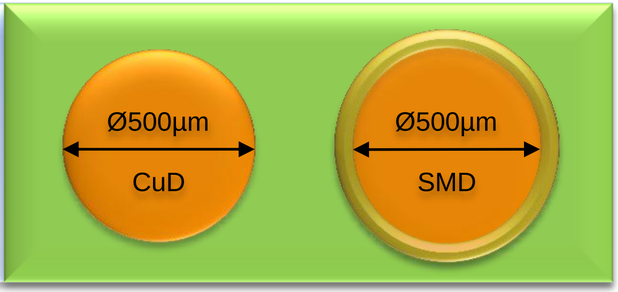


The average number of drops seems slightly higher in the case of HP samples, but the statistical deviation is not significant. Therefore both surface finishes can be assumed as equivalent.

Drop Test

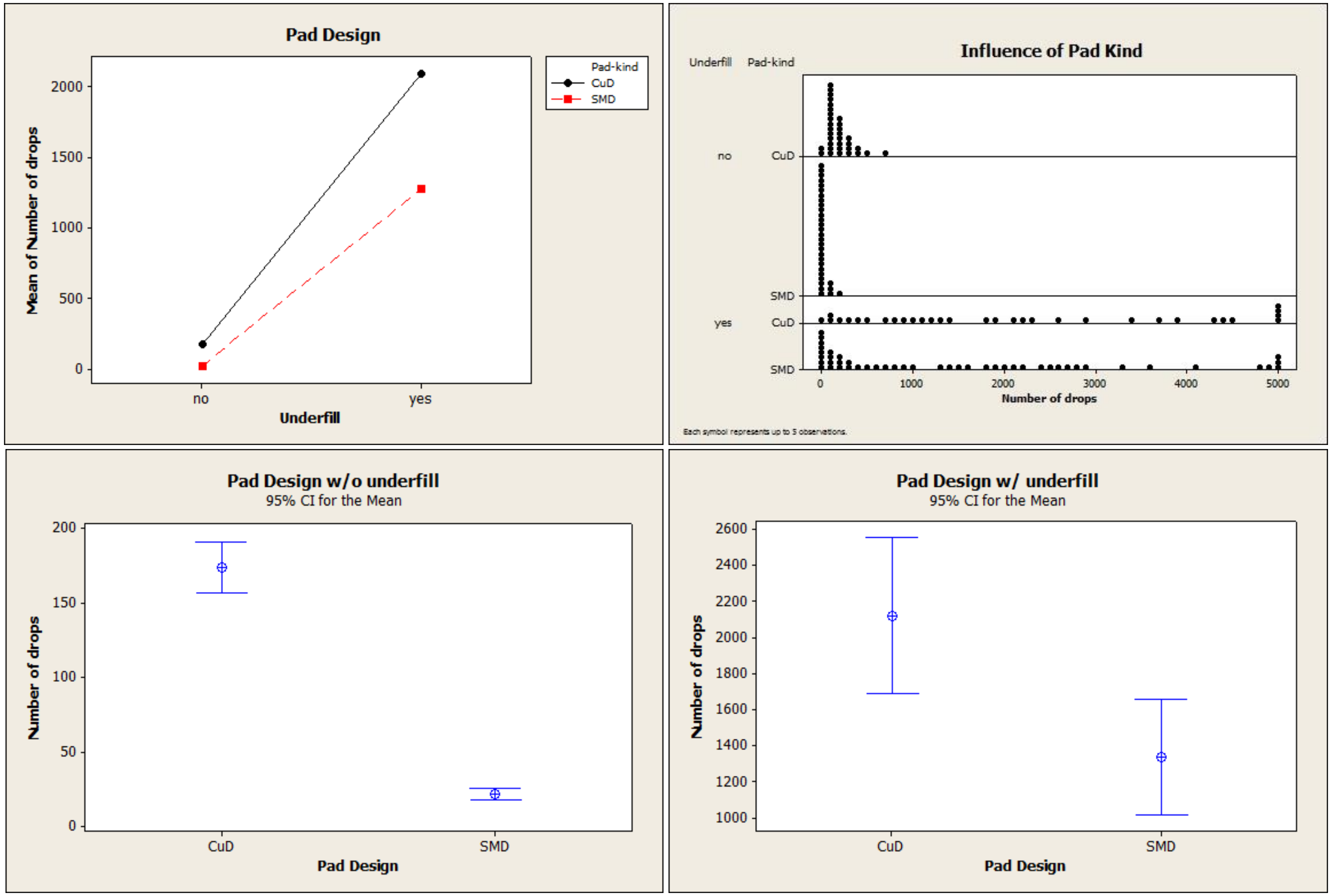
Pad Design

- CuD = Copper defined
- SMD = Solder Mask defined



Drop Test

Pad Design



The main impact in this DOE for samples w/o underfill was the pad design. CuD pads performed clearly better than SMD pads due to additional stress at the boarder of solder mask and solder joint.

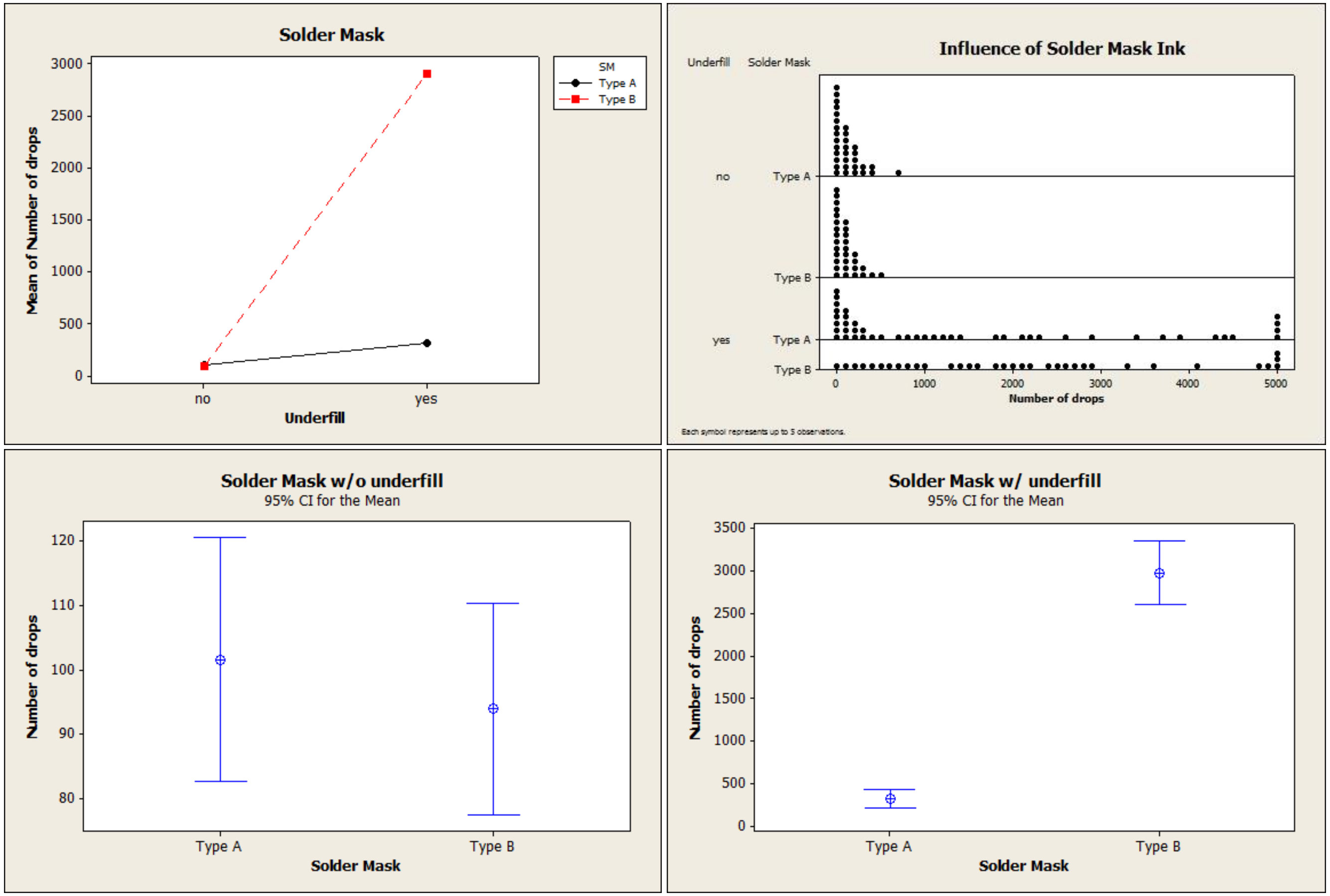
Drop Test

Solder Mask

- Solder Mask Type A – curtain coating ink (high content of additives)
- Solder Mask Type B – screen printing ink (low content of additives)

Drop Test

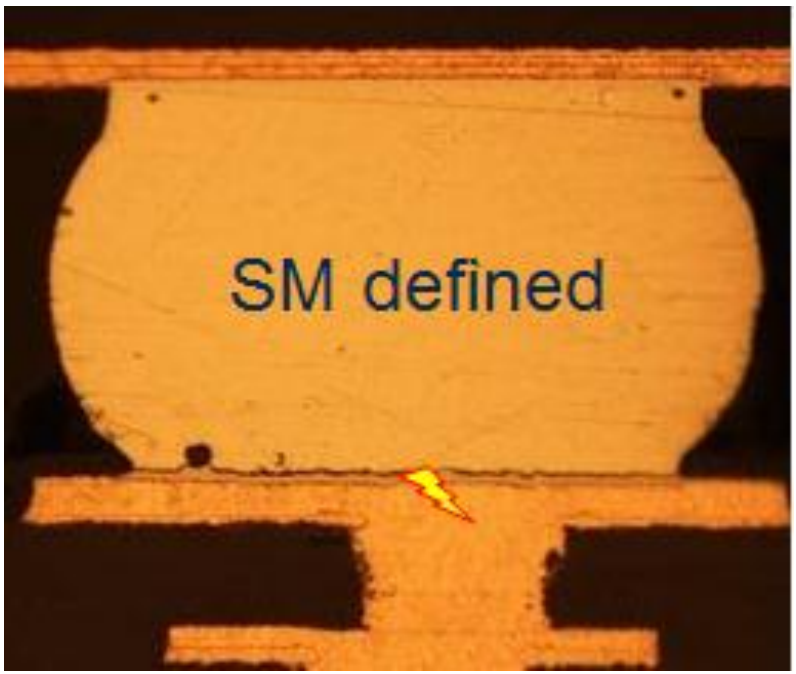
Solder Mask

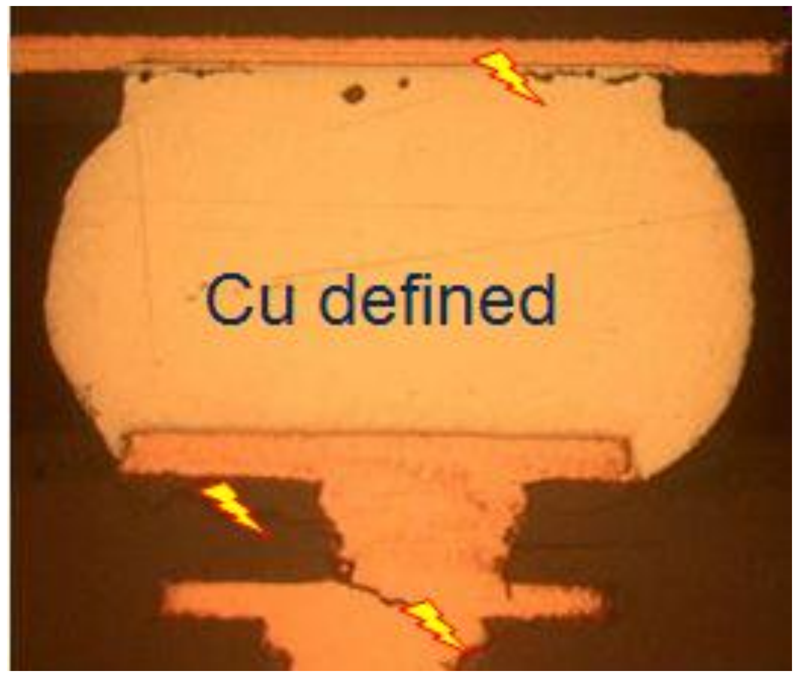


It can be seen that both solder mask types perform similar w/o UF, but an obvious difference occurs using underfill. Conclusive, the interaction of SM / UF has a major impact.

Drop Test

Failure Images

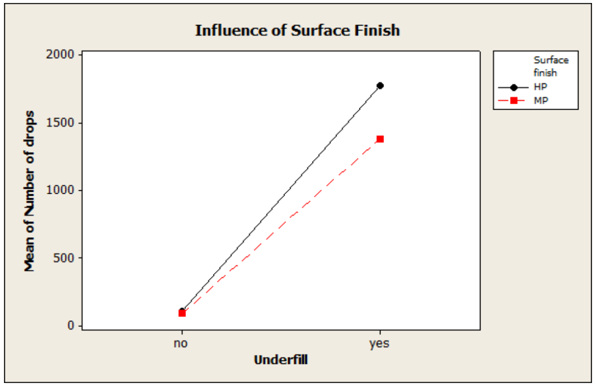


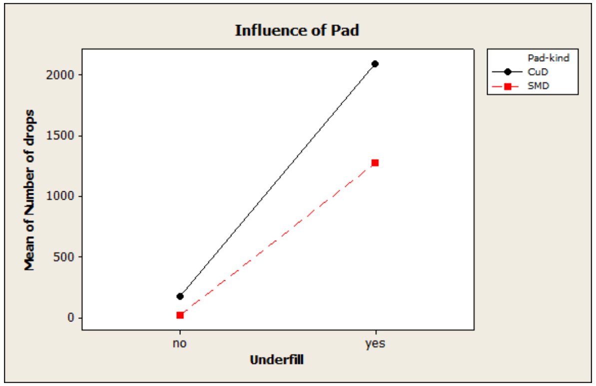


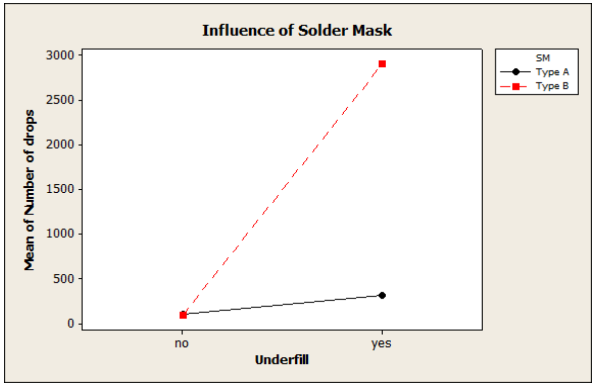
Independent of surface finishing, solder mask or underfill, the failure mode was only influenced by the pad design.

Drop Test

Summary / Conclusion







Surface Finish (HP / MP)
Factor: 1,5x

Pad Design (CuD / SMD)
Factor: 7x

Interaction (SM / UF)
Factor: 14x

Underfill (yes / no) Factor: 106x

Due to the complexity of the interaction of all parameters these results are correlated to the presented analyses. Any change in test setup, design, materials, build-up, processes etc. needs to be verified. But the order of magnitude of the impact of the given parameter gives a good estimation in advance.

Agenda

- Background
- Drop Test DOE
- Contact Angle, Surface Energy & Adhesion
- Summary / Conclusion

Adhesion

Theory

Adhesion attributes attractive forces between two materials to intermolecular interactions. It depends on three main factors:

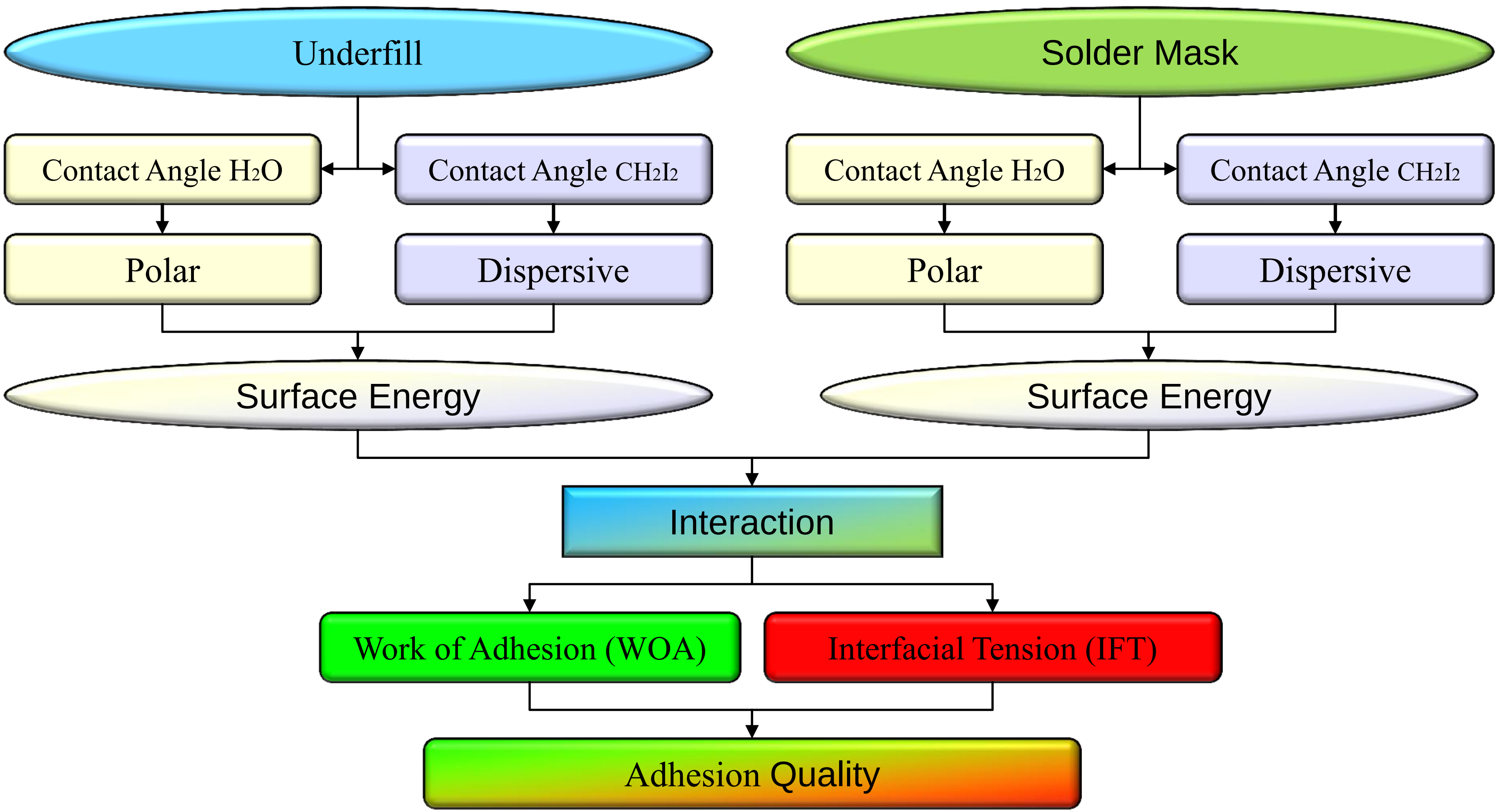
- The <u>chemical structure</u> determines the type and strength of the intermolecular interactions.
- The <u>wetting</u> influences the contact area to the surface and therefore the adhesion force.
- <u>Surface roughness</u> directly influence the wetting behavior, conclusive the adhesion.

Water droplet on metal

Water droplet on glass

Adhesion

Procedure



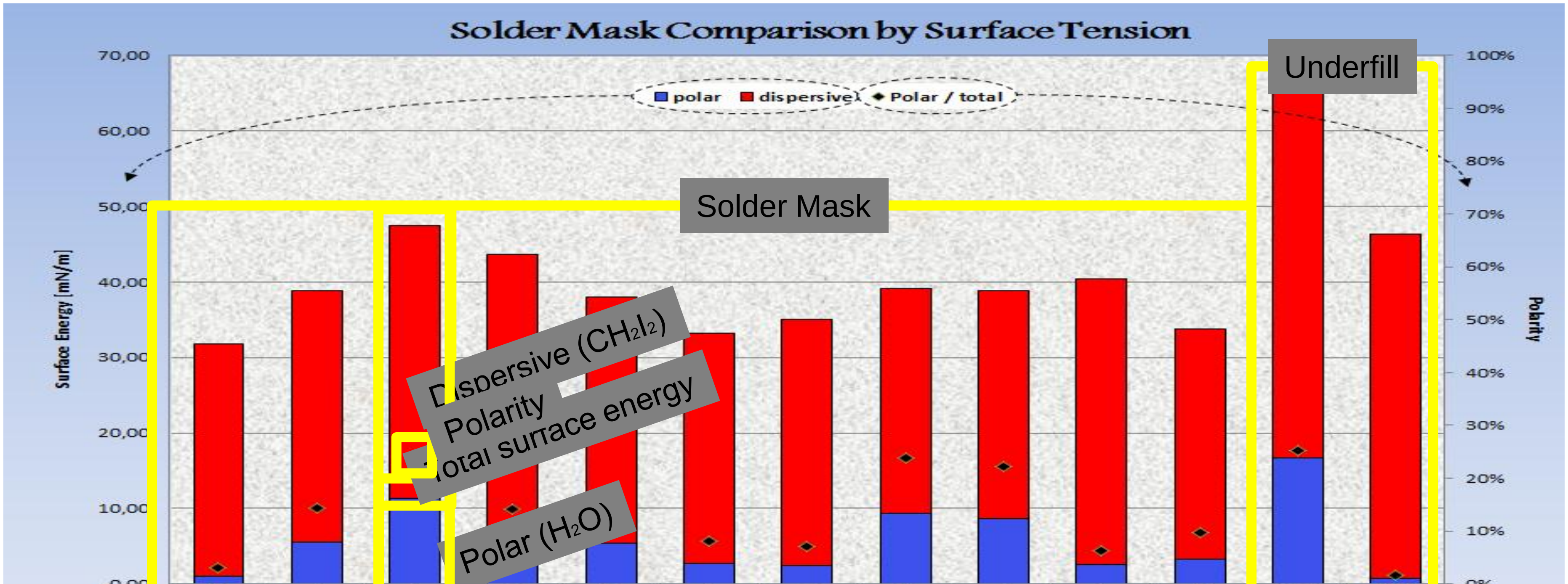
Adhesion

Parameter

Contact Angle - Test Parameter	
Standard	ASTM D7334-08
Equipment Type	Kruess, DSA100
Droplet Volume	1,5µl +/- 0,1µl
Measurement Time	< 5 sec after drop applying
Liquids	Water & Diiodmethane
Sample Condition	after curing & 1 x reflow
Samples	11 different kind of solder mask & 2 underfill types

Adhesion

Surface Energy

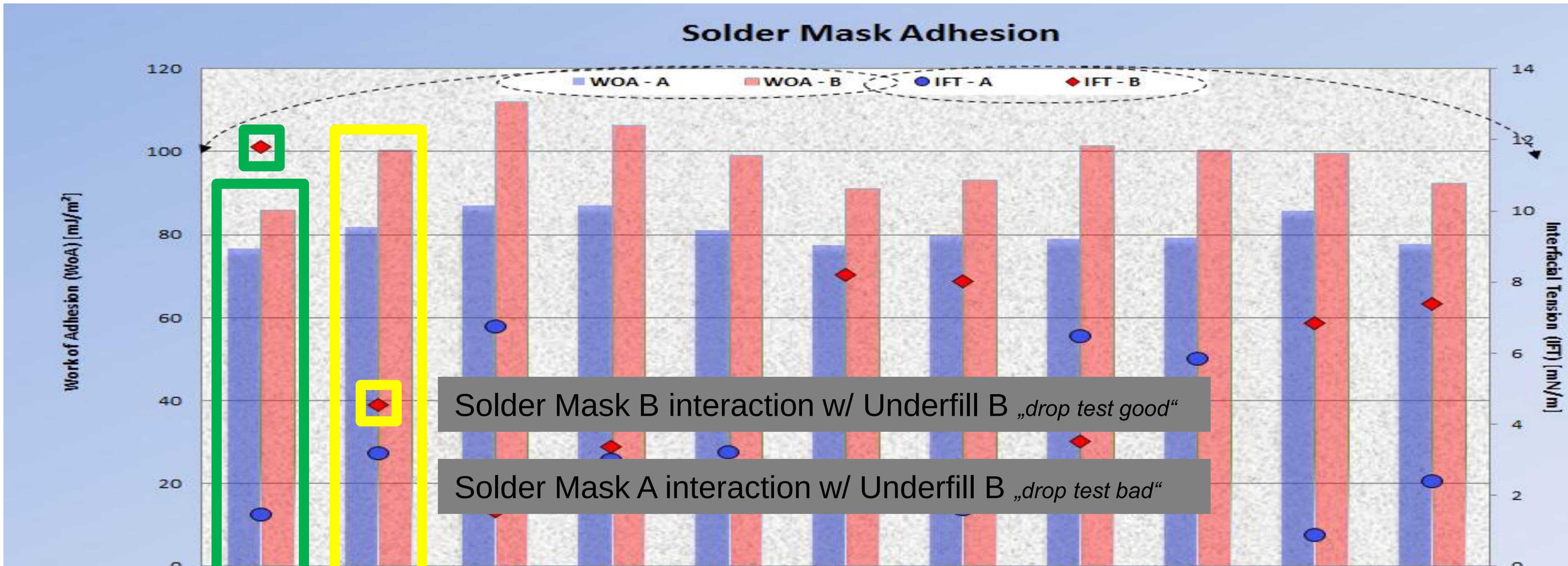


	A	B	C	D	E	F	G	H	I	J	K	UF B	UF A
dispersive	30,82	33,26	36,20	37,54	32,59	30,53	32,59	29,73	30,24	37,87	30,53	49,39	45,60
polar	0,96	5,57	11,27	6,14	5,42	2,70	2,49	9,34	8,60	2,54	3,29	16,66	0,75
Polar / total	3%	14%	24%	14%	14%	8%	7%	24%	22%	6%	10%	25%	2%

The sum of polar (blue) + dispersive (red) part results in the total surface energy. The “point” represents the polarity (polar / total). Basically can be said that higher surface energy causes better adhesion values. But it has to be noted that adhesion always contributes to an interaction of two materials - therefore the total surface energy as single value is too less for precise estimations, also the polarity of two interacting materials has to be compared.

Adhesion

WoA & IFT



	A	B	C	D	E	F	G	H	I	J	K
WOA - A	76,67	81,98	87,07	87,04	81,13	77,47	79,83	78,93	79,35	85,87	77,77
WOA - B	86,03	100,33	111,97	106,35	99,25	91,08	93,12	101,59	100,33	99,63	92,47
IFT - A	1,46	3,20	6,75	2,99	3,23	2,11	1,60	6,49	5,84	0,89	2,40
IFT - B	11,80	4,55	1,55	3,38	4,81	8,20	8,01	3,53	4,55	6,83	7,40

It can be seen that solder mask B (good during drop test) results in higher WoA and lower IFT values than solder mask A (bad during drop test). Based on these results can be assumed that solder mask C would cause even better drop shock reliability.

Agenda

- Background
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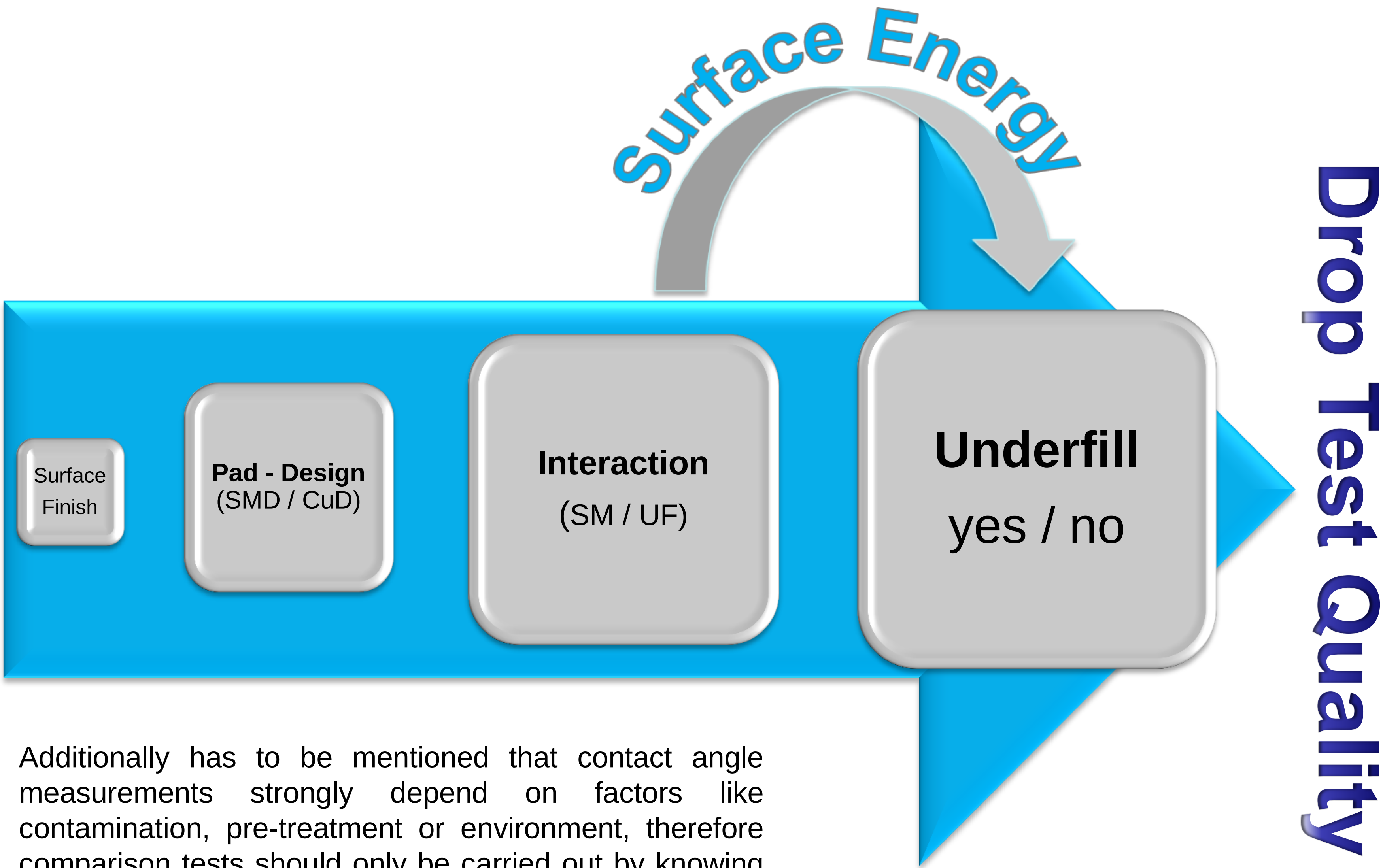
Summary / Conclusion

Overview

I. Drop Test DOE
- It was seen that the use of underfill significant improves the shock reliability, respectively the importance of the interaction of solder mask and underfill system.
- It was also shown that in terms of drop shock reliability copper defined pads are preferable to solder mask defined pads.

II. Contact Angle / Surface Energy
- Several solder mask inks and two underfill types have been analyzed by contact angle. Resulting surface energy has shown considerable differences between the inks for total surface energy and polarity.
- Based on the surface energy and polarity the Work of Adhesion and InterFacial Tension was calculated which reflected the drop test results.

III. Conclusion
- The consensus of drop test DOE and surface energy output proves that contact angle measurements are capable to predict drop-shock performance.



Additionally has to be mentioned that contact angle measurements strongly depend on factors like contamination, pre-treatment or environment, therefore comparison tests should only be carried out by knowing exact experimental setup.

Thank you
for your attention!

Questions?