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(REVIEW ARTICLE)

Validation of the solder paste imprinting process: KOKI S3X58-M650-7 based on an experiment conducted with the use of the DoE methodology

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Abstract

This paper presents an analysis of the influence of selected parameters of the wire bonding process on the occurrence of lift-off defects using the Design of Experiments (DOE) methodology. A structured experimental plan was used to evaluate the effect of key process factors, including ultrasonic power, bonding time, and bond force. Statistical analysis was performed to identify significant variables and optimize the process parameters. The results indicate specific interactions between variables that contribute to the minimization of lift-off defects, thus enhancing bond quality and production yield.

Keywords: Wire bonding; DOE; Lift-off defect; Process optimization; Statistical analysis

1. Introduction

1.1. SMT (Surface Mount Technology)

thus, technology of surface mounting is a method of placing electronic components directly on the surface of the printed circuit board without the necessity to thread them through the holes. Subsequent, consecutive steps within this technology include: printing of the solder paste by means of the screen printing, placing the components on the surface (Pick and Place), soldering, i.e. forming fixed electrical connections through the use of the solder paste that melts in the oven that integrates the previously placed components (reflow soldering). The final step ought to be the automated optical inspection (AOI). We distinguish the following advantages of SMT technology: smaller sizes and weight of devices, greater density of insertion of the components, mechanical resistance to shocks and vibrations. Thanks to automation of this method of placing the components we achieve high precision, fast assembly, incomparably higher in case of assembling the threaded components or manual placement. Hence, decreasing costs in case of larger series may be deemed as a common advantage here. The following are the disadvantages: necessity to perform high precision and correct placement of the components on the printed circuit board. Tolerances are extremely high and they are regulated by a number of IPC standards. Yet another disadvantage is, undoubtedly, the cost of the devices, however, we may safely assume that the high efficiency and precision will enable swift return of the incurred expenditure. Difficulty in inspecting some connections, i.e. beneath the BGA housing (Ball Grid Array) is another disadvantage. Albeit the technology of automated optical inspection (AOI) is currently much more efficient and has greater possibilities. One must keep in mind that either form of assembly will require a specific design form, including the SMT technology; one must consider all restrains it involves.

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2. Printing of the solder paste.

2.1. Printing process

At the first stage of the SMT technology the solder paste (mixture of tin, flux and other additives) is placed by means of a template onto the soldering fields. The most frequently applied method is silkscreen. This step is often underappreciated despite the fact that, in practice, it is of almost critical importance for the quality, dependability and efficiency of the entire SMT process. From the technical perspective, a thin layer of the solder paste placed on the soldering fields of the PCB board by means of the special template (stencil) and the squeegee blade. The objective is to cover all the selected spots on the board in which SMD components will be placed during the subsequent stage.

2.2. Stages of the silkscreen process in SMT

The first stage is the template (stencil) preparation. It is a thin, metal board usually made of stainless steel with spots cut to fit the soldering fields. The holes are cut by means of high-precision laser technology or chemical technology. The thickness of the template remains within the rage of 100 - 150μm and, next to the geometry, it is of crucial importance for the process.

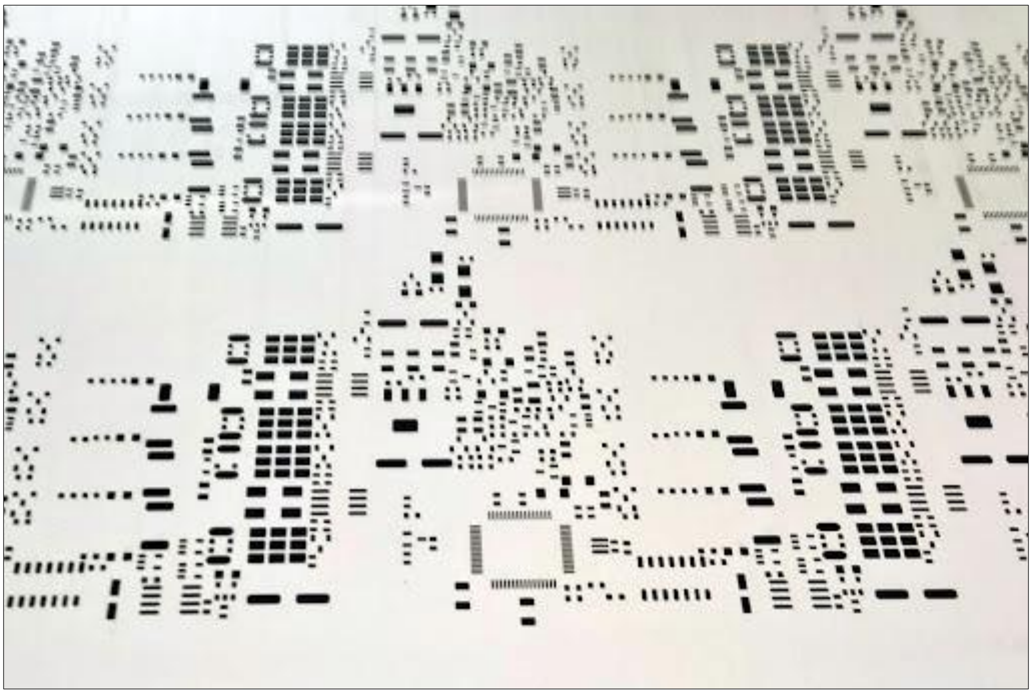

Figure 1 Precise template (stencil) SMT used while placing the solder paste onto the contact fields of the circuit board before assembling minor surface components

Yet another stage is the PCB positioning and its placement in the precisely-set grip of the printing machine. A perfect adjustment of the board and the template is of the essence due to the fact of locating the paste in precise solder fields.

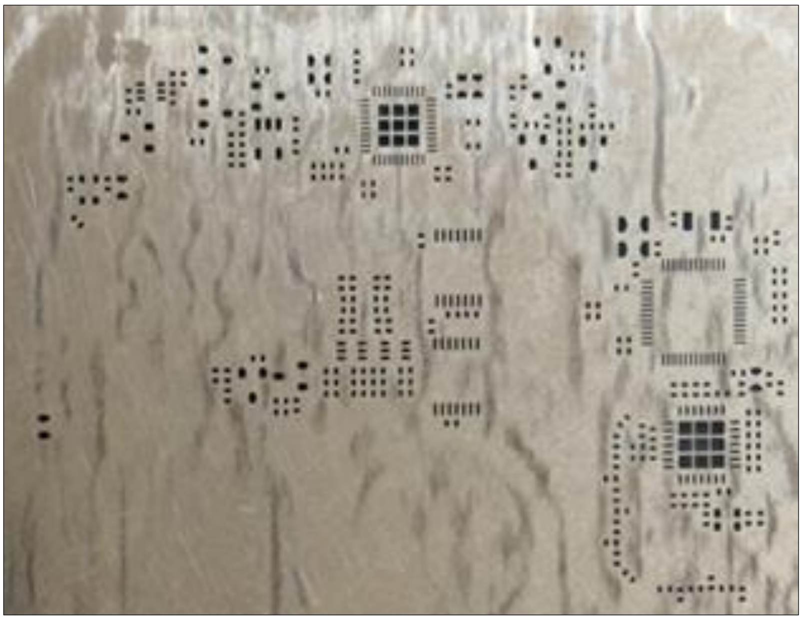

Figure 2 Printing Circuit Board (PCB) placed in the precise grip of the SMT printing machine, ensuring an ideal fit between the *template and* the application of the solder paste. (Image generated by AI *model Imagen* 3)

Another step is placing, printing of the solder paste. Squeegee blade made of metal or plastic is shifted along the template area, pressing the solder paste through the holes in the stencil straight to PCB. Several parameters are of importance within this process: speed, pressure, compression force etc. The scheme of the process of laying the solder paste has been presented on Figure 3. It is clearly visible how the stencil is pressed towards PCB and through it, by means of the squeegee blade, the solder paste is passed covering solely the spots which are cut out in the prepared template.

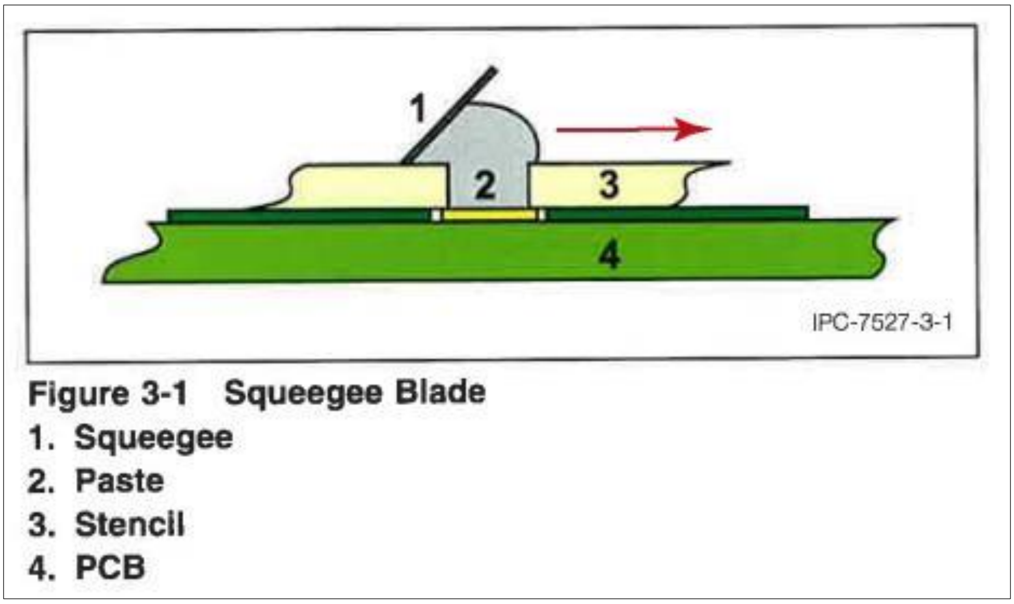

Figure 2 Laying of the solder paste by means of the squeegee blade

The final phase of the process and, in fairness, its completion is the separation of the template from PCB. Lifting the stencil is crucial for the avoidance of paste blurring. The board with the paste reaches the next stage, i.e. assembly of the components.

The above description is brief but critical for the SMT process. Maintaining correctness of itis realization enables obtaining decent quality of the remaining elements in this technology.

3. Assessment of the solder paste KOKI S3X58-M650-7 in the SMT silkscreen process

3.1. Solder paste KOKI S3X58-M650-7 technical data

Solder paste KOKI S3X58-M650-7 is unleaded (Sn3.0Ag0.5Cu_and halogen free (meeting the BS EN14582 standards) and designed for the most effective assembly of the SMT surface assembly. Its key advantages, apart from the composition, include: ICT testability (specially designed remains of the flux with low viscosity preventing adhesion to the test pins), low emptiness level, i.e. elaboration of the flux so that it minimizes the generation of gases during the distribution which minimizes the appearance of empty spots, particularly important for small components such as micro-BGA or LGA. Additional advantages are the perfect moistening, good printability with fine raster >0.4mm, >0.3mm diameter with a good print repeatability, preventing the pillow defect and good inspection properties. The key points from the specification: Alloy composition: Sn 3.0Ag 0.5Cu (Tin, Silver 3.0%, Copper 0.5%), melting point: 217-219 °C, size of particles: 20-38 µm (Type 4), viscosity: 200 Pa.s (typically measured by means of the Malcom spiral viscometer 25°C, 10 rpm), content of the flux: 11.5% (typical range may amount to +/- 1.0%),Halogens' content: 0% (halogen-free), type of flux: ROL0 (resinous, organic, low operations - in line with IPC J-STD-004B), bonding time (Tack Time): > 24 hours (some sources indicate > 48 hours), Halogens' content: 0 ppm (Cl+Br) according to some sources (BS EN14582), storage period: 6 months while storing below 10°C

3.2. Purpose of the conducted experiment

The purpose of the conducted experiment was to define the impact of the printing parameters on the quality of the paste depository as well as the comparison of the results with the referential material: ALPHA 338PT. The test was realized with the use of the DoE methodology (Design of Experiment).

3.3. Range of experiment

The test covered the analysis of paste volume (%), contact surface field (%), length of deposit (µm), range of volatility in the range of one PCB and the number of errors in line with IPC 7257.

Factors (autonomous variables) were tested on two levels: speed of print 30mm/s and 80mm/s, print pressure 5kg and 11kg, speed of separation 1mm/s and 10mm/s, distance of separation 1mm and 10mm, number of print cycles 1 or 2, template gap 0 or 1mm.

3.4. Experiment plan

Table 1 The plan of DoE experiment for the selected factors, each one on two levels

	Print speed [mm/s]	Print pressure [kg]	Separation speed [mm/s]	Separation distance [mm]	Print cycles [strokes]	Stencil gap [mm]
1	30	11	1	1	2	1
2	30	5	10	10	2	0
3	80	5	1	10	2	1
4	30	5	1	10	1	1
5	30	11	10	10	1	1
6	80	11	10	1	2	0
7	30	11	1	10	2	0
8	80	5	10	1	1	1
9	30	5	10	1	2	1
10	80	5	1	1	2	0
11	80	11	1	1	1	0
12	30	5	1	1	1	0
13	80	11	1	10	1	0

14	30	11	10	1	1	0
15	80	11	10	10	2	1
16	80	5	10	10	1	0

3.5. Test Results

The results of subsequent experiments with the results of individual elements of the analysis covered in the range of the experiment have been presented below in the table. These concerned: Volume, contact area, deposit level, range of volatility and number of errors.

Table 2 Results of the DoE test for the solder paste.

ID	Volume [%]	Area [%]	Height [μm]	Volume range [%]	Area range [%]	Height range [μm]	Errors
1-1	121,75	106,27	114,43	150,99	89,46	108,861	0
1-2	123,58	107,15	115,84	159,82	89,307	99,775	0
1-3	125,91	110,05	113,96	150,66	102,458	105,478	1
2-1	119,91	99,72	112,57	137,92	77,205	83,628	0
2-2	116,04	90,45	113,59	80,75	41,447	59,268	0
2-3	113,62	92,04	113,49	80,27	47,505	55,57	0
3-1	129,85	97,27	131,77	213,68	110,558	172,752	111
3-2	127,39	99,47	130,44	199,63	153,824	149,834	27
3-3	126,51	98,22	129,46	201,02	157,562	157,562	34
4-1	105,91	92,66	114,11	124,03	55,514	94,89	0
4-2	106,93	92,54	114,24	125,58	91,539	91,577	3
4-3	104,63	92,62	112,77	139,63	63,026	103,462	0
5-1	102,84	93,86	111,76	162,17	54,504	126,772	1
5-2	106,43	95,24	111,49	124,9	62,084	88,84	0
5-3	102,83	93,72	110,78	173,19	63,759	129,587	1
6-1	117,4	103,95	112,83	154,79	52,173	118,963	1
6-2	119,29	106,35	114,13	161,3	92,163	114,471	1
6-3	117,74	104,25	112,9	157,15	62,079	110,452	1
7-1	123,06	106,52	115,94	104,715	93,027	0	
7-2	121,02	104,64	114,89	143,84	89,154	98,855	0
7-3	119,24	100,25	115,46	129,11	86,159	96,806	0
8-1	109,54	88,7	123,17	164,04	88,832	146,968	103
8-2	113,29	91,83	126,85	170,56	82,57	148,333	65
8-3	115,05	91,99	120,57	143,34	76,615	106,972	7
9-1	115,14	90,84	118,39	124,86	95,915	0	
9-2	115,3	100,72	114,66	103,68	55,336	72,789	0
9-3	119,39	100,23	110,42	110,35	82,022	63,442	0

10-1	111,3	97,48	114,34	153,16	79,02	127,449	6
10-2	114,27	100,17	118,94	151,16	78,97	109,339	1
10-3	113,73	99,33	111,82	137,41	71,886	99,258	0
11-1	113,47	92,29	114,36	144,85	67,119	105,282	2
11-2	105,53	90,29	113,48	134,79	69,516	94,986	0
11-3	104,68	96,64	117,16	117,32	62,469	80,75	0
12-1	113,4	98,56	115,82	116,48	57,296	83,291	0
12-2	106,57	93,45	109,56	134,18	64,553	99,215	0
12-3	102,43	93,95	108,96	129,55	59,447	95,127	0
13-1	108,73	91,08	116,57	160,97	64,85	122,333	1
13-2	108,51	95,08	117,3	121,65	57,029	82,7	1
13-3	108,53	95,57	110,47	160,43	65,09	121,562	0
14-1	108,51	93,42	111,43	148,27	68,207	108,099	0
14-2	108,37	96,78	112,58	129,68	69,588	102,573	1
14-3	105,03	96,3	110,34	123,66	69,763	77,784	1
15-1	102,45	106,2	115,14	150,56	50,015	106,089	1
15-2	128,61	102,26	114,13	146,18	48,416	102,08	1
15-3	120,53	107,34	114,98	153,62	82,977	114,055	0
16-1	108,83	94,18	118,96	144,95	67,557	154,994	26
16-2	108,63	95,06	114,18	134,82	84,29	110,146	14
16-3	112,42	91,6	122,63	163,68	72,876	148,361	0

4. Assessment and description of impact of the assumed factors on the experiment results

The table below presents the analyzed parameters, the greatest impact of factors, interactions, higher order interactions and impact description. The analyzed amounts have been described in chapter 3.3 “Range of experiment”

Table 3 Description of the interaction impact on individual analysed amounts.

<table>
<tr><th>Analysed amount.</th><th>Key factors impacting the analysed amount.</th><th>Level / description of the impact</th><th>Key interactions.</th><th>Impact of interactions / description.

Note: all amounts of the volumes are indicated in % points.</th><th>Higher order interactions.</th></tr>
<tr><td rowspan="3">Volume [%]</td><td>E – number of printing cycles,</td><td>Increase in the number of cycles impacts the increase in volume from 107.75% to 119.7%.</td><td>AB – speed of overprint and pressure,</td><td>Change of overprint speed from 30 mm/s to 80 mm/s with pressure of 11 kg changes the volume from 114.5 to 114.
Pressure of overprint changes the volume from 110.3 to 115.9</td><td rowspan="3">none</td></tr>
<tr><td>F – interval between the template and PCB,</td><td>Increasing the interval by 1mm increases the volume from 112.2% to 115.2%</td><td>EF – number of cycles of the overprint and the interval between the template and PCB</td><td>Changing the number of the printing cycles from 1 to 2 without interval between templates changes the volume from 107.6 to 116.8, the same change but with the interval of 1mm changes the volume from 107.6 to 122.6.
changes the volume from 107.6 to 122.6</td></tr>
<tr><td>A – speed of overprint</td><td>Increasing the speed from 30mm/s to 80mm/s impacts the increase in volume from 112.4 to 115%.</td><td></td><td></td></tr>
<tr><td rowspan="2">Range of volume [%]</td><td>A – Speed of overprint</td><td>Change of overprint speed from 30 mm/s to 80 mm/s increases the range of speed and volume from 131.4 to 156.0.</td><td>AE – speed of overprint and number of printing cycles.</td><td>Changing print speed from 30 mm/s to 80 mm/s with 1 printing cycle range of volume from 137.1 to 147.5 and same changes with 2 printing cycles changes range from 125.3 to 164.5</td><td rowspan="2">BF - Atypical third order interaction was observed. Upon higher speed of print we can observe a greater range of volume. In case of higher pressure, we
can observe a greater range of volume. The same tendency may be observed upon changing the interval between the templates from 0 mm to 1 mm but in case</td></tr>
<tr><td>F – interval between the stencil and PCB</td><td>Change of interval between the templates from 0 mm to 1 mm increases the range of volume from 137.7 to 149.5</td><td>BF- pressure and interval between the stencil and PCB</td><td>Change of the print pressure from 5 kg to 11 kg without interval between the template and PCB changes the range of volume from 130 to 145.5 and the same change with an interval changes the range from 152.5 to 146.4.</td></tr>
</table>

				The gap set to 1 mm changes the range from 152.5 to 146.4	of using the speed of 80 mm/s, pressure of 11 kg and the template gap of 1mm we can observe a decrease in the range of volume
			AB – speed of overprint and pressure.	Change of the print speed from 30 mm/s to 80 mm/s with pressure of 5 kg changes the volume from 116.9 to 165.5 and the same change in case of pressure of 11 kg changes the range of volume from 145.5 to 146.5	
Area [%]	E – number of cycles	Change of the printing cycle from 1 to 2 increases the area from 93.7% to 103.0%.	BE - print pressure and printing cycles connected with AC,	Changing the print pressure from 5 kg to 11 kg increases area from 92.7 % to 94.8 % while with additional printing cycle this process change increases volume from 99.9 % to 106.1 %	none
	B – printing pressure	Change of the printing cycle from 5 kg to 11 kg increases the area from 96.3% to 100.4%.	EF - printing cycle and interval between the template and PCB.	Change in the number of the printing cycles from 1 to 2 without interval between the templates increases the area from 94.5% to 102.3%. mm changes the area from 92.9% to 103.7%.	
	A – speed of overprint	Change of the print speed from 30 mm/s to 80 mm/s decreases the area from 99.2% to 97.5%.			
Area range [%]	C – speed of separation	Change of separation speed from 1 mm/s to 10 mm/s decrease the range of area from 80.3 to 67.8.	AB - speed and pressure of print	Change in the speed of print from 30 mm/s to 80 mm/s whilst maintaining the pressure of 5 kg increases the range of area from 64.1 to 88.6; the same change in case of the pressure of 11 kg changes the range of area from 79.1 to 64.5. kg changes the area range from 79.1 to 64.5	none
	E – number of overprint cycles	Adding an additional cycle of print increases	AB – speed of overprint and pressure	Change in the speed of print from 30 mm/s to 80 mm/s whilst maintaining the pressure of 5 kg changes the height	

		the range of area from 68.2 to 79.9.		from 113 µm to 121.6 µm; the same change in case of pressure of 11 kg changes the height from 113.1 µm to 114.1 µm kg changes the height from 113.1 µm to 114.1 µm	
Height [µm]	A – Speed of print	Change of speed from 30 mm/s to 80 mm/s increases the height from 113.1 µm to 117.9 µm.	BF – pressure and distance between the template and the printed circuit board.	Change in the print pressure from 5 kg to 11 kg without interval between templates decreases the height from 114.7 µm to 113.1 µm; the same change with an interval of 1 mm decreases the height from 119.9 µm to 121.6 µm changes the height from 119.9 µm to 114.1 µm	none
	B – print pressure	Change of pressure from 5 kg to 11 kg decreases the height from 117.3 µm to 113.6 µm.			
	F – interval between the template and PCB	Adding 1 mm of interval between templates increases the height from 113.9 µm to 117 µm			
	D – distance of separation	Change of distance of the separation from 1 mm to 10 mm increases the height from 114.3 µm to 116.6 µm			
Range of height [µm]	A – Speed of print	Change of print speed from 30 mm/s to 80 mm/s increases the range of height from 93.1 µm to 119.8 µm.	AB – speed of overprint and pressure	Change in the speed from 30 mm/s to 80 mm/s whilst maintaining the pressure of 5 kg increases the range of height from 83.1 µm to 133.3 µm; the same change in case of pressure of 11 kg increases the volume from 103 µm to 106.5 µm	ABF – speed of overprint, the print pressure and the interval between the template and PCB - Atypical third order interaction was observed. Upon higher speed of print we can observe a greater

	F- interval between the stencil and PCB	Adding 1 mm of interval between templates increases the range of height from 101.7 µm to 111.2 µm			range of volume. In case of higher pressure we can also observe a greater range of height. The same tendency may be observed upon changing the interval between the templates from 0 mm to 1 mm but in case of when using the speed of 80 mm/s, the pressure of 11 kg and the interval between the templates of 1 mm we can observe a decrease in the range of height.
Errors	A – Speed of print	Change of print speed from 30 mm/s to 80 mm/s increases errors from 0.29 to 17.04.	AB – speed of overprint and pressure	Change in the speed from 30 mm/s to 80 mm/s whilst maintaining the pressure of 5 kg increases errors from 0.33 to 33.41; the same change in case of the pressure of 11 kg increases errors from 0.33 to 0.66.	ABF – speed of overprint, the print pressure and the interval between the template and PCB - Atypical third order interaction was observed. Upon a higher speed of print we observe more errors. Adding interval between templates increases the number of errors. Higher pressure of the print decreases the number of errors. For the low speed with an additional interval between the templates increasing the pressure does not cause the expected drop in the number of errors
	B – print pressure	Increasing the pressure from 5 kg to 11 kg decreases errors from 16.83 µm to 0.5 µm.	BF – pressure and distance between the template and the printed circuit board.	Change in the pressure from 5 kg into 11 kg without an additional gap decreases errors from 4.5 to 0.58; the same change but with an additional gap decreases errors from 29.16 to 0.58	
	F - interval between the stencil and PCB	Adding an additional 1 mm of interval between templates increases errors from 2.45 to 14.87	AF – overprint speed and the distance between the stencil and PCB	Change in the speed of print from 30 mm/s to 80 mm/s without interval between the templates increases errors from 0.5 to 4.83; the same change with an additional interval of 1 mm increases errors from 0.83 to 29.25.	

4.1. Optimizations Results

Table 4 below presents the tested answer, goal, achieved ranges of values (the lowest – target – the highest), the weight and the validity in the process. Based on these data an analysis was performed followed by the choice of optimal parameters.

Table 4 Summary of answers concerning selected sizes and introduction to optimisation.

Answer (dependent variable)	Goal	Range (the lowest value – target – the highest value)	Weight	Validity
Errors	Minimum	0 – 111	10	1
Range of height	Minimum	55.7 – 172.752	1	1
Height	Target	109.075 – 110 – 131.775	1	1
Area range	Minimum	41.747 – 153.824	1	1
Range of volume	Minimum	80.270 – 213.68	1	1
Area	Target	88.699 – 100 – 110.754	1	1
Volume	Target	102.471 – 110 – 129.580	1	1

Based on the experiment, the parameters and their sizes were selected which constitute an optimal answer of the process and which give a better overprint quality. These are: speed of overprint 30mm/s, pressure (print pressure) 11 kg, speed of separation 10mm/s, distance of separation 1 mm, number of printing cycles: 1, interval between the stencil and PCB: 0mm.

For the adopted values, the following values of tested parameters have been obtained (Table 5):

Table 5 Summary of values of adjustment to the optimal value of parameters separated in the course of the experiment.

Parameter	Adjusted value
Errors	0.33333
Range of height	96.152 μm
Height	110.459 μm
Area range	69.186%
Range of volume	139.903%
Area	96.8284%
Volume	107.142%

4.1.1. Comparison with the referential material ALPHA 338PT

Table 6 Comparison of the selected, optimal parameters for the selected paste and the referential material

	Volume	Area	Height	Volume range	Area range	Height range	Errors
338PT	114.221	101.02	108	132.223	63.7667	106.1001	0
M650	107.142	96.82	110.46	139.9	69.186	96.152	0.33

For the selected materials, sizes have been compared to the validity of which is crucial within the process. The ALPHA paste, in case of the same parameters, records 0 errors whilst M650 - 0.33 error. It might thus be stated that these values are quite alike, and the application of material has no impact in this regard. Similarly, the range of volume and the range of area. The M650 material achieves a closer target value for height, which is one of the key parameters. To sum up: M650 better reaches the goal for the height but at a price of higher volatility and the occasionally occurring errors.

5. Conclusion

The experimental DoE analysis turned out to be effective in identifying the key factors and interactions that have a substantial impact on the results of the process, such as volume, print area, height, or number of errors. Applying this methodology allows for an organized testing of the impact of entry parameters, whilst simultaneously minimizing the influence of non-controlled variables. Optimization turned out to be effective and the sizes of parameters which are ideal for achieving the intended results were correctly separated. The new material applied in the silkscreen technology was correctly tested and effectively introduced into standard production.

Compliance with ethical standards

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Disclosure of conflict of interest

All the authors of must disclose the possible conflicts of interest/ Competing Interests they may have with publication of the manuscript or an institution or product that is mentioned in the manuscript and/or is important to the outcome of the study presented. Authors should also disclose conflicts of interest with products that compete with those mentioned in their manuscript.

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