Wave solder process characterization by an experimental design approach

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Abstract

A manufacturing company in Puerto Rico was interested in evaluating the possibility of profiling all printed circuit board assemblies. Experimental design, a method for systematically planning engineering studies, offered the means to accomplish this possibility while at the same time it helped to optimize the profiling process.

Just before this project took place, profiles of all product transfer made at the plant were the same. Further defect reduction could not be obtained with current machine settings. However, a new NU ERA wave solder machine offered many possibilities for improvement.

In this paper we discuss the experimental design that took place at the plant and we are able to identify the important factors which contribute to the response of the profiling process and to determine which factor settings will produce the best profilings.

Sinopsis

Una compañía de manufactura en Puerto Rico interesada en evaluar la posibilidad de caracterizar cada producto o familia de productos en el ensamblaje de circuitos impresos pudo alcanzar esta meta mediante el uso del diseño experimental, método por el cual se planifican sistemáticamente los estudios de ingeniería. El diseño experimental también ayudó a optimizar el proceso de caracterización.

Antes de comenzar con este proyecto, la caracterización de todas las transferencias de productos en la planta eran idénticas. Era imposible disminuir los defectos con la calibración que tenían las máquinas. Sin embargo, la adquisición de una nueva máquina para el proceso de soldadura brindó la posibilidad de mejorar.

En este trabajo se discute el diseño experimental que se llevó a cabo en esta compañía. A la vez se pueden identificar los factores de mayor relevancia en la respuesta del proceso de caracterización de los productos y determinar qué ajustes a estos factores producen la mejor caracterización.

Wave solder process information

A. Solder Defects and Criteria

It was necessary to establish the guidelines by which solder defects were to be accounted for. This step was needed to assure that the same criteria were used from the beginning to the end of this designed experiment.

At the beginning of this experiment, different personnel were contacted to generate a list of the defects encountered after wave soldering. Personnel contacted included quality control, manufacturing engineering, production supervisors, and touch up operators. It could not be expected that touch up personnel be consistent in detecting defects if quality, engineering, and production supervisors could not agree on detecting the same defects.

In the case of this company, a new solder defect criterion was needed in order for touch up personnel to be consistent. This criterion evolved from the need for a non-subjective method to evaluate solder joint defects. For example, how could a touch up operator know whether a plated through hole (PTH) was filled at least 75% as the Institute for Interconnecting and Packaging Electronic Circuits (IPC) recommends.

After much research, we decided to adopt Joe Keller's acceptance criteria for solder joints in a PTH. These acceptance criteria consist of the following statements:

1. Component leads shall be soldered to both the PTH and pad by a fillet with a width greater than the lead width or diameter.
2. PTHs, with or without component leads, need not be filled with solder.

3. Solder filleting may occur within the PTH without any external fillet on the pad.

4. The solder fillet need not bridge the entire circumference of either the pad surface or the PTH.

These criteria were further simplified for the touch up operators with a question format:

1. Do you see a lead (high component defect)?

2. Do you see a solder fillet (no solder defect)?

3. Is the solder fillet width greater than the lead width or diameter (incomplete fillet defect)?

4. Has wetting occurred (excess solder, solder balls, wetting problems)?

An answer of no to any of the questions meant the touch up of the solder joint in question. Furthermore, operators were told to touch up the solder joint whenever in doubt.

These criteria were objective, scientific, verifiable and economical. Economy was obtained because operators were no longer required to look on top of the board for solder rise.

B. Wave Solder Parameters

Wave soldering consists of three simple steps: fluxing, preheating and soldering. These three steps are described bellow:

1. Fluxing

Fluxing has two major functions: to provide tarnish-free surfaces and keep the surface clean, and to influence the surface-tension equilibrium in the direction of solder spreading by decreasing the dihedral angle.

Foam fluxing is the means of application of flux to the printed circuit board. Control over the following items will be needed:

a. vehicle
b. air pressure and air purity
c. height of the liquid over the foaming elements
d. temperature.

Of these four items, vehicle and temperature had the most impact on our experiment. We selected the correct flux to vehicle ratio by measuring the density. Inasmuch as density depends on temperature, we had to be sure that the temperature of the sample being tested was equal to the temperature stated by the manufacturer. The range to be selected from was to be specific gravity stated by the manufacturer ± 0.010.

2. Preheating

Preheating is necessary for volatile evaporation, flux activation, reduction of thermal shock and effect on soldering speed. For our experiment the appropriate temperature range was selected from table 1. The experiment showed which temperature within this range was best for this purpose. Then we tested the process to see whether this temperature was enough to dry the volatiles by listening for signs of excessive spattering at the wave. Finally, we checked the soldering results to make sure that the flux was active.

Table 1. A rule of thumb for best preheat temperatures

Printed circuit board		
Type	**Thickness (in.)**	**Temperature Range (°F)**[1]
Single sided and flexible	all	175-200
Double sided	max 0.063	210-230
Multilayer (up to 4 layers)	max 0.063	220-250
Multilayer (over 4 layers)	min 0.093	230-270

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[1] Measured when leaving the preheat station, on top of the board. Temperature was taken on insulation, in between metallic conductors. Temperature range holds true for average speed and component density. Remember that large ground planes, heavy component population and other heat sinks require more heat.

3. Soldering

The wave solder process involves direct contact between the work and the molten metal. This process was divided into two distinct physical events, as follows:

A. Final heat transfer

Final heat transfer was needed to raise the surfaces to wetting temperatures. It is a function of the following parameters:

1. the solder bath temperature (490 ± 10° F for Sn63)
2. the wave contact length (1-3 in.)
3. the conveyor speed (dwell time 0.7-2.0 seconds)
4. the wave dynamics

B. The supply of molten solder

The supply of molten solder was needed to provide solder for wetting. It is a function of:

1. The solderability of both surfaces
2. Design (hole to wire ratio and fillet control)
3. Wave dynamics

In addition to these parameters, depth of wave immersion was also considered, as table 2 shows.

Table 2. Suggested depth of wave immersion versus board thickness[2]

Printed circuit board type	Thickness in inches	Immersion range	
		Low	High
Single sided	0.062	Kiss	1/3
Double sided	0.062	1/3	2/3
	0.093	1/2	3/4
Multilayer	0.062	1/2	3/4
	0.093	5/8	3/4
	0.125	3/4	7/8

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[2] For an average thermal load only. As a fraction of board height.

Choice of factors and levels

A NU ERA wave solder machine offered six controllable factors, each of which would be studied at two levels (table 3).

Table 3. Controllable factors of the NU ERA wave solder machine

Factor	Description	Level (-)	Level (+)
A	Conveyor speed	3.5 ft/min	4.5 ft/min
B	Conveyor angle	4.11°	4.25°
C	Flux density	0.855	0.875
D	Solder temperature	480 ° F	500 ° F
E	Preheat temperature	220 ° F	2500 ° F
F	Board depth	1/2	3/4

The test vehicle was DCP-80, a high component density product. This product was showing a high number of no solder defects. Each panel had 2309 plated through holes and consisted of six layers. A note must be made about our preheat factor E: Although table 1 indicates that preheat temperature range should be within 230° F and 270° F, specific vendor instructions indicate preheat temperature should not exceed 250° F. For this reason we chose the levels indicated for factor E.

For obvious economic reasons the company could not provide us with fully assembled DCP-80s, but agreed to give us some components to assemble the required panels for the experiment.

Selection of the response variable

The response of the experiment was the total number of solder defects found per panel, although data was subdivided into high component data, no solder data, incomplete fillet data and wetting defects data.

Experimental model selection

Based on the experimental design classification, the best experimental model given the number of factors, levels and experimental restrictions is a factorial design. Due to six controllable factors of the new solder machine, at two levels, a 2^6 full factorial design becomes unfeasible. A fractional factorial design with 2^{6-2} runs and of resolution IV was used. This design required fewer runs, it was balanced and orthogonal, and its resolution meant that the main effects were not aliased with other 2-way interactions but did alias 2-way interactions with other 2-way interactions.

Experimental process

We deemed as important all main effects; 2-way interactions AB, AD, AE, BF, CD, CE and the 3-way interaction ACE. Different defining relationships, I = ACF = ABDE = CDEF (table 4), were studied in order to look for the one that would produce an alias structure that would not have these important interactions aliased. It was assumed that all other 2-way, 3-way and higher order interactions were negligible.

Table 4. Construction of the 2^{6-2} design with the defining relation
I = ACF = ABDE = CDEF

Run	A	B	C	D	E = ABD	F = ABC
1	-	-	-	-	-	-
12	+	-	-	-	+	+
3	-	+	-	-	+	+
4	+	+	-	-	-	-
5	-	-	+	-	-	+
16	+	-	+	-	+	-
2	-	+	+	-	+	-
9	+	+	+	-	-	+
13	-	-	-	+	+	-
8	+	-	-	+	-	+
10	-	+	-	+	-	+
11	+	+	-	+	+	-
6	-	-	+	+	+	+
15	+	-	+	+	-	-
7	-	+	+	+	-	-
14	+	+	+	+	+	+

Each run was replicated once for a total of 32 runs. Since each run consisted of a panel, hence a total of 32 panels or printed circuit boards were needed. A total of 73,888 plated through holes would be observed.

Data analysis

The experimental data is shown in tables 5 and 6.

Table 5. Data of the 2^{6-2} design with the defining relation
I = ABCF = ABDE = CDEF

R[3]	A	B	C	D	E	F	AB	AD	AE	BF	CD	CE	ACE	Y1	Y2	Y	S/
1	-	-	-	-	-	-	+	+	+	+	+	+	-	51	45	48	18
2	-	+	+	-	+	-	-	+	-	-	-	+	-	290	336	313	1058
3	-	+	-	-	+	+	-	+	-	+	+	-	+	31	38	34.5	24.5
4	+	+	-	-	-	-	+	-	-	-	+	+	+	49	46	47.5	4.5
5	-	-	+	-	-	+	+	+	+	-	-	-	+	24	31	27.5	24.5
6	-	-	+	+	+	+	+	-	-	-	+	+	-	35	30	32.5	12.5
7	-	+	+	+	-	-	-	-	+	-	+	-	+	284	288	286	8
8	+	-	-	+	-	+	-	+	-	-	-	+	+	9	9	9	0
9	+	+	+	-	-	+	+	-	-	+	-	-	-	61	44	52.5	144.5
10	-	+	-	+	-	+	-	-	+	+	-	+	-	12	14	13	2
11	+	+	-	+	+	-	+	+	+	-	-	-	-	42	35	38.5	24.5
12	+	-	-	-	+	+	-	-	+	-	+	-	-	25	30	27.5	12.5
13	-	-	-	+	+	-	+	-	-	+	-	-	+	35	31	33	8
14	+	+	+	+	+	+	+	+	+	+	+	+	+	47	37	42	50
15	+	-	+	+	-	-	-	+	-	+	+	-	-	45	47	46	2
16	+	-	+	-	-	-	-	-	+	+	-	+	+	41	43	42	2

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[3] Stands for run number

Table 6. Marginal means, standard deviations and sum of squares for all factors

Factor	Mean (-)	Mean (+)	Standard deviation (-)	Standard deviation (+)	Sum of squares
A	98.4	38.1	120.8	13.98	29100
B	33.2	103.3	12.4	118.0	39410
C	31.4	105.1	14.1	116.6	43586
D	74.2	62.5	94.2	88.2	1069
E	66.2	70.4	87.4	95.3	140
F	106.7	29.8	115.5	14.4	47355
AB	96.4	40.2	122.2	9.6	25256
AD	66.8	69.8	86.5	96.1	75
AE	71.0	65.6	95.8	86.8	237
BF	97.7	38.9	121.3	12.6	27671
CD	66.1	70.5	97.8	84.5	158
CE	68.2	68.4	85.5	96.97	0
ACE	71.4	65.2	95.6	86.99	306
Error					1396

To analyze the data by way of marginal mean plots, consider figure 1. The appropriate factor settings which minimize the response are A_+,B_-,C_-,D_+,E_- and F_+. These factor settings corroborated run number 8 of our experiment which produced the fewest defects. But, were all factors important?

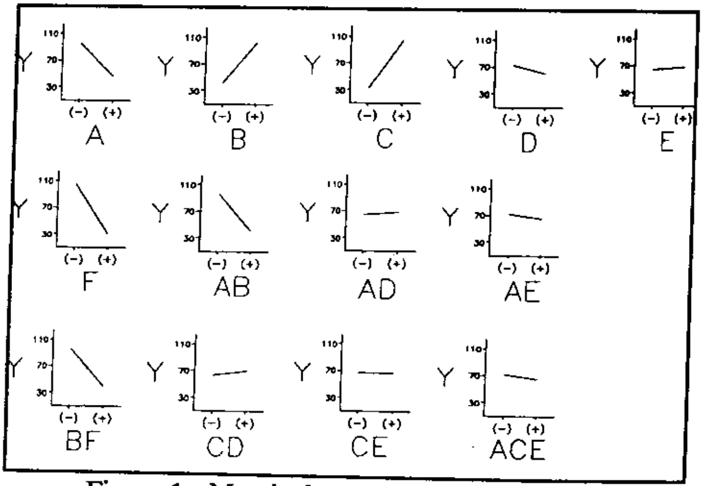

Figure 1. Marginal mean plots of treatments

Table 7. Analysis of Variance (ANOVA)

Factor	SS	df	MS	F[4]
A	29100.0	1	29100.0	333.652 *
B	39410.0	1	39410.0	451.855 *
C	43583.0	1	43583.0	499.735 *
D	1069.5	1	1069.5	12.263 *
E	140.3	1	140.3	1.608
F	47355.0	1	47355.0	542.945 *
AB	25256.0	1	25256.0	289.573 *
AD	75.0	1	75.0	0.860
AE	236.5	1	236.5	2.712
BF	27671.0	1	27671.0	317.262 *
CD	157.5	1	157.5	1.806
CE	0.3	1	0.3	0.003
ACE	306.3	1	306.3	3.512
Error	1395.5	16	87.2	
Totals	215760.9			

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[4] An asterisk (*) represents a significant factor. / = 0.05, critical region: $f_1 > 4.49$

Analysis of variance or regression could answer this question, but since our design was balanced, results would be equal for both analyses. Results are shown on table 7. According to this table factors A,B,C,D, and F, along with two way interactions AB and BF, are significant. Factor E was to be set based on economics and/or convenience.

Conclusions

The objectives of this experiment were:

1. To identify important factors which contribute to the response of the process
2. To determine which factor settings could produce the best response of the process

To answer the first objective refer to table 7. For this table we used the analysis of variance or ANOVA. Since $F_{0.05}(1,16) = 4.49$, the following factors are significant:

- conveyor speed (A)
- conveyor angle (B)
- flux density (C)
- solder temperature (D)
- board depth (F)
- conveyor speed and conveyor angle (AB)
- conveyor angle and board depth (BF)

These results can be confirmed in figure 1. A steep slope means that the factor has a large effect on the response, total defects, as it changes from one level to another. Thus the slopes of the marginal mean plots of all factors clearly show that the steepest slopes belong to the factors indicated above.

For our second objective, let's take a look at those factors one at a time. The F-ratio of 333.7 for factor A is highly significant. Hence, there is a significant difference between the mean response at the low level and the mean response at the high level. Table 6 shows that the total defects falls off as the conveyor speed goes from 3.5 ft/min to 4.5 ft/min. For this reason, factor A, conveyor speed, must be set at 4.5 ft/min.

The F-ratio for factor B is 451.9, which is also significant. In this case, the mean total defects decreases when the conveyor angle is changed from the high level to the low level. For this reason, factor B, the conveyor angle, must be set at 4.11°.

Factor C, the flux density, will be set at 0.855. Figure 1 shows that defects can be reduced when density is changed from 0.875 to 0.855. The F-ratio of 499.7 for factor C made it the second most significant factor in the response of the process.

Factor D, the solder temperature, turned out significant with an F-ratio of 12.3. We recommend setting this factor at 500° F.

Factor E, the preheat temperature, with an F-ratio of 1.6, is not significant. Referring to interaction AE, shown in figure 2, we see a definite interaction in the A_+ level. Hence, we can conclude that as long as A stays at this level, as it is recommended, factor E can have either value. However, the average defects are minimum in the E_- level, which is the most economical setting. Thus, factor E will be set so that board temperature before wave soldering reaches 220° F.

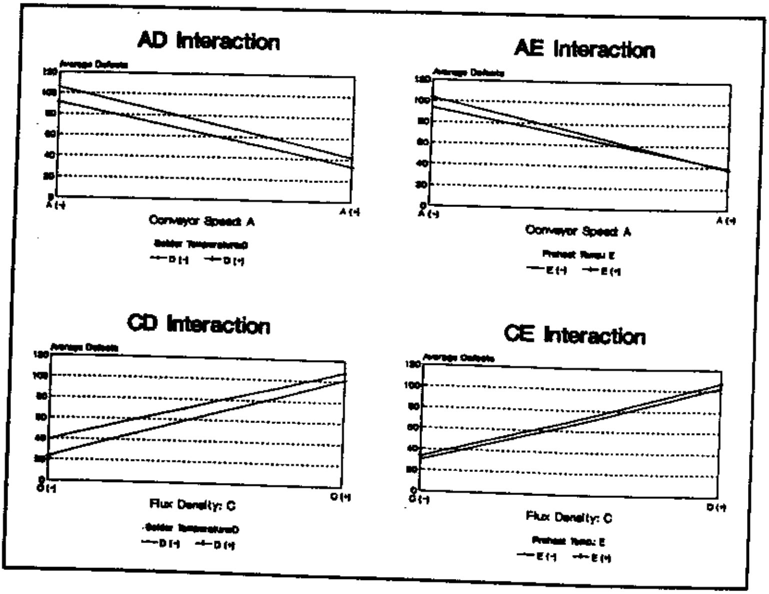
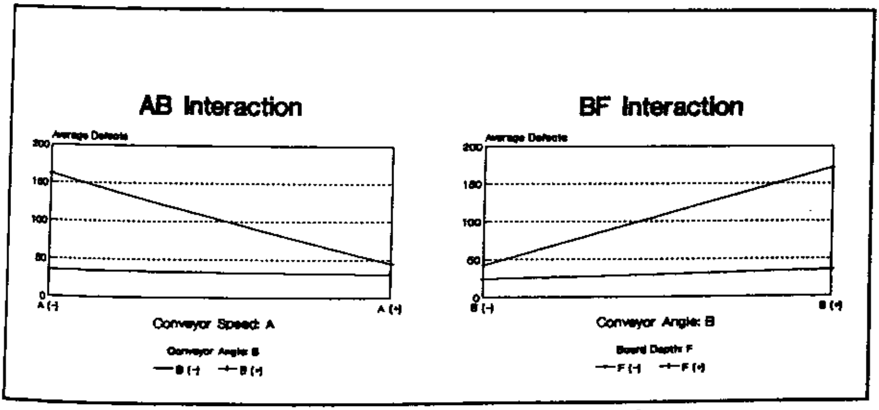


Figure 2. Non significant two-factor interactions

Factor F, board depth, with an F-ratio of 542.9, is the most important according to ANOVA. This factor must be set so that 3/4 of board thickness is submerged in the solder pot. These results can also be corroborated by looking at the BF interaction in figure 3. Although there is a definite BF interaction, the average amount of defects is not affected that much when factor F is kept at a positive value while factor B changes. Interactions AB, conveyor speed and conveyor angle, along with interaction BF, conveyor angle and board depth, with F- ratios of 289.6 and 317.3, respectively, were highly significant. Figure 3 shows a plot of these interactions. Notice that the interaction between factors A and B occurs at the high level of factor A, as recommended. This interaction optimizes the reduction of the total defects when factor B is set at its low level, also as recommended. Looking at the side to which the BF interaction occurs, we can note that the average defects reduction is the best when factor B is set at its low level and factor F is set at its high level. This fact does not contradict the settings mentioned above.



AB Interaction

BF Interaction

Figure 3. Significant two-factor interactions

With all factors set according to these recommendations, experiment objectives were obtained.