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QUALITY IMPROVEMENT THROUGH DESIGN OF EXPERIMENTS: A CASE STUDY

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Key Words

Orthogonal array; ppm; Analysis of variance; Confidence interval; S/N ratio; Optimum combination.

Introduction

The performance of all manufacturing processes is influenced by more than one variable. These variables include machine parameters, raw materials, process followed, environmental conditions, and so forth; all of them may not be exactly controllable from a cost point of view. In the case of machine parameters, even though they are exactly controllable, the level of each parameter that gives the optimum results may be unknown. This article deals with the case study of the wave soldering process in an electronics industry in India. In the wave soldering process, several variables affect solderability and, hence, the defect levels.

Background

A Printer Circuit Assembly–Encoder (PCA–Encoder) is a functionally critical component for the "base carriage assembly," which is used in a printer. Any defect in any of the solder joints will lead to the failure of the circuit. Hence, it is important to make sure that the soldering is defect-free. The usual types of defects were blowholes and bridges. Insufficient solder was considered as blowholes, and solder between two joints was considered as bridges. The existing defect level in parts per million (ppm) for different days were collected from past records (during August 1997). Chart 1 represents the ppm level for different days. (The ppm for each day is calculated by dividing the total number of bridges and blowholes by the total number of joints to be soldered).

From the chart, it is evident that, on average, the defect level was above 6000 ppm. Because of a high level of soldering defects, 100% inspection is done for all the boards just after soldering. Also, all the defects identified during

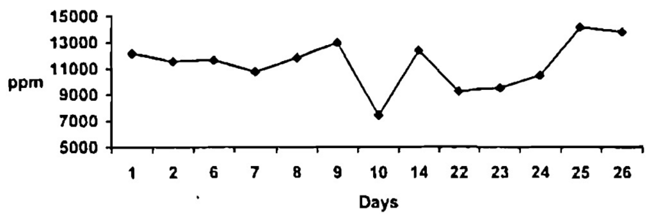

Chart 1. Defect level in ppm for different days.

the inspection are being reworked by manual soldering. This inspection and rework are consuming much time.

Process

The PCA–Encoder is produced by first stuffing the electronic components (i.e., capacitor, Encoder-IC, and connector) on paper phenolic printed circuit boards (known as panels) which contain eight small boards and then soldering the components by the wave soldering process. During the process of wave soldering, four panels are fixed in a frame and sent for soldering. After soldering each of the eight boards (PCA–Encoders), they are separated from the panel by an operation known as the pop-out operation.

The wave soldering process consists of a foam flexor applying flux to the solder side of the panels. After the flexor, there is an air knife to remove excess flux from the panel. Three preheaters in the wave soldering machine are for evaporating the hydrocarbon carriers of fluxing material, by heating the panels, both top and bottom. These preheaters are designated as preheater-1, preheater-2, and the overhead preheater, in which preheater-1 is closer to the solder bath. The temperatures of the preheaters are adjustable. A solder pot, which has a variable-speed motor driving the solder at different heights (i.e., wave height), is used for soldering. A vibrator controls the vibration of the solder wave (known as omega). The panels in the frame are carried on a conveyor with adjustable speed. The angle of the conveyor with solder wave is also adjustable. (Figure 1 represents the schematic diagram of a wave soldering machine.)

Objective

The study was undertaken with the aim of the optimization of wave soldering process parameters for reducing defects and thereby eliminating the inspection stage after the wave soldering process through continuous process improvements.

Identification of Critical Process Parameters

A detailed study on the solder defects was made to investigate the major types of solder defects and different param-

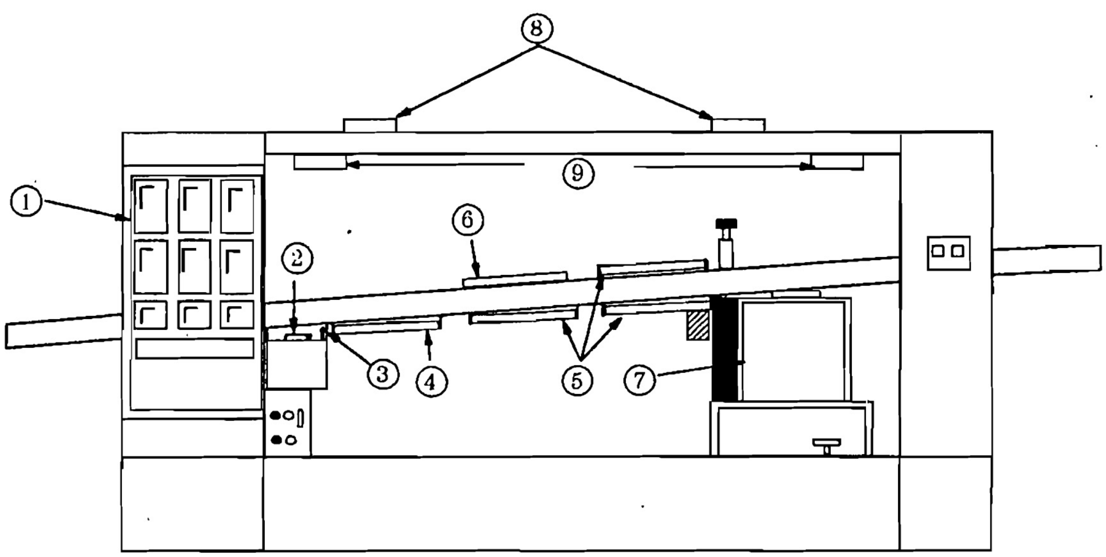

Figure 1. Wave solder machine overview: 1: control panel; 2: flux tank; 3: air knife; 4: dip tray; 5: preheaters; 6: reflector; 7: solder bath; 8: exhaust stacks; 9: hood lights.

eters related to solderability. After discussion with the technical personnel, it was identified that the quality of soldering by the wave soldering process may depend on the following process-related parameters:

1. Conveyor speed
2. Conveyor angle
3. Solder bath temperature
4. Solder wave height
5. Vibration of wave
6. Preheater temperature
7. Air knife
8. Acid number (solid content in the flux)

Of the above-listed parameters, the company does not control the acid number of the flux, as it is difficult to control because on exposure to atmosphere it increases continuously.

Need for Experimentation

In the conventional method, the production manager makes a number of trials by changing the process parameters that he suspects to be critical. In practice, it was observed that this type of trial-and-error approach requires a long time to arrive at a reasonably satisfactory level of performance. The main drawback of the approach is the lack of insight into the possible joint effect of different parameters. Hence, it was decided to use experimentation after selecting the appropriate levels for each factor.

Plan and Design of the Experiment

After discussions with the technical personnel involved in the process, seven factors at three levels were identified for experimentation. The selected factors and their levels are given in Table 1.

Fixed Factors and Their Specification

The fixed factors are the conveyor speed at 1.50 m/min and the conveyor angle of 6.05°.

Seven factors, one at two levels and the rest at three levels, would require $2^1 \times 3^6 = 1458$ trials to conduct a full factorial experiment. It will take a long time to conduct all 1458 trials. The 7 main effects could be well estimated by conducting 18 trials. Hence, orthogonal array L_{18} ($2^1 \times 3^7$) was selected for experimentation. Assignment of different factors in the columns of L_{18} is given in Table 2. It was decided that the response in the experiment would be the number of defective solder joints (i.e., bridges and blowholes) in a frame (i.e., total number of solder joints out of 352 joints). Each experiment was repeated three times.

Table 1. Factors and Levels for Experimentation

FACTOR	CODE	LEVEL 1	2	3
Bath temperature (°C)	A	248[a]	252	
Wave height[b]	B	4.38	4.40[a]	4.42
Overhead preheater (OH-PH) (°C)	C	340	360[a]	380
Preheater-1 (PH-1) (°C)	D	340	360[a]	380
Preheater-2 (PH-2) (°C)	E	340	360[a]	380
Air knife	F	0	3[a]	6
Omega[c]	G	0	2[a]	4

[a]Existing level.
[b]The wave height is measured as the rpm of the motor pumping the solder.
[c]Omega refers to the vibration of the solder wave.

Table 2. Assignment of Factors in L_{18}

SL. NO.	FACTOR	CODE	COLUMN NO.
1	Bath temperature	A	1
2	Wave height	B	2
3	Overhead preheater	C	3
4	Preheater-2	D	4
5	Preheater-1	E	5
6	Air knife	F	6
7	Omega	G	7
8	Error	—	8

Experimentation and Data Collection

Experiments in the physical layout were randomized to avoid the chance of systematic bias and the experiments were conducted by changing the experimental parameters as per the requirements of the randomized order. Data were collected for the 18 experimental runs, with each repeating 3 times; the collected data along with the physical layout are given in Table 3.

Table 3. Data Corresponding to the First Experiment

EXP. NO.	(1) BATH TEMP. (°C)	(2) WAVE HEIGHT	(3) OH-PH (°C)	(4) PH-2 (°C)	(5) PH-1 (°C)	(6) AIR KNIFE	(7) OMEGA	RESPONSE 1	RESPONSE 2	RESPONSE 3
1	248	4.38	340	340	340	0	0	1	2	1
2	248	4.38	360	360	360	3	2	0	2	0
3	248	4.38	380	380	380	6	4	0	1	0
4	248	4.4	340	340	360	3	4	1	0	1
5	248	4.4	360	360	380	6	0	4	2	0
6	248	4.4	380	380	340	0	2	8	1	6
7	248	4.42	340	360	340	6	2	2	4	3
8	248	4.42	360	380	360	0	4	4	1	0
9	248	4.42	380	340	380	3	0	2	2	4
10	252	4.38	340	380	380	3	2	1	3	1
11	252	4.38	360	340	340	6	4	1	2	1
12	252	4.38	380	360	360	0	0	6	3	2
13	252	4.4	340	360	380	0	4	3	3	4
14	252	4.4	360	380	340	3	0	4	3	8
15	252	4.4	380	340	360	6	2	2	1	1
16	252	4.42	340	380	360	6	0	2	7	3
17	252	4.42	360	340	380	0	2	2	1	3
18	252	4.42	380	360	340	3	4	4	2	1

Analysis

The data on the number of defects were subjected to analysis of variance (ANOVA) to find the significant factors. Thus, the ANOVA was carried out for a signal-to-noise S/N ratio smaller-the-better type $\{$i.e., $-10 \log[(1/n) \Sigma y_i^2]\}$ and contribution percentage for each of the factors were calculated. The ANOVA table is presented in Table 4.

It can be observed from Table 4 that the factors bath temperature (A), wave height (B), and omega (G) have a significant effect on the soldering defects. The best levels of these factors were identified from the average response curves. (The average response curve is given in Figure 2.) Level 1 of the bath temperature and wave height and level 3 of omega were found to give better results. The optimum level of different factors obtained from the experimentation is given in Table 5.

The expected number of defects at the optimum combination of the critical factors was estimated as

$$\mu_{opt} = \overline{A}_1 + \overline{B}_1 + \overline{G}_3 - 2\overline{T}$$
$$= (-1.57842) + (-0.63798) + (-0.97405) - 2(-2.74792)$$
$$= 2.30539.$$

The 95% confidence interval for the estimated results,

$$\mu_{opt} \pm \left[F_{\alpha;1,\nu} V_e \left(\frac{1}{n_e} + 1\right)\right]^{1/2} = 2.30539 \pm 5.54658$$
$$= (-3.24119, 7.85197),$$

where V_e is the error variance, ν is the degree of freedom (d.f.) of error, and

$$n_e = \frac{\text{No. of experiments}}{1 + \text{Sum of d.f. of significant factors and interactions}}$$

Because these calculated values are from the S/N ratio, the expected number of defects per frame is given by antilog$(-\mu_{opt}/10)$ = 0.5881. In terms of ppm, the expected

Table 4. ANOVA Table for First Experiment

SOURCE	D.F.	S.S.	M.S.	ρ%
A	1	24.69497	24.69497	13.06
B	2	40.55802	20.27901	21.01
C	2	0.83127	0.41563	
D	2	13.17662	6.58831	5.19
E	2	17.92107	8.96053	7.94
F	2	15.73681	7.86840	6.67
G	2	37.90738	18.95369	19.48
A × B	2	14.74560	7.37280	6.10
Pooled error	4	8.36890	2.09222	
Total	17	173.10937		

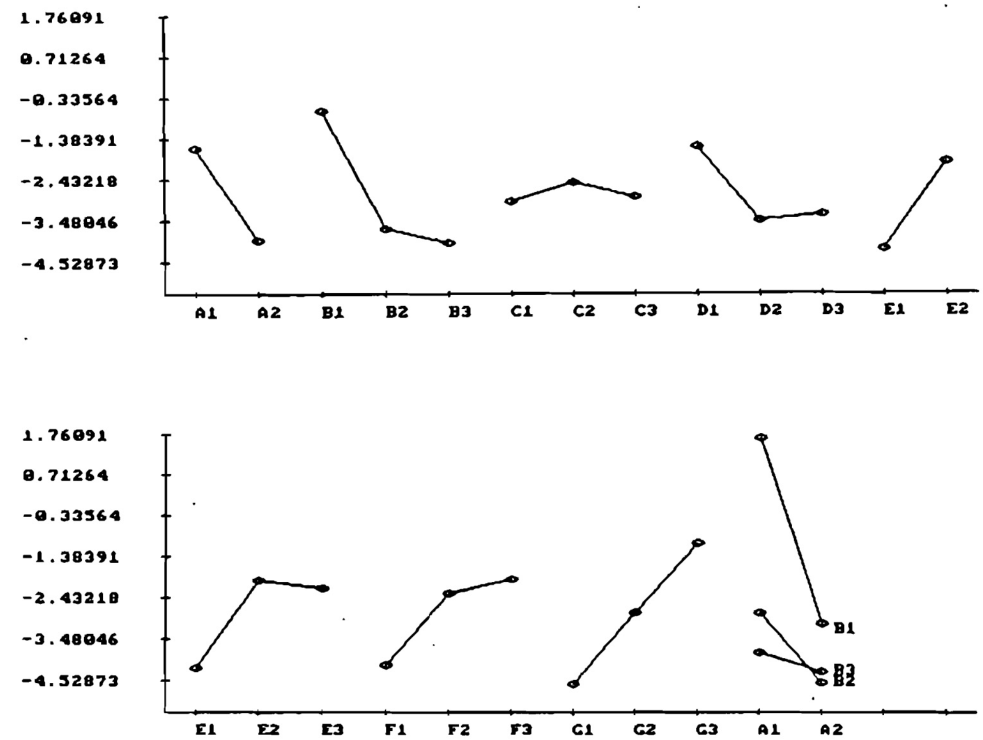

Figure 2. Average response curve for the first experiment.

Table 5. Optimum Levels of Factors

SL. NO.	FACTOR	OPTIMUM LEVEL
1	Bath temperature	248°C
2	Wave height	4.38
3	Overhead preheater	360°C
4	Preheater-2	340°C
5	Preheater-1	360°C
6	Air knife	6
7	Omega	4

defect level is 1670. The 95% confidence interval corresponding to the expected number of defects is (0.1639, 2.1092) in terms of proportion and (465, 5992) in terms of ppm.

Because the predicted average and the result of the confirmatory trial were not sufficient for eliminating the inspection stage, it was decided to conduct further experiments for reducing the defects.

Further Experimentation

It was concluded from the brainstorming that for the march toward an inspectionless process, more experimentation is required. Hence, the next experiment was designed by considering the feedback from the first experiment and considering some of the uncontrollable (noise) factors. The least significant factors (viz. temperatures of preheater-2 and the overhead preheater) were kept fixed. Also, the boards in the panel were not symmetric with respect to the direction of feeding. Hence, in addition to the old factors, the direction of the feeding of the panel with two levels (forward and reverse) was also considered as one factor. The different levels of the significant factors from the first experiment were selected in such a way that the new levels were allowed to vary around the optimum level of first experiment. The controllable factors and their selected levels are given in Table 6.

The fixed factors and their specifications were conveyor speed of 1.50 m/min, conveyor angle of 6.05°, temperature of preheater-2 of 340°C, and temperature of the overhead preheater of 360°C.

The flux used for cleaning the panels was an isopropyl

Table 6. Factors and Levels of Controllable Factors

FACTOR	CODE	LEVEL 1	2	3
Direction of panel	A	Forward	Reverse	—
Bath temperature (°C)	B	242	248	254
Wave height	C	4.34	4.38	4.42
Omega	D	3	5	7
Preheater-1 (°C)	E	350	360	370
Air knife	F	4	6	8

Table 7. Noise Factors and Levels

FACTOR	CODE	LEVEL 1	2	3
Acid number	X	16	20	24
Production rate	Y	Low	High	—
Frame	Z	F1[a]	F2	—

[a]F1 = the frames from the first lot; F2 = the frames from the second lot.

alcohol-based chemical, and on exposure to atmosphere, the solid content of the flux (i.e., acid number) increased. The company was not interested in accurately controlling the acid number for the purpose of production because of real-time continuous variation of the parameter. Hence, during this experiment it was decided to consider the acid number as a noise factor with three levels. Even though the quantity of production each month is approximately constant, the production rate may vary from day to day due to operational reasons. By considering this, the production rate was selected as a noise factor with two levels: high and low. Also, the metallic frames used for feeding the panels came from two different lots. Because of the suspected alignment in the two lots of frames, they were also considered as noise. An outer array was constructed with these three noise factors [viz. acid number (X), production rate (Y), and frame (Z)]; see Table 7. A full factorial experiment, $3^1 \times 2^2$, was used for the outer array.

The orthogonal array L_{18} $(2^1 \times 3^7)$ was used as the inner array for experimentation. The response in the experiment was decided as the number of defective solder joints in *three frames*. Each of the 18 experiments was conducted at all the 12 combinations of the noise factors. The collected data along with the physical layout are shown in Table 8. As before, ANOVA was performed on the data by taking the S/N ratio.

From Table 9, it was found that except for the air knife (F), all factors had a significant effect on the response. Of the significant factors, the contribution percentage for the factor direction of frame was found to be 83.31%. Level 1 of factors A, B, C, and D and level 3 of factor E were found to give better results. (See Fig. 3.)

After finding the optimum levels from the second experiment (Table 10), the technical personnel of the process noticed some problems regarding the backflow of the solder bath. For good solderability, the "dross" (i.e., lead oxide) has to be removed from the solder pot. The accumulation of dross is possible only when there is no backflow of solder bath. Hence, the company contacted a technical expert for adjusting the backflow. During repair, it was found that the seating of one of the plates was not proper inside the solder bath. Because of the improper seating of that plate, it was required to pump the molten lead with a high rpm for getting a specified wave height. Hence, after adjusting the plate at the proper position, it required only 4.13 rpm instead of 4.34 rpm, which was used earlier, for getting a solder wave of the same height. Therefore, after the adjustment, the 4.13 wave height was used instead of 4.34 in the optimum combination. One more experiment was conducted in the wave soldering process for accurately adjusting the influencing parameters. The factors selected for this experiment were conveyor speed, wave height, preheater-1 temperature, and omega. The selected factors and the respective levels are given in Table 11.

The fixed factors and their specifications are a conveyor angle of 6.05°, temperature of the overhead preheater of 360°C, temperature of preheater-2 of 340°C, and air knife = 6.

The orthogonal array L_{18} $(2^1 \times 3^7)$ was used for experimentation. The response was decided as the proportion of defective solder joints in three frames. This is because during this experiment, due to rejections at vendor side, some of the boards were removed from the panels. Hence, panels used in this experiment had different numbers of boards (viz. 6, 7, and 8). Because the data are in the form of proportions, the variance stabilization transformation $\sin^{-1}(\sqrt{p})$ was taken for ANOVA analysis. The ANOVA table is given in Table 12.

Factors A and B (i.e., conveyor speed and wave height) were found to be statistically significant. Level 3 of the conveyor speed (1.55 m/min) and level 1 of the wave height (4.10) were found to give better results (refer to Fig. 4). Prediction was done by considering the significant factors. The expected ppm at the optimum level was 247 and the 95% confidence interval was estimated as (0, 1410).

Table 8. Data Corresponding to the Second Experiment

	CONTROL FACTORS						NOISE FACTORS											
EXP. NO.	(1) DIRECTION	(2) BATH TEMP. (°C)	(3) WAVE HEIGHT	(4) OMEGA	(5) PH-1 (°C)	(6) AIR KNIFE	16 L F1	16 L F2	16 H F1	16 H F2	20 L F1	20 L F2	20 H F1	20 H F2	24 L F1	24 L F2	24 H F1	24 H F2
1	F	242	4.34	3	350	4	3	0	2	0	4	2	1	1	1	1	2	1
2	F	242	4.38	5	360	6	4	2	5	4	3	1	2	4	4	0	6	3
3	F	242	4.42	7	370	8	5	5	2	4	3	1	1	4	9	1	1	2
4	F	248	4.34	3	360	6	1	3	1	2	0	6	4	1	4	3	6	3
5	F	248	4.38	5	370	8	7	3	3	3	2	4	2	1	8	1	4	2
6	F	248	4.42	7	350	4	7	3	9	1	14	3	2	3	5	3	4	3
7	F	254	4.34	5	350	8	5	2	6	2	11	11	2	7	10	1	3	3
8	F	254	4.38	7	360	4	5	2	5	4	8	7	12	8	6	10	8	6
9	F	254	4.42	3	370	6	4	3	1	5	6	2	9	2	5	3	16	5
10	R	242	4.34	7	370	6	18	6	14	11	20	9	18	13	16	7	10	4
11	R	242	4.38	3	350	8	15	11	16	4	32	11	28	9	12	16	8	5
12	R	242	4.42	5	360	4	28	23	28	7	19	22	30	19	23	10	21	22
13	R	248	4.34	5	370	4	24	9	19	9	21	18	15	11	6	11	8	9
14	R	248	4.38	7	350	6	21	20	27	26	37	8	13	23	11	15	12	10
15	R	248	4.42	3	360	8	29	24	31	24	34	14	25	13	5	15	12	13
16	R	254	4.34	7	360	8	41	21	26	27	22	22	25	19	18	8	15	16
17	R	254	4.38	3	370	4	34	28	28	18	19	23	19	28	15	8	17	20
18	R	254	4.42	5	350	6	35	37	35	32	39	18	43	31	23	26	21	7

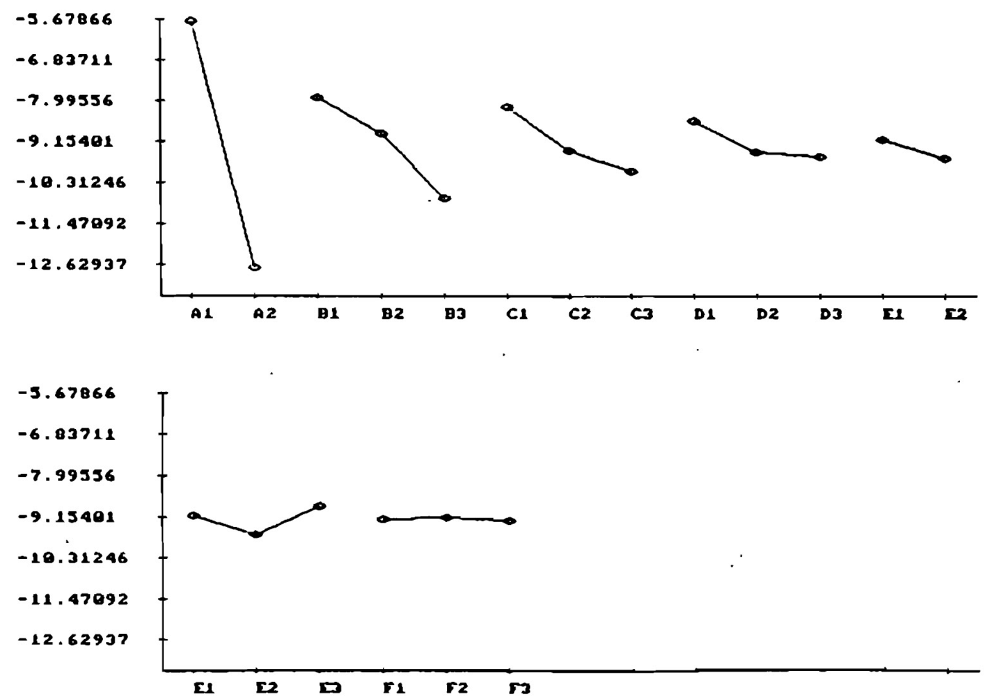

Figure 3. Average response curve for the second experiment.

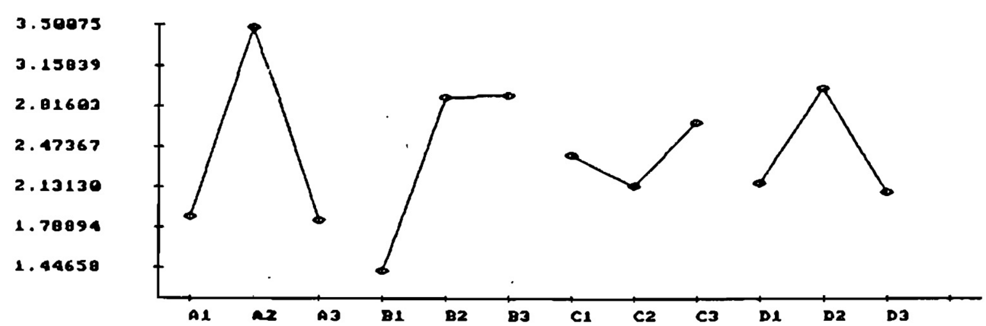

Figure 4. Average response curve for the third experiment.

Table 9. ANOVA Table for the Second Experiment

SOURCE	D.F.	S.S.	M.S.	ρ%
A	1	217.40569	217.40569	83.31
B	2	12.15032	6.07516	9.18
C	2	9.89582	4.94791	3.66
D	2	3.70693	1.85336	1.28
E	2	2.04173	1.02086	0.65
F	2	0.02299	0.01149	
A × B	2	2.31153	1.15576	0.75
Pooled error	6	1.07242	0.17874	1.17
Total	17	260.73487		

Table 10. Optimum Levels of Controllable Factors

SL. NO.	FACTOR	OPTIMUM LEVEL
1	Direction of frame	Forward
2	Bath temperature	242°C
3	Wave height	4.34
4	Omega	3.0
5	Preheater-1	370°C

Table 11. Factors and Levels for the Third Experiment

FACTOR	CODE	LEVEL 1	LEVEL 2	LEVEL 3
Conveyor speed (m/min)	A	1.45	1.50	1.55
Wave height	B	4.1	4.13	4.16
Preheater-1 (°C)	C	355	370	385
Omega	D	2.5	3.0	3.5

Table 12. ANOVA Table for the Third Experiment

SOURCE	D.F.	S.S.	M.S.	*F*
A	1	10.42745	5.21372	4.47050[a]
B	2	8.60651	4.30325	3.68982[a]
C	2	0.88001	0.44000	
D	2	2.85208	1.42604	1.22276
Pooled error	48	12.82879	1.16625	
Total	53	34.71483		

[a] Significant at the 5% level of significance.

Table 13. Optimum Levels of Factors

SL. NO.	FACTOR	OPTIMUM LEVEL
1	Conveyor speed	1.55 m/min
2	Bath temperature	242°C
3	Wave height	4.10
4	Overhead preheater	360°C
5	Prehaeter-2	340°C
6	Preheater-1	370°C
7	Air knife	6
8	Omega	3.5

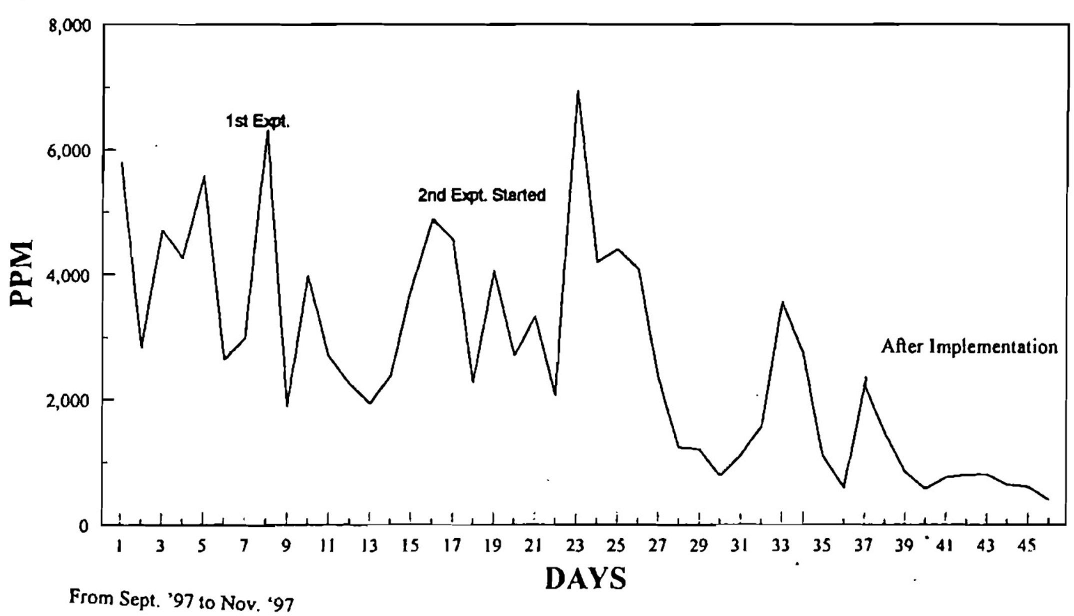

Chart 2. Wave soldering defect trend.

Results

The optimum levels of different factors obtained from the sequence of experimentation are given in Table 13.

Implementation

The optimum factor level combinations obtained from the experiment were implemented with immediate effect. Chart 2 shows the ppm level for different days; before, during, and after the experimentation.

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