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# Experimental Design – An Experience to Optimize a Soldering Process

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# Experimental Design: An Experience to Optimize a Soldering Process

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***Abstract***

This report explains an application of experimental design in a factory which had no previous experience in this area, although some of its technicians had some information about it. We focus our attention to initial steps of the experimental design process, emphasizing the importance of detailed planning to run experiments, and to run it carefully in a planned way.

# 1. BACKGROUND: APPROACH TO THE NECESSITY

The experiment was done in a factory belonging to a multinational company near Barcelona which makes trains, including high-speed ones. To increase productivity, they bought an automatic process machine ('robot') to make the solders in the chassis of the train.

Because of the soldering process and material to solder was quite specific, it was necessary to run a lot of experiments to optimize the parameters of the process. Although people in charge of the experimentation had an excellent background in solder processing, their background in experimental design was minimal and the experiments were run without accurate planning and changing one variable at a time. After these experiments, the process was started and the production was good in general. However, it was difficult to explain some of the results which appeared contradictory to the results of the initial experiments. This made the people in charge of the process very insecure. Actually, they were not absolutely sure about their conclusions from the experimentation process and were afraid that they might face some unexpected problems. Therefore, the issue was how to obtain knowledge about the conditions which would lead always and without surprises, to a perfect solder.

Because some people, including the Quality Manager, had some knowledge about experimental design techniques, they thought that this was an excellent opportunity to introduce this practice in the factory. The objectives were:

1) To clarify the performance of the soldering process through a well designed and well running experimental plan, and
2) To introduce experimental design to the factory technicians in order to utilize it in future opportunities.

Thus the company got in touch with the Department of Statistics and Operation Research from the Universitat Politècnica de Catalunya (UPC), which has experience in advising companies for quality control and improvement.

## 2. MAKING A TEAM: WHAT DO WE KNOW?

Our first step was to create a team with people concerned in any way with the problem. The team included the Quality Manager himself, the person in charge of the solder processing (another direct collaborator of him), a person from the Quality Department related to the problem under study, the person in charge of the metrology laboratory, a professor from UPC and a student also from UPC with a practice agreement in the company. The student's presence was very useful to follow closely all the details of the planning of experimentation.

Initially, we always follow the rule of documenting in our problem solving efforts the important available process knowledge, with the help of the team members. This practice has some advantages, like:

- It forces one to think about the aspects of the process that are really known, making a difference between assumptions or intuitions, from the real knowledge adequately verified.
- It avoids communication problems among the members of the work team. It is necessary to avoid devoting time and effort to 'discover' aspects that are already known, or to consider sure things that perhaps aren't there.
- It permits one to value the success or failure of the experimental plan. It is not unusual that someone familiar with the process had an intuition about the result. However, it is one thing to have an intuition and another to actually know the result. If some final conclusion isn't in this initial report, this is new knowledge.

In our case, this initial report had the following sections: theoretical knowledge of solder processing, the current way of production (procedures, parameters, results); quality attribute desirables and variables that can influence quality attributes.

## 3. RESPONSES SELECTION AND ITS MESAUREMENT

The team agreed that the quality of the solder can be summarized by the following characteristics:

Mechanical: Shearing strength resistance, larger is the better

Resistance to the traction, larger is the better

Hardness in the solder point and in the area thermally affected. Smaller is better in both areas, since the hardness implicates fragility.

Measuring: Button's diameter, lower is better.

Imprint of the button, lower is better.

Internal defects: Incomplete solder

Porosity and fissures

Figure 1 summarizes some aspects related to two plates with spot welding.

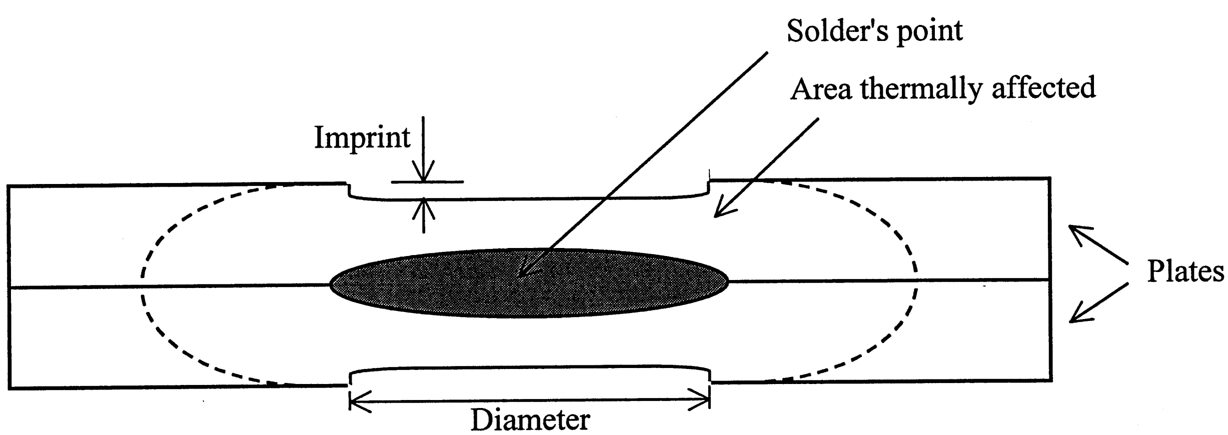



Figure 1: Plates with spot welding

For the measurement of these responses, three (3) test pieces are necessary:

1) For the shearing strength resistance (plates solder in parallel and is a destructive test);
2) For the resistance to the traction (plates solder in cross and is also a destructive test); and
3) For the dimensional characteristics (Button's diameter and imprint), the hardness in the solder point and in the area thermally affected, and the internal defects (plates solder in parallel, which are cut to measure the hardness and afterwards receive a special treatment to identify the internal defects).

## 4. VARIABLES SELECTION

### Possible variables which affect some of the responses

After two meetings altogether, and some individual discussions with the team's members, we arrived at the following variables which probably affected some of the responses.

**Surface condition**: A very smoothly painted surface would make it difficult to pass the electricity from one plate to another. A rough surface allows the microcontacts from one plate to flow to the other through the painting which makes it easy to pass the electricity to obtain a good solder.

**Painting**: There are two kinds of painting. The first is a shop primer, to guarantee for 2 or 3 months that the chassis in the shop floor is protected against environmental humidity. The other is an anti-rust painting to protect the plate definitively. Both paintings must be good electrical conductors. The conductivity depends on the concentration of some components in both paintings.

**Pincers**: The robot manufacturer supplies also the pincers. According to the manufacturer, the robot takes into account the type of pincer that is placed in, in order to adjust the system to avoid possible influences of the pincer's geometry. But, among the people in charge of the process, there were doubts about the possible existence of a "pincer effect".

**Electrodes**: There are electrodes with different shapes (spherical, cylindrical-conic) and diameters. It is possible that the electrode type influences the geometry of the solder's button.

**Materials**: They had planned to work with 3 types of steel (S355, S275 and S235) and 6 different thicknesses (1.5, 2.0, 2.5, 3.0 and 4.0 mm). The optimum conditions of soldering depend on the type of steel and the thickness.

**Pressure**: The pressure performed by the electrodes on the plates was considered an important factor.

**Intensity-Time curve (I-t curve)**: The I-t curve was considered as the most characteristic and the most important factor in the solder processing. It represents the intensity (in kA) which is passed through the plates throughout the time (in periods) that go on during the solder process. People in charge of the process, after a detailed study of the standard procedures and technical reports about this topic, had represented the soldering process by the following steps:

- Preheating: To burn the painting and heat the plates
- Soldering: After preheating, the intensity rises during a time 'x' until a certain value
- Annealing: After soldering, and after a certain time 'y' without a current, pass the current another time in order to obtain good metallurgy conditions.

These steps are represented in Figure 2.

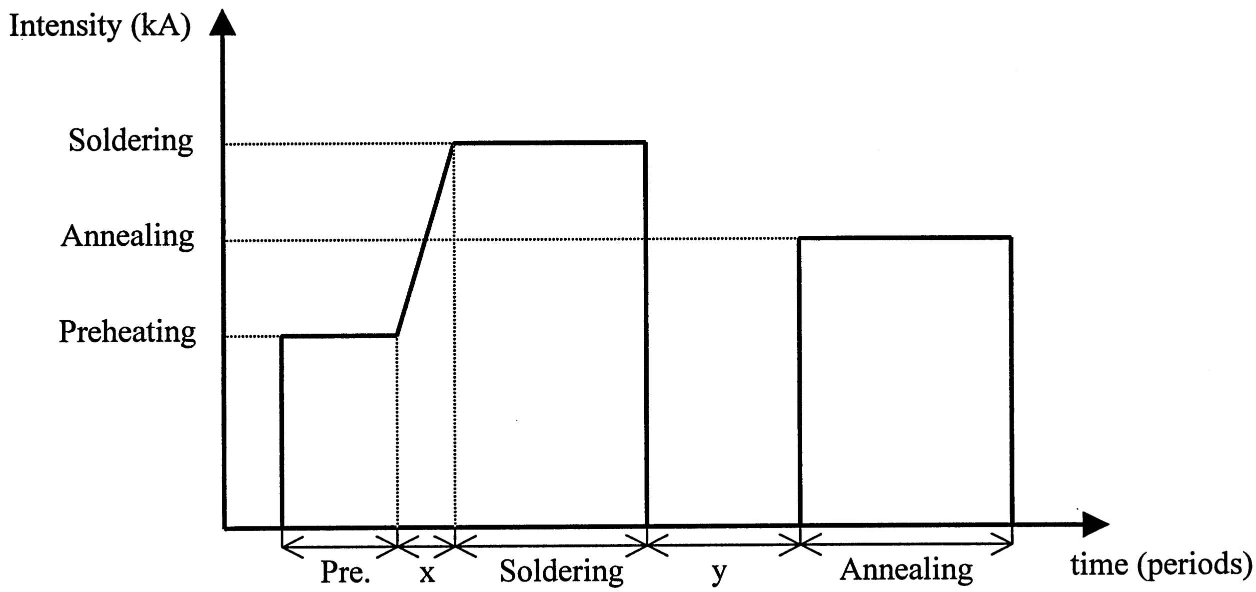



Figure 2: Steps in the soldering process

**Selection of variables to experiment**

It was evident that we could not experiment with all the variables. It was necessary therefore to select only a few of these possible variables.

There was a general agreement regarding surface conditions. Although in theory there were several possibilities, in practice, due to the possibilities of the suppliers, the specificity of the material and the process, we decided that the best (and perhaps the only possible in practice) was the one that they were already utilizing called pickling.

We had a long discussion regarding painting. There were several factors related to the painting, like the proportion of some components in both types (shop primer and anti-rust) and also the thickness of both coats. The painting process was manual and hence there was a lot of variability in thickness. Initially, the team was considering thickness of the coat as a noise factor, but there was a lot of difficulties to change the standard composition, which was already good enough. Finally we decided to use the normal composition of the painting. As for the thickness we decided to paint the plates with the normal procedure, but trying to use a thickness in the upper extreme of the variation interval, since these were the most unfavorable conditions.

Regarding pincers, we decided to use two types to experiment. We selected the two pincers that were used more often which also had a very different geometry. With regard to the electrodes, we decided to continue using which were used before, because our discussion led to the conclusion that these electrodes performed satisfactorily.

We decided to experiment with the two couples of thickness and material which were used often: 2.5mm(S355)+2.5mm(S275) and 1.5mm(S235)+4.0(S355). The quantity in parenthesis indicates the material, but for simplicity we write 2.5+2.5 and 1.5+4.0.

It was considered necessary to experiment with pressure but we decided also to change the name from pressure to force, because actually we are referring to a force.

And finally we confronted the I-t curve. All people considered that this curve was very important in the performance of soldering. But actually this curve was more than a simple variable and was necessary to decide how to incorporate it in the experimentation. The technicians considered that the shape of the curve was correct, and also the values of the times 'x' and 'y'. Therefore, the decision was to characterize the curve by six parameters: preheating intensity, preheating time, soldering intensity, soldering time, annealing intensity and annealing time.

*Adequate selection of the variables to the experimentation is critical for the success of the plan, and it is very important to lead the work team adequately in order to achieve a consensus taking account of all the experience and knowledge of the team.*

## 5. EXPERIMENTAL DESIGN

After some discussion we decided that the best option was to run two fractional factorial experiments each with 8 factors in 32 runs ($2^{8-3}$), one for the 2.5+2.5 plates and another for the 1.5+4.0. The $2^{8-3}$ is a resolution IV design using the generators:

F = ABC; G = ABD; H = BCDE where A,B,C,D,E,F,G,H represent the factors.

This produces the following confounding:

AB = CF = DG; AC = BF; AD = BG; AF = BC; AG = BD; CD = FG; CG = DF

We divided the variables into four groups using technical knowledge:

1. Force and pincers
2. Preheating intensity and preheating time
3. Soldering intensity and soldering time
4. Annealing intensity and annealing time

The first group of variables can interact with any other. For the other groups, a priori we considered that the variables can interact inside its group, but the interactions between groups 2, 3 and 4 were not probable.

In order to avoid confounding of 2 factor interactions that were considered potentially important, we assigned the following labels to factors:

| | | | | | |
|---|---|---|---|---|---|
| 1 | E: | Pincer | 3 | A: | Soldering Intensity |
| | H: | Force | | C: | Soldering Time |
| 2 | F: | Preheating Intensity | 4 | B: | Annealing Intensity |
| | G: | Preheating Time | | D: | Annealing Time |

In addition to the 64 runs in the 2 experiments we also decided to take 2 runs under the current conditions. So, the number of solders was:

$$(32 + 2) \times 3 \times 2 = 204 \text{ solders}$$

| $2^{8-3}$ | current conditions | plates test by run | type of plate |
|---|---|---|---|

This number was considered reasonable by the team and others.

## 6. LEVELS SELECTION

For the pincers, we decided to test with the two most often used (and what was quite different). For the quantitative factors (all the others) the criterion was to establish the experimental levels around the current values.

It was not easy to decide by the technicians how much the fork should be open. Our advice, as usual in statistics, was only that the levels must be far enough to distinguish the possible effect of the factors from experimental noise, and near enough to consider the linearity of the response between the two levels acceptable. The final decision was, of course, a technical one.

## 7. PREPARATORY TASKS BEFORE RUNNING THE EXPERIMENTS

At this point, we may think that the mission of the conductor of this plan is only to wait to have the results of the experiments. We consider this to be a serious mistake. It is necessary to plan carefully the conduct of the experiments to assure success of the plan. In the following sections we describe some aspects that were consider important, and in the appendix we show a diagram similar to what was done to plan the activities before and after the experimentation.

**Calibration of measurement instruments**

It was necessary to be sure that the value of the factors in each experiment was actually the value which it was supposed to be. In the robot, it was possible to program the work conditions, but it was not sure that in fact the real values were the programmed ones. To measure the real force in the pincers, it was necessary to use a special device which was calibrated adequately. There were also doubts about how to measure intensity. After the calibration of the ammeter included in the robot, to be sure about the intensity that actually passed, we planned to use another ammeter, with more accuracy than the one included in the robot, to measure the intensity with both ammeters.

**Preparation of the material and the experimentation process**

It was necessary to get the plates ready, painted in the way commented with both types of paint (shop primer and anti-rust) with thickness values in the higher end of the usual range of variability. Also, it was necessary to mark an identification number with a permanent marking-pen for each one.

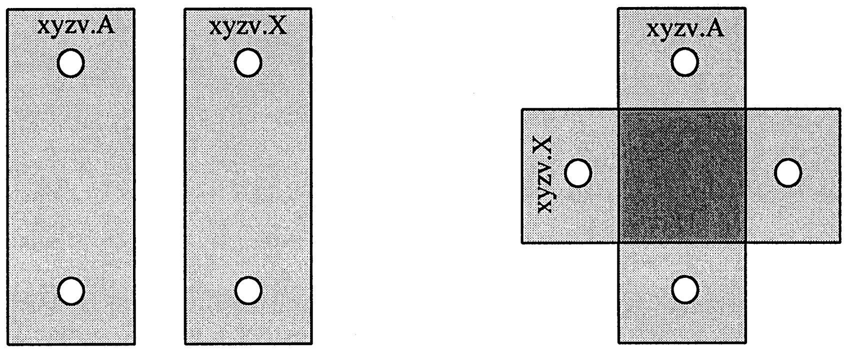
The plates which were to be prepared are listed in Table 1.

Table 1: Plates prepared for the experiment

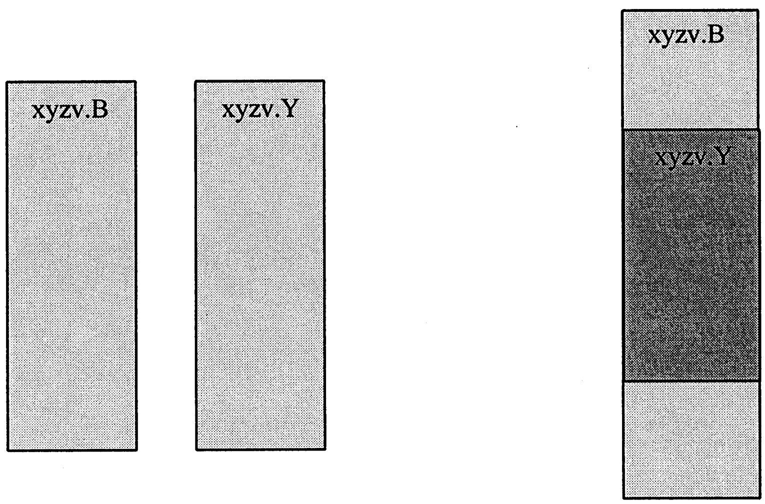
| Quantity | Steel | Thickness | Size | Notes | Identification Number |
|---|---|---|---|---|---|
| 34 | S355 | 2.5 | 50 x 150 | With holes | 1000.X → 1033.X |
| 34 | S355 | 2.5 | 140 x 60 | | 1000.Y → 1033.Y |
| 34 | S355 | 2.5 | 60 x 60 | | 1000.Z → 1033.Z |
| 34 | S355 | 4.0 | 50 x 150 | With holes | 2000.X → 2033.X |
| 34 | S355 | 4.0 | 140 x 60 | | 2000.Y → 1033.Y |
| 34 | S355 | 4.0 | 60 x 60 | | 2000.Z → 2033.Z |
| 34 | S275 | 2.5 | 50 x 150 | With holes | 1000.A → 1033.A |
| 34 | S275 | 2.5 | 140 x 60 | | 1000.B → 1033.B |
| 34 | S275 | 2.5 | 60 x 60 | | 1000.C → 1033.C |
| 34 | S235 | 1.5 | 50 x 150 | With holes | 2000.A → 2033.A |
| 34 | S235 | 1.5 | 140 x 60 | | 2000.B → 2033.B |
| 34 | S235 | 1.5 | 60 x 60 | | 2000.C → 2033.C |

The plates with an X in its identification number were soldered with the plates with an A. This set was destined to the tensile strength test. Similarly, plates with a Y were soldered with plates with a B to do the shearing strength test, and plates with a Z were soldered with plates with a C to do the cut to measure the hardness. The shape of the plates was indicated by internationally accepted standards procedures. The technician considered that the results with these test pieces could be considered similar to the results obtained in normal production. Figure 3 shows schematically the plates' shape.

Plates for the tensile strength test, before and after the soldering. Both plates have the same number ('xyxv') but one has the letter A and the other letter X.




Plates for the shearing strength test. Same number but letter B and Y.




Plates to measure the hardness and internal defects. Same number but letters C and Z.

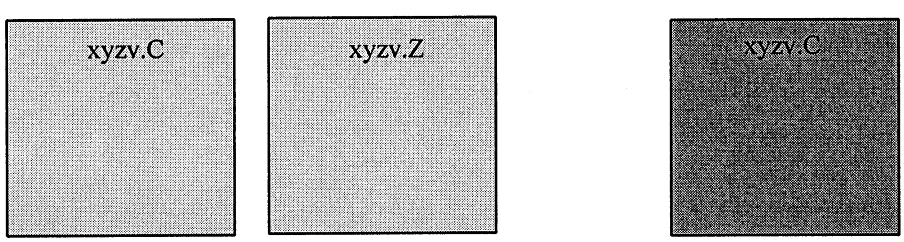



Figure 3: Plates' shape

## Organization of the experimentation process

To avoid confusion, and/or waste time during experimentation, we prepared some spreadsheets to manage the test pieces, the solders programs and also to identify the experiment with the results obtained in each condition. Full randomization of the order of experimentation would have dedicated a lot of time to change the pincers and the programs. We considered the advantages and the inconvenience of the possible alternatives and decided to run a partial randomization with 68 program changes and 4 pincer changes. The solders arrangements were as shown in Table 2.

Table 2: Solders arrangements

| Run | Test piece 1 | Test piece 2 | Program | Pincer | Assembly | Use |
|---|---|---|---|---|---|---|
| 1 | 1000.X | 1000.A | 1000 | P3 | Cross-shaped | Tensile strength test |
| 2 | 1000.Y | 1000.B | 1000 | P3 | Overlap | Shearing strength test |
| 3 | 1000.Z | 1000.C | 1000 | P3 | In parallel | To cut |
| Change of program | | | | | | |
| 4 | 1001.X | 1001.A | 1001 | P3 | Cross-shaped | Tensile strength test |
| 5 | 1001.Y | 1001.B | 1001 | P3 | Overlap 45 mm | Shearing strength test |
| 6 | 1001.Z | 1001.C | 1001 | P3 | In parallel | To cut |
| Change of program | | | | | | |
| ... | ... | ... | ... | ... | ... | ... |
| 51 | 1016.Z | 1016.C | 1016 | P3 | In parallel | To cut |
| Change of pincer and program | | | | | | |
| 52 | 1017.X | 1017.A | 1017 | P12 | Cross-shaped | Tensile strength test |
| ... | ... | ... | ... | ... | ... | ... |
| ... | ... | ... | ... | ... | ... | ... |
| 204 | 2033.Z | 2033.C | 2033 | P12 | In parallel | To cut |

**When to run the experiments?: Calendar**

As in general when the experiments must be done in a normal process operating mode, to find an appropriate day to run wasn't easy. At first, an idea was to use the time out in the normal operation of the process. This possibility had the advantage that the process would not be tied up due to experimentation and the people in charge of production liked that; but this had the inconvenience that it was very difficult to secure the safe running of the experiment with necessary care.

The choice of stopping production and running the experiments was discarded because of the necessity of making the planned production. Putting aside the preceding possibilities, the only option was to run the experiments on a holiday day. This option was not easy to carry out, but we were able to solve some of the difficulties and finally were able to experiment on a Saturday.

## 8. RUNNING THE EXPERIMENTS

On the "D-day" almost all the team members were present together with two operators well trained about the experimentation process. All people had different tasks assigned in order to be sure that everything was going well.

To make the solders, we followed the planning summarized in Table 2. We also registered, in appropriate data sheets previously prepared, all the aspects that we had considered relevant, like the real intensity in each step of the soldering process measured with two ammeters and the existence or not of sparks during the soldering process.

*The clear ideas about the experimentation process, and the good atmosphere among the work team and also with the operators, made easy, and even pleasant, this time of experimentation. It's very important to run the experiments just as have planned and to enter all the relevant information. If the data are inaccurate or incomplete it is very difficult - or impossible - to get correct conclusions.*

## 9. ANALYSIS OF THE CURRENTS

Once the experimentation was over, we analyzed the information that was picked up during the experimentation. We were especially interested in the analysis of the currents and actually we had some surprises.

### Ammeter Bosch versus Ammeter Miyachi

The relation between the two ammeters is summarized in Figure 4. The doted lines are at ±1.5 kA. So, with some exceptions for which we can't find any special cause, measurement Bosch (normally used with the robot) = measurement Miyachi (a more precise one) ±1.5 kA.

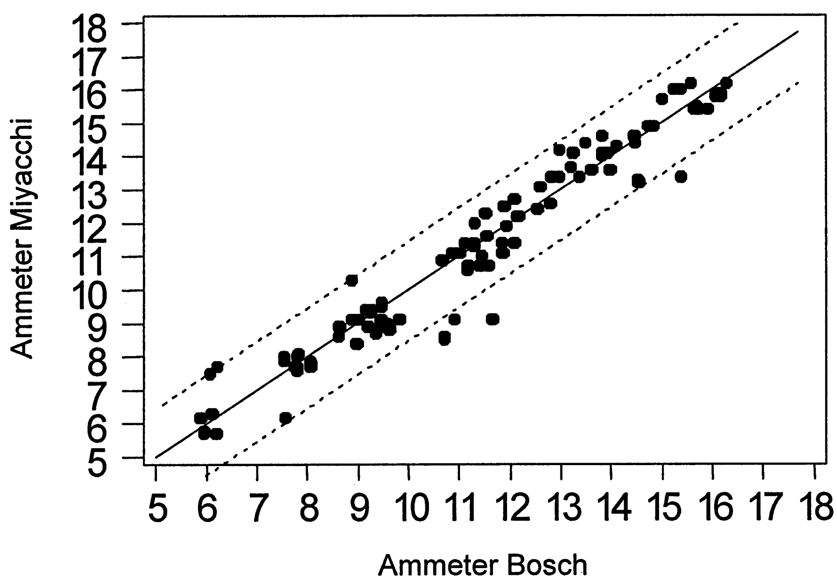



Figure 4: Measurement in Ammeter Miyachi vs. Ammeter Bosch

Therefore we have a measurement error of the order of 1.5 kA. This error was unknown and was not taken into account to fix the values for the currents.

**Current programmed versus current that actually passed**

The more surprising result was to discover important differences between the programmed intensities in the robot's central panel and the real ones. Figure 5 shows the real current intensity in the soldering step measured by the Miyachi ammeter whereas the programmed values were 14 and 17 kA. Similar differences were found for the preheating and annealing currents as well.

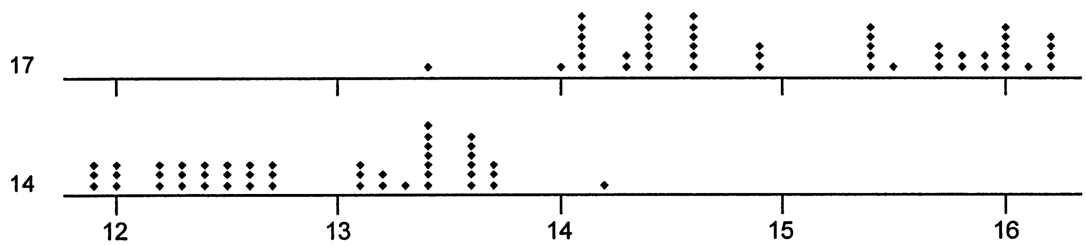



Figure 5: Real currents in the soldering step. The levels "fixed" were 14 and 17 kA

**What were the causes of the current variability?**

The way we took and entered the data, allowed us to compare the current as a function of the other factors, and we discovered that the intensity of the currents was a function of the pass time, as shown in Figure 6.

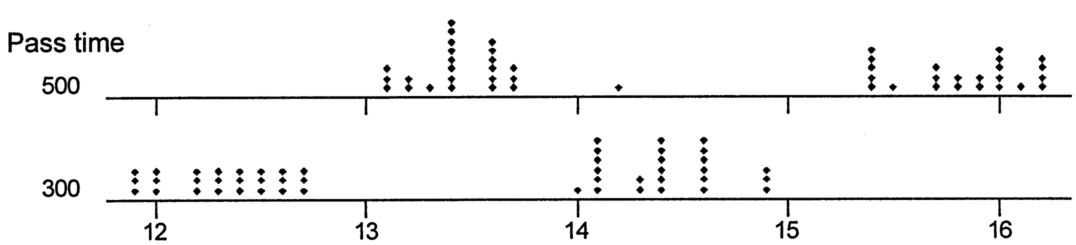



Figure 6: Soldering intensity by soldering time

This phenomena, probably due (according to the technician) to the way in which high currents are measured in a very short time, hadn't been taken into account until that time. We also could observe that the pincers also affected the current, as shown in Figure 7 for the annealing current.

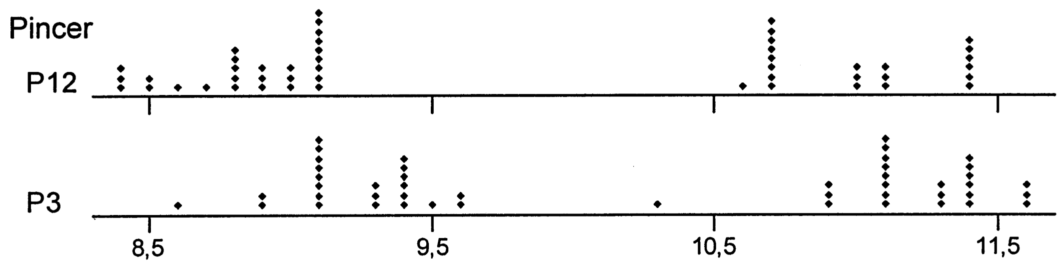



Figure 7: Annealing current by type of pincer

**Spark**

At the time of soldering it is undesirable to have sparks because (according to the technicians) this produces loss of material particles which may result in a decrease of the soldering resistance. Moreover, the sparks shorten the electrode life.

We recorded whether there were sparks or not in each soldering, and the analysis of this data shows a relation between the soldering intensity and the existence of spark, as shown in Figure 8.

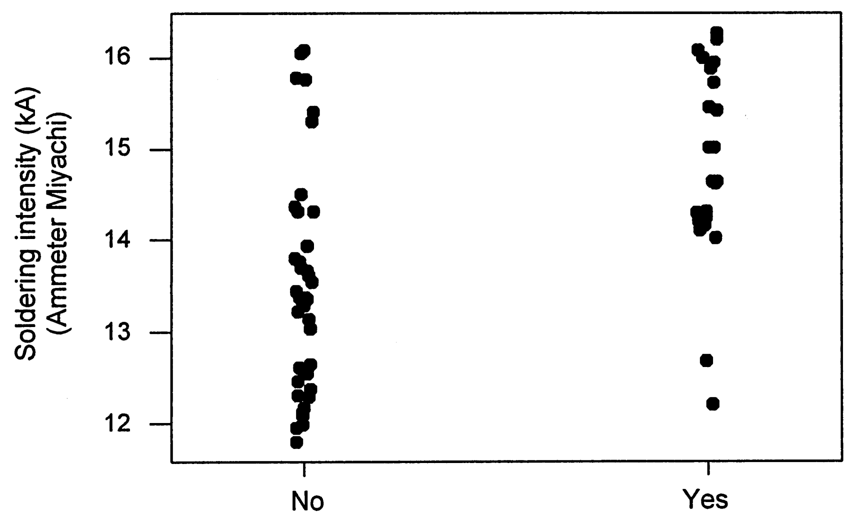



Figure 8: Presence of sparks in funtion of the soldering intensity

If the current of soldering is below 14 kA there are hardly any sparks. There are two anomalies for which we can't find any explanation.

## 10. MEASUREMENT OF THE RESULTS

Measurement of the results was also an operation which demanded time, effort and care. It was necessary to perform 68 traction tests, 68 shearing tests and 68 cuts to measure hardness. Although we had planned to do a microscopic analysis to each cut, this idea was discarded because of the time required and the little additional information that was expected.

All the results were entered into previously prepared spreadsheets and the data were ready to be analyzed.

## 11. FACTORS INFLUENCE OVER THE RESPONSES

The results were analyzed by regression using the real values measured for the currents and by the standard method used to calculate the effects in an orthogonal design. Actually, we did not find important differences between these two ways of analysis.

**Effect of paint thickness**

Although the paint thickness wasn't considered an experimental variable, we measured it in all the plates before soldering and we obtained a set of values which varied somewhat due to random causes. Then, we studied whether some of the responses may have any relation with the thickness of painting. We couldn't find any relationship between the responses and the painting thickness.

The operator who painted the plates knew that this was for a special test. A person from the team indicated that the variability of the painting thickness probably would be different if the operator knew that the painted plates would be studied and controlled, than in the normal process of painting. Obviously, he was right.

## 12. CONCLUSIONS AND ACTION PLAN

People in the team discovered the importance of carefully planned experimentation and the existence of strategies which are much better than changing one variable at a time.

The more important conclusions for 2.5+2.5 plates were[1]:

- Except in some extreme conditions, the resistance obtained went beyond the minimum values required;
- There is an important difference between the current measured by the ammeters and the programmed one;

- Increasing the soldering time, increases the shearing strength resistance, but also increases the button's diameter;
- To use a soldering current below 14 kA to avoid sparks; and
- Neither the preheating time, nor the annealing time, nor its intensities affect the responses within the studied intervals.

**Action Plan**

After this first experiment they planned some actions:

- To contact the robot's supplier to study and solve the difference between the programmed and the measured intensities.

- To continue experimentation for:
  - Reducing the soldering time
  - Minimizing wear in the electrodes
  - Obtaining a valid range to work with the studied factors

- To write a procedure to paint the plates in order to assure minimum variability in thickness.

**Final comment**

This experimentation project was part of the factory objectives for the first six months of 1998. Because of this, the team presented a brief concluding presentation to the direction team. The experiment was considered a success and the team was congratulated; the team also obtained **resources** to continue with their action plan, but now without any external permanent support, since it was no longer necessary.

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[1] For 1.5+4.0 conclusions were not identical but similar.

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**APPENDIX**: Diagram to plan some activities before and after the experimentation.

| Task | Person in charge | Schedule (week) 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|
| PLATES TEST PREPARATION | | | | | | | | | |
| Plates cut | | ■ | | | | | | | |
| Painted | | ■ | | | | | | | |
| Thickness measurement | | | ■ | | | | | | |
| DATA BASES PREPARATION | | | | | | | | | |
| Plates test identification | | ■ | | | | | | | |
| Solder programs | | ■ | | | | | | | |
| Results | | ■ | | | | | | | |
| PLATES TEST IDENTIFICATION | | | | | | | | | |
| Marked | | | | ■ | | | | | |
| Arrangement | | | | ■ | | | | | |
| LOGISTIC SOLDERING | | | | ■ | | | | | |
| ***SOLDERS' DAY*** | | | | | • | | | | |
| FIRST ANALYSIS | | | | | | ■ | | | |
| MEASUREMENTS 1 | | | | | | | | | |
| Tensile strength | | | | | | ■ | | | |
| Shearing strength | | | | | | | ■ | | |
| CUTS | | | | | | ■ | | | |
| MEASUREMENTS 2 | | | | | | | | | |
| Dimensions | | | | | | ■ | | | |
| Hardness | | | | | | ■ | | | |
| GLOBAL ANALYSIS | | | | | | | | | |
| Analysis | | | | | | | | ■ | |
| Report | | | | | | | | | ■ |
| PRESENTATION DIRECTION | | | | | | | | | |
| Preparation | | | | | | | | | |
| Presentation | | | | | | | | | |