CASE 69

Application of Mahalanobis Distance for the Automatic Inspection of Solder Joints

Abstract: In order to solve a problem with an appearance inspection of soldering using lasers, we applied the Mahalanobis–Taguchi system (MTS) to a soldering fine-pitch quad flat package (QFP) implementation process where erroneous judgment occurs quite often, and attempted to study (1) the selection of effective inspection logic and (2) the possibility of inspection using measurement results.

1. Introduction

Figure 1 illustrates the appearance of a QFP. The QFP studied in our research has 304 pins with a 0.5-mm pitch and is reflow soldered using tin–lead alloy solder paste onto a copper-foil circuit pattern on a glass epoxy board.

NLB-5000, laser inspection apparatus developed by Nagoya Electric Words Co. Ltd., was used. Figure 2 outlines this apparatus's basic principle of inspection. An He–Ne laser, following a prescribed route, is swept over a soldered area of an inspection subject. The solder forms a specific fillet shape whose angle changes the reflection angle of the laser. Since several receptor cells are located separately and independently, we can quantitatively capture the solder's shape according to changes in a laser swept over the solder's surface. Therefore, by using this inspection apparatus, we can grasp the entire shape, from the copper-foil pattern's end to the QFP lead's end in the form of sequential data for a resolution of the laser sweeping pitch. Calculating these sequential data in accordance with a particular inspection logic and comparing them with the judging standard, we can make a judgment as to a good or defective solder.

An example of sequential data is shown in Table 1. From left to right in the table, each sequence represents a periodic change of reflection angle when a laser is swept. A blank in the middle indicates the tip of a lead. Each numeral signifies an allocated value that corresponds uniquely to the angle of a solder's fillet. The larger it becomes, the more gentle the fillet's slope becomes, and conversely, the smaller, the steeper. The most gentle slope close to a flat surface is denoted by 6; the steepest is represented by 2. Therefore, a downward trend in a sequence indicates that a solder's fillet retains a concave shape. By analyzing the numerical order and magnitude of a sequence, we attempted to organize an appropriate inspection logic.

Figure 3 shows the cross section of a soldered area on a QFP lead, and Figure 4 shows good and defective soldering.

2. Collection of Normal and Abnormal Data

In an appearance inspection process of soldering in a mass production plant, based on a judgment result shown by an automated appearance inspection machine, a final inspector rechecks a product with an inspection tool such as a magnifying glass. When finding a true defect, he or she repairs it and passes it on to the next process.

From 11 QFP leads judged as defectives that had to be rechecked, selected from the boards produced

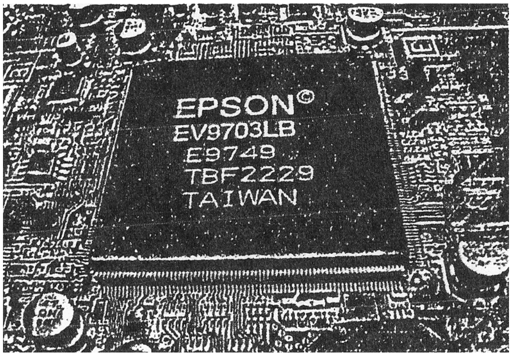


Figure 1
Appearance of QFP implementation

Table 1
Example of sequential data

No.	Data
1	666666666554443332 34466666
2	666666666554433322 34446666
⋮	⋮
n	66666666654433332 33466666

in one week and from randomly choosing 2670 QFP leads judged as normal, we measured a solder shape using automated laser appearance inspection apparatus. The pitch for sweeping a laser from the tip of a pattern to that of a lead was set at 20 μm.

In our research, since we assumed that normality and abnormality are discriminated properly, we verified the validity of discriminability by the bonding strength, which is the generic function required for soldering. Since the function required is the bonding strength after a product is shipped to market, bonding strength should be measured after a tem-

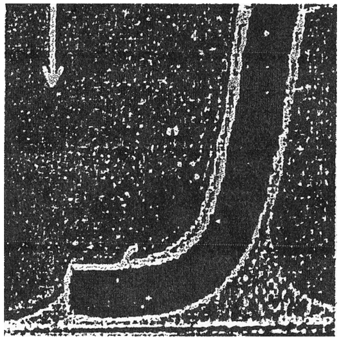


Figure 3
Cross section of soldering on QFP lead

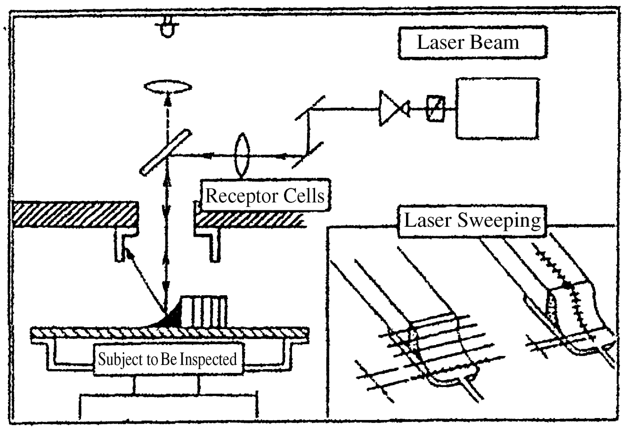
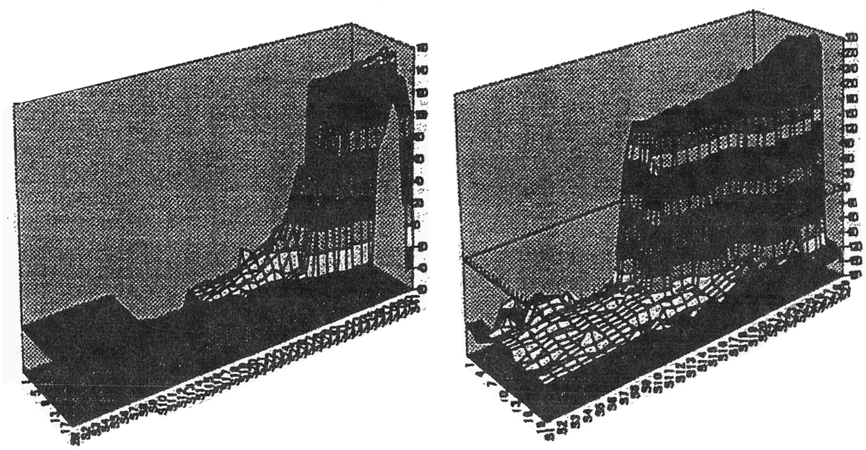


Figure 2
Basic principle of laser appearance inspection of soldering



(*a*) Good Soldering (*b*) Defective Soldering

Figure 4
Good and defective soldering

perature cycle test. But due to time constraints, we substituted initial bonding strength. As for a measuring method, after obtaining data for a soldering shape, using a pull tester supplied by Rhesca Co. Ltd., we measured the destructive tensile strength in the direction perpendicular to the surface of a circuit pattern on a board. For normal products, we measured 50 products randomly. All of the measurement results are shown in Figure 5. The clear-cut difference in bonding strength between normal and abnormal products proves good discriminability.

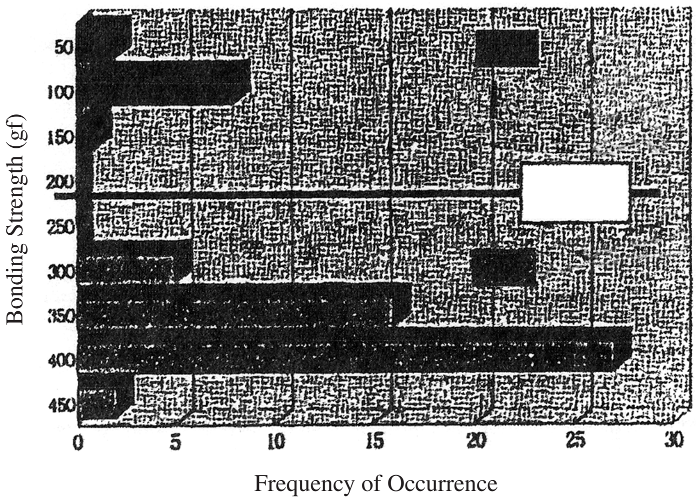


Figure 5
Bonding strength of normal and abnormal units

Table 2
Classification of inspection logic items

Category	Frequency	Used or Not Used for Standard Space
1. Item for base space	77	Use
2. Item with variance of zero	49	Do not use
3. Item with different value for normality and abnormality	3	Do not use
4. Item with character data mixed up	1	Do not use

3. MTS Method Using Inspection Logic Terms

After verifying 130 types of inspection logic from the data obtained, Y_{ij}'s, we categorized them into four groups and, as a result, used 77 items to create a base space (Table 2).

The findings that the three items can distinguish normality and abnormality indicate that a proper inspection can be performed only with them. However, considering that we need to develop an inspection method with more logic in order to enhance the validity of inspection for various defects, we decided to leave them for further study.

Table 3
Mahalanobis distances of normal and abnormal data

Normal Data				Abnormal Data,
Class	Frequency	Class	Frequency	Distance
0	0	5.5	4	37.09
0.5	267	6	1	28.24
1	1626	6.5	2	100.39
1.5	423	7	9	37.91
2	175	7.5	2	31.96
2.5	79	8	1	89.38
3	36	8.5	2	89.75
3.5	21	9	2	29.49
4	11	9.5	0	36.64
4.5	8	10	0	49.19
5	5	Next classes	5	25.17
Distances in next classes	29.20 10.12 11.92 12.69 10.39			

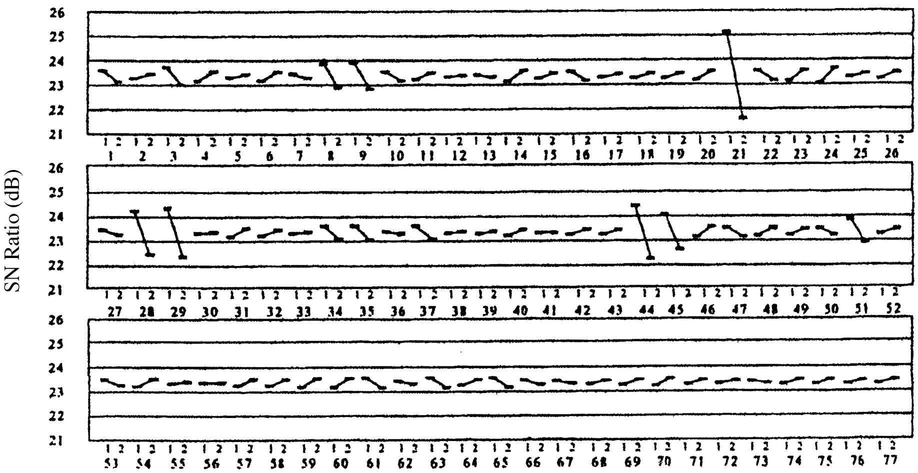


Figure 6
Response graphs of the SN ratio for inspection logic item

Table 3 shows the distribution of the Mahalanobis distances calculated. This table reveals high discriminability of normal data (proper products) and abnormal data (defective products) by the use of the 77 pieces of data as the base space. In the table, the bottom part in a longer middle column shows the distribution of higher classes.

In an actual inspection process, a smaller number of inspection logic items is desirable for a high-performance inspection, due to the shortened inspection time and simpler maintenance. Next, we verify whether we were able to select appropriate inspection logic items. The following is our verification procedure. Because of using the aforementioned 77 items, we took advantage of an L_{128} orthogonal array and allocated two levels, "use of an item" and "no use of an item," to this array to create a standard space.

As a next step, forming a base space for each row according to the orthogonal array, we calculated the distance for each abnormal data item from the corresponding base space. Defining as D_1, D_2, ... , D_n the square root of the Mahalanobis distance for each abnormal data in each row, we performed an evaluation with a larger-the-better SN ratio. For all 77 inspection logic items, Figure 6 shows the response graphs with the two levels "use of an item" and "no use of an item."

Each lower number below the x-axis in Figure 6 indicates each logic item, and each upper number represents use or no use (i.e., 1 for use of an item and 2 for no use of an item). Therefore, an item with a decreasing value from left to right was regarded as effective in an actual inspection, whereas an item with a contrary trend was considered to blunt the inspection accuracy (discriminability of normality and abnormality).

Analyzing these results with the criterion of a more-than-1-dB difference in the SN ratio, we se-

Table 4
Inspection logic items after selection

No.	Content of Inspection Logic
8	Convexity of tip in pad
9	Average height of solder
21	Degree of diffused reflection at the back of the swept laser
28	Circuit pattern's flatness 1
29	Circuit pattern's flatness 2
44	Roundness 1 of solder shape
45	Roundness 2 of solder shape
51	Convexity of solder shape

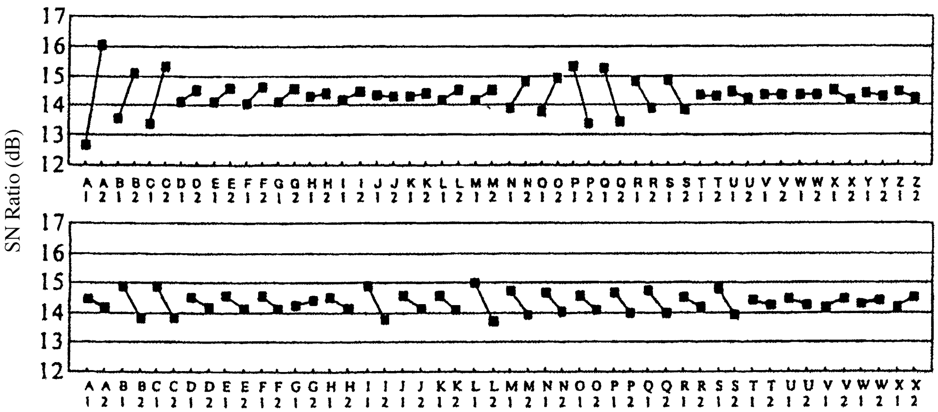
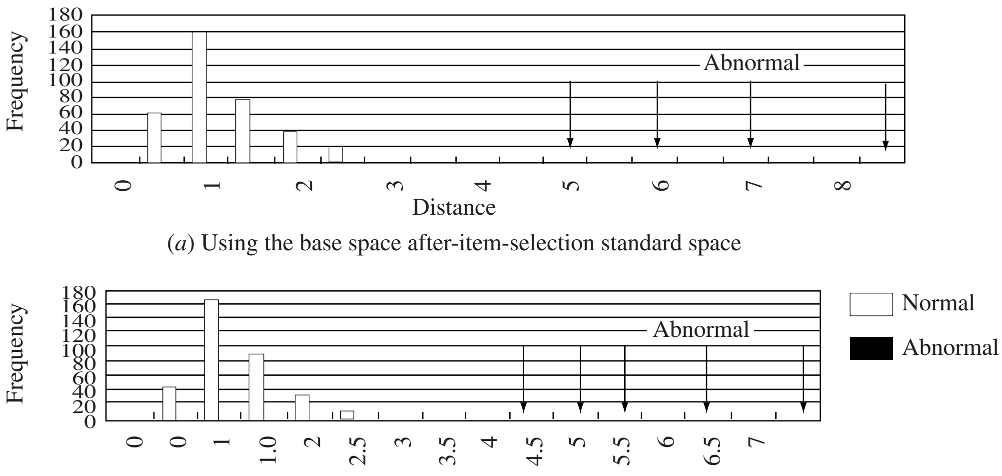


Figure 7
Response graphs of SN ratio by laser reflection data

lected extremely effective inspection logic items (Table 4). Since these items were selected from the 11 abnormal data obtained for our research, they do not reflect a whole diversity of defects that take place in an inspection process of a mass production line. However, together with three inspection logic items (height and length of a solder's fillet and convexity of a solder's shape) for category 3 in Table 2, they can be regarded as very important inspection logic items to identify abnormality.

Furthermore, using 30 inspection logics that are not necessarily considered to have no effect in Figure 6 (with decreasing value from left to right), we created a new base space and selected effective inspection logic items (selection 2) in a manner similar to the prior selection (selection 1). As a result,



(*a*) Using the base space after-item-selection standard space

(*b*) Using the base space before-item selection

Figure 8
Mahalanobis distances for normal and abnormal units

interestingly, some inspection logic that has been judged as extremely effective in selection 1 (e.g., inspection logic 28 and 29: circuit pattern's flatness) turned out to be ineffective.

4. MTS Method Using Reflection Data

Similar to inspection logic items, we obtained 350 normal and 9 abnormal sets of data for laser reflection in a mass production line. Each set of data consisted of 50 items with a 20-μm pitch in a total sweep length of 1000 μm. Using an L_{64} orthogonal array, items were selected in the same way as in the previous analysis. Figure 7 shows the response graphs.

These results demonstrate that laser reflection data as raw data also enabled us to select effective items. We created a base space using only 31 selected items (with decreasing value from left to right in Figure 7). Figure 8*a* shows the result of distances calculated for normal and abnormal data, and Figure 8*b* indicates the distances for normal and abnormal data in the base space formed with all 50 items before item selection.

According to these results, we can see that while the data in the after-item-selection base space are distributed somewhat broadly, the distance between the normal and abnormal data were sufficient for discrimination. Thus, we concluded that we could discriminate normality and abnormality by Mahalanobis distances using a base space created only with laser reflection data.

Reference

Akira Makabe, Kei Takada, and Hiroshi Yano, 1998. An application of the Mahalanobis distance for solder joint appearance automatic inspection. Presented at the Quality Engineering Forum Symposium, 1998. Japanese Standards Association.

This case study is contributed by Akira Makabe, Kei Takada, and Hiroshi Yano.