AJChE 2002, Vol. 2, No. 1, 97-106

Use of the Taguchi Design of Experiments to Optimize the Parameters of Cleaning Machines for Sensitive Plastic Products

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The Taguchi Design of Experiments (DOE), an optimization technique, was used to establish stabilized operating parameter settings for an ultrasonic cleaning machine for a new and very dirt sensitive plastic product referred to as type A plastic produced in a company in the Philippines. The optimization process is done in actual industrial setting. Taguchi DOE defined quality as minimum variation around the target specification of a product. The matrix used for the project is the L_8 2^7 orthogonal array wherein the experiment is comprised of eight runs with seven maximum possible factors at two levels. After each experimental run, the percentage rejection rate was monitored as the measurable characteristic of the finished product. Since rejection rate was the parameter used, the ultimate value closer to zero is better (the smaller the better). Confirmation runs showed that the percentage of rejection rate has improved from 62% to 17% when the established optimized machine parameters were used. Moreover, production yield has increased from 75% to more than 90% for product type A.

INTRODUCTION

The Taguchi Design of Experiment (DOE) was actually used to optimize the parameters of an ultrasonic cleaning machine used to clean a very sensitive plastic product referred to as type A special plastic manufactured by a company in the Philippines. To protect the trade secrets of the company, the company's name will not be mentioned as well as the names of the chemicals used and the actual description of the product. This paper describes the results of a successful optimization operation using the Taguchi techniques in an actual industrial operation setting. The optimization goal is to find a set of operating parameters for ultrasonic cleaning machine that would provide the cleanest quality for type A special plastic. This could lead to less product rejects and consequently increases production yield and total output.

The company used spray wash and ultrasonic cleaning in the manufacture of two types of very dirt sensitive special plastic products. In spray wash cleaning, the plastics were placed on conveyor track and a specialized soap and de-ionized water were used. Ultrasonic cleaning, on the other hand, utilizes a specialized cleaning agent, which is in conjunction with applied current while the plastics were loaded in baskets.

Refer to Figure 1 for the schematic diagram of the cleaning process. In these two types of cleaning process, type A plastics can be processed only at the spray wash cleaning to meet the cleanliness requirements of type A plastics. Type B plastics can be cleaned by either the spray wash or the ultrasonic cleaning machine. It was arranged such that the spray washer was used for both the type A and type B plastics and the ultrasonic cleaner was used for type B plastic only. The spray washer was used mainly for type A plastics but sometimes when need arises it is also used for type B plastics. However, a third product (type C), which was introduced late, strictly required to be processed at the spray wash cleaning station. Product C cannot be processed through the ultrasonic cleaning for it requires baskets for loading the plastics during cleaning. So the bulk of the new product is being cleaned in spray washer. It raised the concern of volume capacity for the spray washer since it is mainly used for type A plastics only.

Because of bigger volume that the spray washer has to process due to the introduction of type C plastics, partial volume of type A plastics has to be processed at the ultrasonic cleaning unit. But using the ultrasonic cleaning machine to clean type A plastics causes some cleanliness issues. The ultrasonic cleaning machine cannot thoroughly clean the type A plastics such that it will pass the cleanliness standard. Because of this, a process optimization is required to resolve the cleanliness issue at the ultrasonic cleaning process. The Taguchi design of experiments technique was used to design a series of experiments that will need minimum resources. This technique improves process robustness and lessens product variations from the standards caused by controllable and uncontrollable factors. It allows the least experimental runs possible, thus, decreasing costs and shortening experimental time. Likewise, it eliminates the effect of noise without removing the cause. After the optimization process, the operations of the ultrasonic cleaning machine achieved its optimum

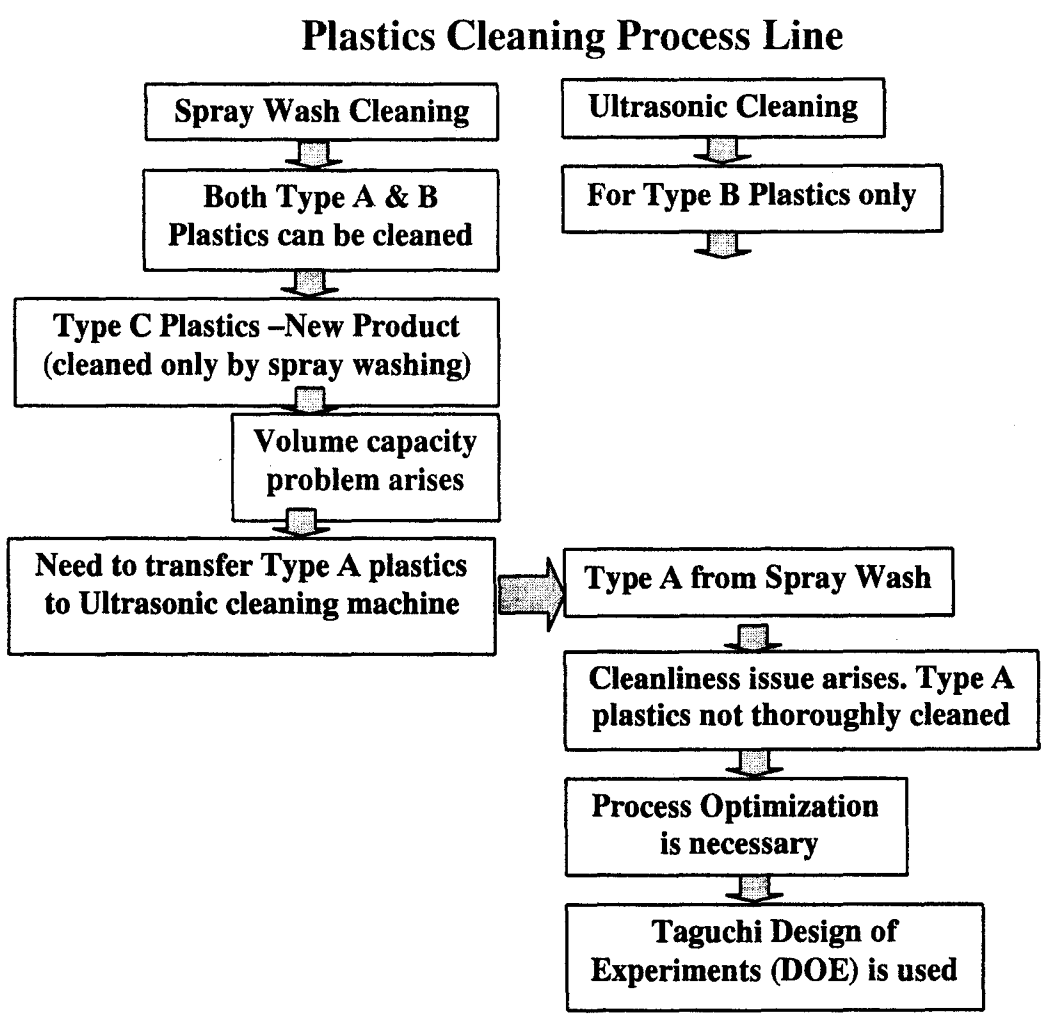


Fig. 1. Schematic diagram of the cleaning process in the plant.

capacity leading to greater output of type A plastics and minimizing the percentage of rejection of the product due to damage.

THEORETICAL BACKGROUND

Taguchi Design of Experiments (DOE)

The Taguchi Design of Experiments was a modification of the full-factorial design formulated by Genichi Taguchi [1]. It has some advantages over the full factorial design. Taguchi approach helps in establishing the best design in the least number of experimental trials, reducing the need for expensive equipment, materials and other resources. It enhances the identification of the most efficient combination of machine settings and other elements of production when used for process optimization. For problem solving efforts involving many people within an organization, the Taguchi approach is useful for those who are not statisticians or experts in the design of experiments.

Measurable characteristics

Measurable characteristics are product/ process output requirements monitored on a continuous basis. They serve as parameters in the quantitative or qualitative outcome or result of an experiment. These are classified into three based on the requirements of the experiment's objective. For example, a design of experiments is set-up to decrease the % rejection rate of the process. In here, % rejection rate of the process stands as the measurable characteristics. The classifications are as follows:

a. ***Nominal the best.*** These are measurable characteristics with a specific target value (i.e. plating thickness, weight, height and diameter) [2].
b. ***Smaller the better.*** These are the measurable characteristics wherein the ultimate target is zero (i.e. %rejection rate, down time, absenteeism and material waste).
c. ***Larger the better.*** These are measurable characteristics wherein the target is preferably higher (i.e. production output and income).

Steps involved in conducting Taguchi DOE

Taguchi DOE involves eight basic steps to successfully establish the desired optimized machine parameters. Here are the basic steps in conducting Taguchi DOE: 1.) define the problem, 2.) determine the objective, 3.) brainstorming, 4.) design the experiment based on appropriate orthogonal arrays, 5.) conduct the experiment and collect data, 6.) analysis of results, 7.) selection of influential factors and optimum levels, 8.) confirmatory runs using the optimum combination of parameters. These steps will be discussed in the following sections.

Define the problem

Design of experiments is applicable to solve problems in relation to product or process quality. Most of the time, the problem is having products whose quality do not meet the specification. The first step of Taguchi DOE is to identify what aspect of product quality related problem to be solved.

Determine the objective

In this step, the objective function is determined. A quantitative or qualitative measurable characteristic of the outcome or result of experiment are defined and monitored in order to measure the effectiveness of a certain factor setting during the conduct of the experiment. Example of optimization objective is reduction in percentage rejection of the product.

Brainstorming

Brainstorming is a group activity in which a list of possible factors, both controllable and noise factors, that affect the process or product output and quality are defined. The levels or specific settings for these factors are also determined. It is valuable because each group member contributes a unique view of a situation. In here, all possible factors are considered and then analyzed. Finally, the group decides which factors to include in the experiment.

Design the experiment based on appropriate orthogonal arrays

An orthogonal array is an experimental design constructed to allow a mathematically independent assessment of the effect or influence of each of the factors in the experiment [3]. Taguchi has established six specialized arrays, which include L_4, L_8, L_{12}, L_{18}, L_{36}, and L_{54}. The subscripts represent the number of runs. These arrays are fewer in experimental runs as compared to the full factorial design. Conventionally, Taguchi's orthogonal array is named as $L_a\ b^c$ where, a = number of experimental runs, b = number of levels of each factors and c = maximum number of factors considered.

Table 1. Experimental matrix based from an orthogonal array.

RUN No.	FACTORS A	B	C	D	E	F	G	RESULT
1	1	1	1	1	1	1	1	Y1
2	1	1	1	2	2	2	2	Y2
3	1	2	2	1	1	2	2	Y3
4	1	2	2	2	2	1	1	Y4
5	2	1	2	1	2	1	2	Y5
6	2	1	2	2	1	2	1	Y6
7	2	2	1	1	2	2	1	Y7
8	2	2	1	2	1	1	2	Y8

Table 1 is an orthogonal array for an experimental design with eight runs, eight factors at two levels. Entry 1 in the array represents the first level and entry 2 represents the second level. Example, entry 1 represents the lower value of a parameter and entry 2 represents the upper value of a parameter. The last column represents the value of measured result of the experiments. Based on the ***Table 1,*** Run 1 is an experimental run using the values of the seven factors (A to G) at level 1. Run 2 is an experimental run wherein factors A, B and C use values at level 1 and factors D, E, F, and use values at level 2.

Taguchi DOE uses orthogonal arrays to evaluate the effect of factor levels with respect to robustness because the noise has been considered. An orthogonal experiment design is not focused in the results of one treatment combination, but in the average change in response over a number of experimental runs. The conditions of orthogonality are as follows:

a. Every level of every factor must appear in combination with every level of every other factor.
b. In every pair or columns, all combinations of all levels must occur and they must occur an equal number of times.
c. The degrees of freedom of a factor is the number of levels minus one. The total degrees of freedom is the sum of the degrees of freedom of all the factors. The number of runs is equal to total degrees of freedom plus one.

Conduct the experiment and collect data

Based from the appropriate orthogonal array, the experiment is conducted one run at a time, taking note of the result of the measurable per run. This conduct of the experiment is repeated for every noise factors considered. Thus, the number of sets of the results depends on the number of the noise factors chosen.

Analysis of Results

After conducting each experimental runs and gathering their respective measurable characteristics, the results are analyzed through: (1) main effects computations and (2) linear graphs [4].

a) ***Main effect.*** Main effect is the effect of a factor on the results when it changed from one level to another. The main effect manifests the influence of factor levels to the results. Referring to ***Table 2***, all results of factor A with values at level 1 is averaged, giving a value coded as A1. Referring to ***Table 1***, the value of A1 = (Y1 +Y2 +Y3 + Y4)/4. This is the average of the values of the measurable characteristics of all runs having factor A at level 1. Similarly the results of all runs having factor A with values at level 2 is averaged and coded as A2 = ((Y5 +Y6 +Y7 + Y8)/4. At this point, A1 and A2 manifest the effects of Factor A to the measurable characteristic when changed from level 1 to level 2. Likewise, this was done for factor B, where B1 = (Y2 + Y5

+ Y6)/4 and B2 = (Y3 + Y4 + Y7 + Y8)/4. B1 is the average of the results of all runs having factor B at level 1 and B2 is the average of the results of all runs having factor B at level 2. This procedure should be repeated for all the factors.

Table 2. An example of tabulated main effects

Run No.	Factor A	Factor B	Factor	Level 1	Level 2
1	1	1	A	A1	A2
2	1	2	B	B1	B2
3	1	2			
4	1	2			
5	2	1			
6	2	1			
7	2	2			
8	2	2			

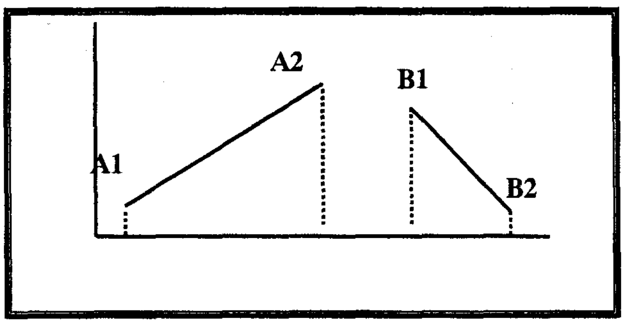


Figure 2. A representative linear graph of the computed main effects.

b) ***Linear graphs***. To see the relationship between main effects more clearly, the values are plotted as linear graphs. Values of A1 and A2 are plotted and connected by a straight line and the same is done for values of B1 and B2 as shown in ***Figure 2***. Figure 2 shows that A1 is lesser than A2. This means that using level 1 values for factor A gives smaller values for measurable characteristics compared to using level 2 values for factor A. On the other hand, level 2 values for Factor B give lower values to measurable characteristics than level 1 values.

Selection of Influential Factors and Optimum Levels and Confirmation Runs

Finally, optimum conditions are selected based from the linear graphs generated. Main effects are evaluated according to the measurable characteristics of the finished product. After establishing the optimum set of process parameters, confirmation runs are conducted to verify the effectiveness of the parameters especially when used in full production operations.

Confirmatory Runs Using the Optimum Combination of Parameters

After establishing the optimum set of process parameters, confirmation runs are conducted to verify the effectiveness of the parameters especially when used to a full production operations. Usually, confirmation runs begin with a small-scale experiment using the same methodologies established within the experiment. Normally, this is done in parallel with the existing parameters to compare their effectiveness.

Afterwards, confirmation runs are extended to normal production to check its effect if applied to bigger volumes. This is done through a close monitoring of results on a daily, weekly or monthly basis until the experimenter is already confident with the results of the obtained optimized set of parameters.

Ultrasonic Cleaning

Ultrasonic cleaning involves removing dirt particles adhering to surfaces by using ultrasonic waves. Frequencies higher than 18 kilohertz are considered ultrasonic. Frequencies for ultrasonic cleaning range from 20,000 to 100,000 hertz [5]. Cleaning in most instances requires that a contaminant be dissolved or displaced or both dissolved and displaced. The mechanical effect of ultrasonic energy can be helpful in both speeding dissolution and displacing particles [6].

METHODOLOGY

The first step in the optimization process is to establish measurable characteristics. In this study, the measurable characteristic is the degree of cleanliness. Judgments on the cleanliness of the plastics are subjective since tests are conducted through manual inspections under a specific amount of light. To establish a quantifiable degree of cleanliness for the experiment, five fingerprints at the side and one at the center were marked on the plastics. Furthermore, dust coming from other machines was intentionally applied to produce plastics at their worst condition. The samples that retained fingerprints after the runs were considered rejects. The indicator for the degree of cleanliness is the percentage rejection. The smaller the percentage rejection the better. The next step is to determine the factors that affect the degree of cleanliness. After a series of brainstorming with key manufacturing personnel and small-scale experiments of each factors discussed, the following factors were considered to have potential effects on the degree of cleanliness of the plastics cleaned by the ultrasonic cleaning machine.

Controllable Factors

1. ***Filter size***. Cleaning solution is periodically filtered to remove accumulated dirt. The filter size is the size of the pores of the filter used.
2. ***Re-circulation rate***. The solution within the tank is re–circulated at a certain pressure to enhance stripping action against contaminants.
3. ***Degassing time***: Degassing the cleaning solution is extremely important in achieving satisfactory cleaning results. The presence of bubbles restricts effective cavitation and implosion of the cleaning agent. The duration of the degassing process affects the cleaning effectiveness.
4. ***Ultrasonic power***: Cavitation intensity is related to ultrasonic power at the power levels generally used in ultrasonic cleaning systems. Thus, higher ultrasonic power promotes better cleaning power.
5. ***Temperature***: The effectiveness of the cleaning chemical is also related to temperature. Although the cavitation effect is maximized in pure water at a temperature of approximately 71° C, optimum cleaning is often seen at higher or lower temperatures because of the effect that temperature has on the cleaning chemical. It is necessary to include the temperature in optimization since in some cases lower temperature resulted in better cleaning and in another case higher temperature resulted in better cleaning. Although the cleaning agent used dictates the optimum temperature, it is not included in the optimization process since there is only one set of cleaning used throughout he process. There is no other option for this factor. Besides, the cleaning agent used is a company secret and cannot be disclosed.

Uncontrollable or noise factors

1. ***Basket loading.*** For every cycle of the machine, its full capacity is two baskets.

Table 3. A list of controllable factors considered at two levels

FACTOR		LEVEL	
		1	2
A	Filter size	2 μ	10 μ
B	Re-circulation rate	High	Low
C	De-gassing time	20 min	30 min
D	Ultrasonic power (dial setting)	4	7
E	Temperature	55 °C	60 °C

Table 4. Summary of the experiment's orthogonal array.

Run	FACTORS				
No.	A	B	C	D	E
1	2	High	20	4	55
2	2	High	20	7	60
3	2	Low	30	4	55
4	2	Low	30	7	60
5	10	High	30	4	60
6	10	High	30	7	55
7	10	Low	20	4	60
8	10	Low	20	7	55

However, only one basket is loaded at the end of every production batch because there are not enough plastics to fill the two baskets. To validate the effectiveness of cleanliness between full loading and one–basket loading, every experimental run within the orthogonal array are repeated for these noise factor to be considered.

Table 3 summarizes the factors selected with their respective levels while ***Table 4*** includes the experimental matrix where factor settings or levels are already placed. The experiment was conducted following the factor settings for each experimental run indicated in ***Table 4***. After each run, the plastics were immediately inspected to check for the degree of cleanliness and retained fingerprints and the percentage of rejected plastic is computed. Applying the percentage of those with retained fingerprints to Taguchi's main effects computation and graphical analyses, the optimized process parameters for the ultrasonic cleaning machine were derived based on the ***smaller the better measurable characteristic*** of the output.

RESULTS AND DISCUSSION

During the entire process of the experiment, a thorough observation was done for every experimental run conducted. Likewise, the percentage of retained fingerprints were monitored for every run. This will be used in the main effect computations and graphical analyses for the derivation of the optimum combination of parameters. Results of the experiment are as follows:

1. Based from the ultrasonic power experiment, changes in the plastics' surface were observed starting at the 8th dial setting. Thus, the 7th dial setting was used as the maximum level (level 2) in the design of experiments. The 4th dial setting which was used as the minimum level (level 1) is the existing machine setting.
2. Based on visual inspection, there is a general improvement on the cleanliness and quality of the plastic materials using the new set of parameters compared to the previous set.
3. For every experimental run, the percentage of retained fingerprints were monitored. ***Table 5*** shows the result for every experimental run with full–loading and one–basket loading.

The main effects of each factor are computed and summarized in ***Table 6***. As shown in the table, the values on the column labeled Level 1 are the

Table 5. A summary of the percentage of fingerprints retained

RUN No.	TWO-BASKET FULL LOADING		ONE-BASKET FULL LOADING	
	Total	% with finger prints	Total	%with finger prints
1	63	39 = 61.90	32	32 = 100
2	63	35 = 55.56	32	22 = 68.75
3	64	30 = 46.88	32	20 = 62.50
4	64	11 = 17.19	32	5 = 15.63
5	63	10 = 15.87	32	11 = 34.38
6	64	13 = 20.31	32	13 = 40.63
7	64	21 = 32.81	32	17 = 53.13
8	64	17 = 26.56	32	11 = 34.38

Table 6. A summary of the results using Taguchi's Design of Experiments.

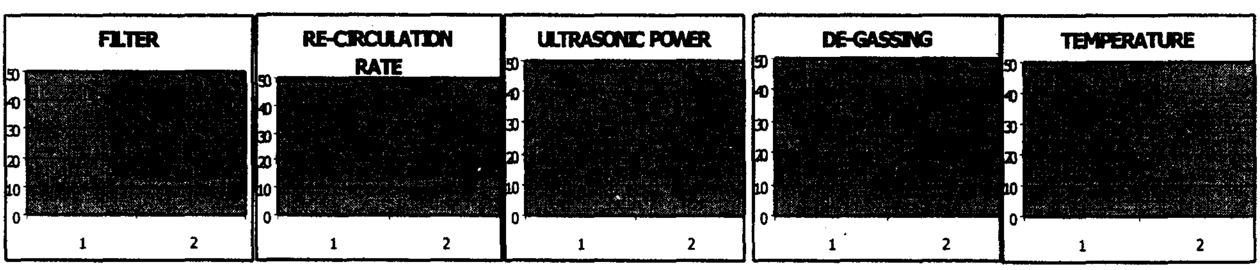
FACTORS	TWO-BASKET LOADING		ONE-BASKET LOADING	
1.0 Filter size	45.38		61.72	
2. Re-circulation rate	38.41		60.94	
3. Degassing time	44.21		64.07	
4. Ultrasonic power	39.37		62.50	
5. Cleaning-agent temperature	38.91		59.38	

averages of the percentage of rejects for all the runs with values of parameters using Level 1.

For example, the value 45.38 % in the row labeled Filter Size and column labeled Level 1 in Two-Basket Full Loading is the average of all results (% reject) of all the runs which used Level 1 values for factor A (Filter Size). The value 45.38 % is the average of all the results (% reject) of runs 1 to 4, since these runs are all at Level 1. Similarly, the value 23.89 % is the average of all the results (% reject) of runs 5 to 8, since these are all at level 2. Similar computations are done for all the other factors.

Numerical values tabulated as levels 1 and 2 above are the effects of each factor to the probable % rejection rate when changed from one level to another. Looking at filter size as an example, the % rejection rate decreased from 45.38% to 23.89% when changed from level 1 to level 2. This means that a change from level 1 to level 2 of the filter size will result in a decrease in the % rejection rate.

TWO-BASKET FULL LOADING



ONE-BASKET FULL LOADING

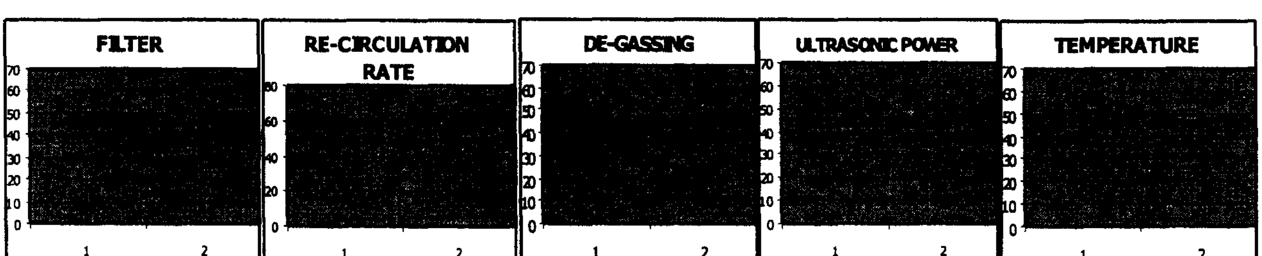


Figure 3. Linear graphs of the main effects ((the smaller the better) measurable characteristic)

Table 7. Established optimum parameters based from the analysis of data

FACTORS	SETTING
1. Filter	10 μ
2. Re-circulation Rate	Low
3. De-gassing	30 min
4. Ultrasonic Power	7
5. Cleaning Agent Temperature	60 °C

Table 8. A summary of confirmation run results on good lenses.

Batch No.	Quantity In	Dirt-related defects	% Yield
20102001	607	3	99%
20102508	975	2	99%
20102509	1490	1	99%
20102603	1900	1	99%
20102604	570	0	100%
20102704	440	3	99%
20102705	670	0	100%
20102706	655	1	99%
20102707	480	2	99%

The results were linearly plotted as shown in **Figure 3** to see the main effect visually. Since the measurable characteristic of the output used in this experiment is the percentage of fingerprints retained, the desirable measurable characteristic is "the smaller the better". Thus, the level that gives a lower percentage of fingerprints retained is chosen to be more effective in ultrasonic cleaning machine performance.

Finally, the optimum combination of parameters based from the analyses mentioned is selected. Since the measurable characteristic is "the smaller the better", all factors at levels which contributes to a lower % rejection rate are considered to be the optimum condition (**Figure 3**). Thus, the optimum combination of ultrasonic machine parameters for type A plastics are tabulated in **Table 7**.

Confirmation Runs

The first confirmation run was a comparison between the established optimized parameters and the existing parameters of the ultrasonic cleaning machine. Comparison of effectiveness was also based on retained fingerprints after the cleaning process. Confirmation run using the optimized parameters on test plastics showed 17.19% retained fingerprints compared to the existing parameters which has 62% retained fingerprints. This manifested the effectiveness of the optimized parameters.

Later, the optimized parameters were applied to good type A plastics. During this process, dirt-related defects such as unidentified substances, miscellaneous defects and stains were closely monitored using criteria for type A plastics at window inspections. Moreover, the plastics were thoroughly inspected prior to cleaning to increase the probability that the defects are induced by the ultrasonic machine. Confirmation done was with: (1) one production batch, (2) one day, and (3) three days. In total, confirmation runs were conducted for a week. Results are tabulated in **Table 8**. As shown, the occurrence of dirt–related defects is very minimal, proving the effectiveness of the optimized parameters in cleaning Type A plastics.

CONCLUSION

Optimized parameter settings for ultrasonic machines were successfully obtained using the Taguchi Design of Experiments. The established optimized parameters for ultrasonic cleaning machines proved to be very effective as shown by confirmation runs conducted on plastics with fingerprints and on production batches of good type A plastics for one day and extended up to one week. Thus, the parameters are currently implemented at the company's ultrasonic cleaning process. Based on the results of actual runs using the optimized parameters, it was proven that optimization using Taguchi DOE technique gave significant improvements in terms of efficiency and product quality.

REFERENCES

Taguchi, Dr. Genichi. *Taguchi Methods (Case Studies from the U.S. and Europe)*. ASI Press, Michigan, 1989, pp. 57-72.

Celestino, Sherwin D.G., et al. *Process Optimization for Multiple Plating Thickness Requirements: A Case Study for Dynamic Parameter Design*. ASEMEP Proceedings, 1999.

Walpole, Ronald E. and Myers, Raymond H. Probability and Statistics for Engineers and_Scientists. Macmillan Publishing Company, New York, 1985.

Ealey, Lance A. Quality By Design (Taguchi Methods in U.S. Industry). ASI Press, Michigan, 1988, pp. 293-299.

Fuchs, John F. Precision Cleaning '94 Proceedings (May 16-18, 1994 – Rosemont Convention Center). Witter Publishing Co., Inc., 1994, 212-224.

The Textwipe Company Inc. Contamination Control Products for the Microelectronics Industry and Critical Manufacturing. 1999 pp. 36-38.