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Implementation of Six Sigma in a Manufacturing Process: A Case Study

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This paper presents a Six Sigma project conducted at a semiconductor company dedicated to the manufacture of circuit cartridges for inkjet printers. They are tested electrically in the final stage of the process measuring electrical characteristics to accept or reject them. Electrical failures accounted for about 50% of all defects. Therefore, it is crucial to establish the main problems, causes and actions to reduce the level of defects. With the implementation of Six Sigma, it was possible to determine the key factors, identify the optimum levels or tolerances and improvement opportunities. The major factors that were found through a design of experiments 3 factors and 2 levels were: abrasive pressure (90-95 psi), height of the tool (0.06-0.05) and cycle time (7000-8000 msec.). The improvement was a reduction in the electrical failures of around 50%. The results showed that with proper application of this methodology, and support for the team and staff of the organization, a positive impact on the quality and other features critical to customer satisfaction can be achieved

Significance: Six Sigma literature is extensive, although there are many reports on its application, it is extremely important the gathering empirical evidence to build a body of Six Sigma with better explanatory capability.

Keywords: Six Sigma, Repeatability and Reproducibility Gauge Study, Quality Improvement

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1. INTRODUCTION

The Six Sigma Methodology is a customer focused continuous improvement strategy that minimizes defects and variation towards an achievement of 3.4 defects per million opportunities in product design, production, and administrative process. Gutierrez et al. (2004) state that Six Sigma is a strategy of continuous improvement of the organization to find and eliminate the causes of the errors, defects and delays in business organization processes. The specific objectives of the project were grouped in three categories; measurement equipment, failure analysis, and process improvement.

Regarding the measurement equipment, the objectives were to determine if the current measurement system provides a reliable estimate of the quantity and type of defect and to assess the repeatability and reproducibility of the electric tester.

In relation to the method of failure analysis, several objectives were established: (1) to evaluate the standardization of criteria for the technical failures; (2) to develop a procedure and sampling plan for defective parts and obtain a reliable estimate of the distribution of faults in the total population; (3) to propose an alternate method for the analysis of defective parts and (4) to identify and measure the defects, specially the main electrical defect.

About the analysis of problems and process improvement, the objectives were: (1) to identify the factors or processes that affect the quality feature in question (electrical function of the circuit); (2) to identify the levels of the parameters in which the effect of the sources of variation will be minimal; (3) to develop proposals for improvement and (4) to implement and monitor the proposed improvements.

2. METHODOLOGY

2.1 Phase 1: Define

During the years 2006 and 2007 the main product had a low level of performance in electrical test. Historical data shows that on average, 3.12% of the material was defective. Figure 1 shows a Box diagram of the failure rate.

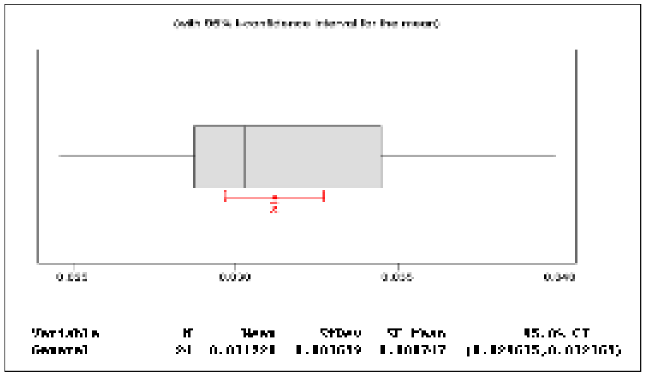

Figure 1. Box Diagram of Failure Rate (2007)

The first step was the selection of the Critical Customer Characteristics and the response variable. The critical characteristic, in this case, was the internal electrical defects detected during testing electrical.

- Critical to Quality (CTQ), represents the percentage of good parts to total parts, tested electrically.
  Y1 = (Total electrical fault x 100)/ Total of items tested,
- Critical to Cost (CTC). Represents the cost caused by waste material in the last stage of the process.
  Y2 = (amount of electrical failures x cost feedstock)/ Number of pieces produced.

2.2. Phase 2: Measurement

This phase was to certify the validity of the data through the evaluation of the measurement system. The first step was a normality test of the data and an analysis of the process capacity. This began with the measurement of the percentage of electrical failures. The percentage of electrical faults was obtained after a test was performed to the 100% of electric circuits.

Table 1. Measured by Operator (Reference Value = 73.5 Ohms)

Repetition	Measurement	Moving Range	Repetition	Measurement	Moving Range
1	80.1	0	11	80.0	0.2
2	79.9	0.2	12	80.1	0.1
3	80.1	0.2	13	80.1	0
4	79.8	0.3	14	79.9	0.2
5	80.1	0.3	15	79.9	0
6	80.1	0	16	80.0	0.1
7	79.9	0.2	17	79.8	0.2
8	80.2	0.3	18	79.8	0
9	80.1	0.1	19	80.1	0.3
10	79.8	0.3	20	80.0	0.1

In order to evaluate the accuracy of the equipment, was used a standard piece with a reference value of 75.3 Ω, which was measured 20 times by the same operator. According to the results of the data shown in Table 1, it was concluded that a 0.05% accuracy of the calibration of the instrument was acceptable.

The evaluation of the capability of the measurement process in terms of precision was conducted through a study of repeatability and reproducibility (R&R). The evaluation was conducted with 10 pieces of production taken at different hours, with 3 operators and 3 repetitions; results of the R&R study performed with Minitab© by ANOVA are shown in Table 2.

Table 2. Repeatability and Reproducibility R & R Study (Number of Distinct Categories = 3)

Source	StdDev	Study Var (6 * SD)	%Study Var (%SV)	%Tolerance (SV/Toler)	%Process (SV/Proc)
Total Gauge R&R	4.43E-02	0.265832	48.59	3.32	28.90
Repeatability	3.78E-02	0.232379	42.47	2.90	25.26
Reproducibility	2.15E+00	0.129099	23.60	1.61	14.04
Operator	0.00E+00	0.000000	0.00	0.00	0.00
Operator*Part	2.15E-02	0.129099	23.60	1.61	14.04
Part-To-Part	7.97E-O2	0.478191	87.40	5.98	51.99
Total Variation	9.12E-02	0.547114	100.00	6.84	59.48

An important purpose of the measurement system was to ensure the consistency of the criteria used by the four-area tests and for this point, a study of repeatability and reproducibility for attributes was done. The Table 3 shows the result.

Table 3. Study of Repeatability and Reproducibility for Attributes

Evaluation	Shift A Inspector	Shift B Inspector	Shift C Inspector	Shift D Inspector
% Matched	96.67%	96.67%	93.33%	90.00%
%Appraised Vs. known standard	93.33%	93.33%	86.66%	76.67%

2.3. Phase 3: Analysis

The analysis phase consisted of searching through brainstorming rounds the possible factors that may be affecting the electrical performance of the product. The factors that were considered most important were raised as hypotheses and tested by several statistical tests. The objective was to identify key factors of variation in the process. For the identification of potential causes were prepared Pareto Charts of Defects, in one of them, about 33% of the electrical faults analyzed cannot be identified with the test equipment and 21.58% were attributed to the defect called "Waste of Aluminum Oxide", given that the current equipment did not detect 33% of faults. Samples were sent to an external laboratory, observing that more than 50% of the parts had traces of aluminum oxide so small that they could not be detected with the microscope used in the laboratory of failure analysis. Because this waste may cause several problems, a cause and effect matrix shown in Figure 2 was prepared to prioritize areas of focus.

Cause and Effect Matrix							
Rating of Importance to Customer		5.91	2.3	1	0.78		
Y's		1	2	3	4	5	
X's		Residuals AIO	Scratch	Error Tester	PadContaminate	Requirement	Total
Process Step	Process Input						
1	Grit Blast	9	9	0	3		75.96
2	Nozzle Attach	6	6	0	6		53.76
3	Lexfilm	0	9	0	9		27.45
4	Electric Test	0	0	9	0		9.36
5	Dicing	0	3	0	0		6.81
6	Tab Bond	0	0	0	0		0
	Total	89	61	9	14		

Figure 2. Cause-Effect Matrix

The causes considered as important were the quantity of wash cycles, the thickness of the Procoat layer, Lots circuit, the parameters of grit blast equipment and the operational differences among shifts. The analysis and corresponding results are presented in the following points:

- Regarding the quantity of wash cycles and to determine the influence upon the apparition of electrical defects, was applied a three runs ANOVA with 30 wafers each, under one, two and three wash cycles. Data was tested for normality. The statistical differences among wash cycles are insignificant, concluding that Wash Cycle is not an important factor, and for space reasons, the results of these tests are not shown, (but are available on request).

- In relation to the thickness of the Procoat finish, it was suspected that the increase of the thickness will reduce the percentage of electrical failures (to reduce the impact of grains of aluminum oxide on the semiconductor), an experiment with a single factor was made. The factor assessed was the thickness of the layer of Procoat under 4 levels and 30 repetitions. The 120 runs were conducted on a random basis. The hypotheses states were:

  H_0: The defective fraction of electrical switches is the same with different thicknesses of Procoat (0, 14, 30, 42 microns).

  H_1: The defective fraction of electrical switches is reduced with increasing thicknesses of Procoat (0, 14, 30 and 42 microns).

To test these hypotheses, an ANOVA was run and the results are shown in Table 4.

Table 1. ANOVA Table of Procoat Layer Thickness Results

```
One-way ANOVA: Evaluation Layer Thickness Procoat

Analysis of Variance
Source     DF        SS        MS        F        P
Factor      3 0.0046162 0.0015387    23.28    0.000
Error     116 0.0076688 0.0000661
Total     119 0.0122850
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev ------+---------+---------+---------+
0 micron   30  0.026520  0.011065                            (----*----)
14micron   30  0.011585  0.005927 (----*----)
30 micro   30  0.013405  0.007448     (----*----)
42 micro   30  0.011868  0.007169  (----*----)
                                  ------+---------+---------+---------+
Pooled StDev = 0.008131              0.0120    0.0180    0.0240    0.0300
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The data indicate that there was a difference between the levels, as the p-value is less or equal to 0.0001. Only the level of 0 micron is different from the rest of the half and that the other three levels fall within its three different confidence intervals. Figure 3 shows the comparisons of the four levels of procoat in relation to the percentage of electrical faults.

The layer of procoat improves electrical performance up to 14 microns (a condition of the current process); however it was not justifiable to increase the thickness of the layer, as it did not represent improvement in the average electric performance or to reduce the variation.

- Regarding Lots Circuit, in order to prove that the condition of the raw material was not a factor that is influencing the electrical performance, it was necessary to test the following hypotheses:

  H_0: There is no difference in the fraction of defective units between different batches.

  H_1: There is a difference in the fraction of defective units between different batches.

Because the four lots that were selected randomly contain different amounts of wafers, the experiment was an unbalanced design. Each batch contains between 20 and 24 wafers, which in turn contain about 200 circuits (each circuit is mounted in a cartridge for inkjet printers) that are electrically tested on an individual basis. Data was tested for normality before the test the hypothesis by means of an ANOVA, testing the equality of the averages of the batches.

The ANOVA results are summarized in Table 5, indicating that there was no difference in the percentage of electrical failures of wafers per batch.

The p-value = 0. 864 indicate a high probability that the lots have equal means. Therefore, the null hypothesis was not rejected. Then it was concluded that the lots of wafers show no difference in electric behavior and the assumption that some batches posses a lower electrical performance was discarded. Additionally, the test of equal variances (for the four lots) concluded that there was no hard evidence to suggest that the variability in the percentage of electrical failures depends on the lot or semiconductor wafers. Figure 4 shows the results of Bartlett test, where the value of P = 0.926 (P> 0.05).

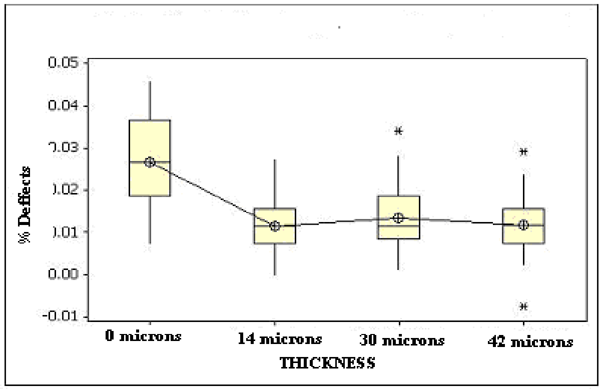

Figure 1. Boxplot Diagrams of the Percentage of Electrical Faults vs. the Thickness of the Procoat Layer

Table 2. ANOVA for Different Lots of Wafers

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One-way ANOVA:

Analysis of Variance
Source     DF        SS         MS         F        P
Factor      3   0.000294   0.000098     0.25    0.864
Error      86   0.034350   0.000399
Total      89   0.034645
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  -------+---------+---------+---------
Lot  1     24   0.96930   0.01974           (------------*-------------)
Lot  2     24   0.96445   0.02165   (------------*-------------)
Lot  3     21   0.96655   0.01896     (--------------*-------------)
Lot  4     21   0.96596   0.01926    (--------------*-------------)
                                   -------+---------+---------+---------
Pooled StDev =  0.01999                 0.9600    0.9660    0.9720
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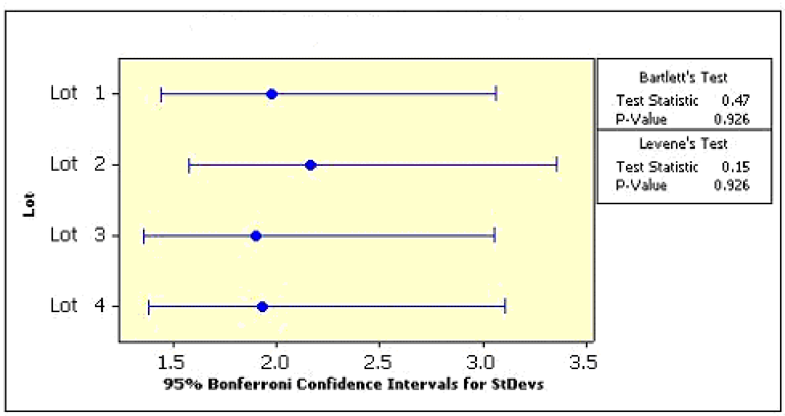

Figure 2. Variance Test for Lots of Wafers

About the parameters with greater effect on the electrical failures, in the process of grit blast, was used an experiment with 4 factors and 3 levels each. The factors evaluated are shown in Table 6.

Table 3. Factors Evaluated in Equipment Grit Blast

Factor	Levels		
Pressure (psi)	95	100	110
Tooling Height (inches)	0.060	0.070	0.080
Cycle Time (millisecond)	6000	7000	8000
Machine	1	2	3

Factor 1: Pressure: H_0: All levels of the factor pressure produce the same average electrical performance.
H_1: Not all levels of the factor pressure produce the same average electrical performance.
Factor 2: Tool Height: H_0: All levels of the factor height have the same average of electrical performance.
H_1: Not all levels of the factor height have the same average of electrical performance.
Factor 3: Oper. Time: H_0: All levels of the factor time have the same average of electrical performance.
H_1: Not all levels of the factor time have the same average of electrical performance.
Factor 4: Machine: H_0: All the machines have the same average electrical performance
H_1: Not all machines have the same average electrical performance.

There was an important assumption in the model for this experiment, which was that there were not significant interactions among the factor. The runs were conducted on at random basis to reduce the potential error of the treatment order on the response variable. The results of the 9 runs are presented in the Table 7.

Table 4. Results of Runs in Grit Blast

Pressure (psi)	Tooling Height (in)	Cycle Time (millisec)	Machine	% Acceptable
95	0.060	6000	1	0.9951
95	0.070	7000	2	0.9838
95	0.080	8000	3	0.9908
100	0.060	7000	3	0.9852
100	0.070	8000	1	0.9713
100	0.080	6000	2	0.986
110	0.060	8000	2	0.9639
110	0.070	6000	3	0.9585
110	0.080	7000	1	0.9658

The analysis of the data in Table 7 was made with a main effect full model. This model was saturated; therefore the two main effects with the smallest Sum of Squares were left out from the model. This was that Machine and Cycle time did not affect the electrical Performance. The analysis for the reduced model is presented in Table 8. It can be observed that the Pressure and the Tooling Height are significant with p-values of 0.001, and 0.020, respectively. Figure 5 shows the main effects plot for all four factors, which confirms that only Pressure, Tooling Height and Cycle Time are affecting the quality characteristic. Figure 6 shows that conditions of normality and constant variance are satisfied.

Table 5. ANOVA for the Reduced Model for the Grit Blast Parameters

General Linear Model: % Acceptable versus Pressure (ps, Tooling Heig

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Factor               Type   Levels  Values
Pressure (psi)       fixed       3  95, 100, 110
Tooling Height (in)  fixed       3  0.06, 0.07, 0.08


Analysis of Variance for % Acceptable, using Adjusted SS for Tests

Source               DF     Seq SS     Adj SS     Adj MS      F      P
Pressure (psi)        2  0.0011478  0.0011478  0.0005739  70.37  0.001
Tooling Height (in)   2  0.0001978  0.0001978  0.0000989  12.12  0.020
Error                 4  0.0000326  0.0000326  0.0000082
Total                 8  0.0013782


S = 0.00285589   R-Sq = 97.63%   R-Sq(adj) = 95.27%
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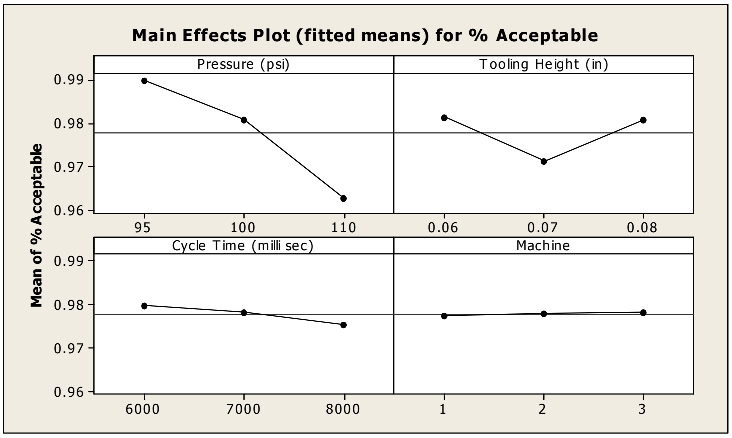

Figure 3. Chart in Benchmarks Main Effects of Grit Blast

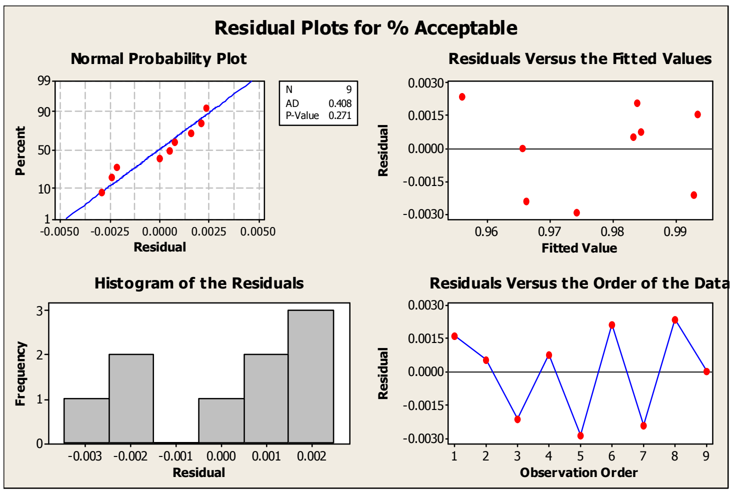

Figure 4. Residual Plots for the Acceptable Fraction.

Finally, to determine whether there is a difference in performance of four shifts, a test analysis of variance and equality of means was performed. The Table 9 shows that there is a difference between at least one of the shifts, since the p-value is less or equal to 0.0001.

Table 6. ANOVA Difference between Shifts

One-way ANOVA: Shifts A, B, C y D					
Source	DF	SS	MS	F	P
Factor	3	13.672	4.557	9.23	0.000
Error	124	61.221	0.494		
Total	127	74.894			
S = 0.7027 R-Sq = 18.26% R-Sq(adj) = 16.28%					

Individual 95% CIs For Mean Based on Pooled StDev				
Level	N	Mean	StDev	+---------+---------+---------+---------
A	32	3.0283	0.4350	(-----*-----)
B	32	3.6078	0.6289	(-----*-----)
C	32	3.5256	0.8261	(-----*-----)
D	32	3.9418	0.8412	(------*-----)
				+---------+---------+---------+---------
				2.80 3.20 3.60 4.00
Pooled StDev = 0.7027				

The above analysis indicates that all four shifts are not operating with the same average efficiency. For some reason shift A presents a better performance in the electrical test. Also it can be observed that shift D has the lowest performance. To confirm this behavior a test of equal variances was conducted. It was observed that the shift A shows less variation than the rest of the shifts, see Figure 7. This helps to analyze best practices and standardize shift A in the other three shifts.

2.4. Phase 4: Improvement

Once it was identified the factors that significantly affect the response variable being analyzed, the next step was to identify possible solutions, implement them and verify that the improvement is similar to the expected by the experimental designs. According to the results obtained, corrective measures were applied for the improvement of the significant variables.

- Regarding the inefficient identification of flaws in the failure analysis, that could not be identified with the test equipment being used at that time, a micromanipulator was purchased. It allows the test of circuits from its initial stage. Furthermore, it is planned the purchase of another equipment currently used in the laboratory of the parent plant at Lexington. This equipment decomposes the different layers of semiconductor and determines the other particles that are mixed in them. These two equipments will allow the determination of the particles mixed in the semiconductor and clarify if they are actually causing the electrical fault, the type of particle and the amount of energy needed to disintegrate.
- About the percentage of defective electrical switches with different thicknesses of Procoat (0, 14, 30 and 42 microns). The use of Procoat will continue because the layer protects and has a positive effect on the electrical performance. However, because the results also showed that increasing the thickness of the layer from 14 to 42 microns, does not reduce the level of electrical defects. The thickness will be maintained at 14 microns.

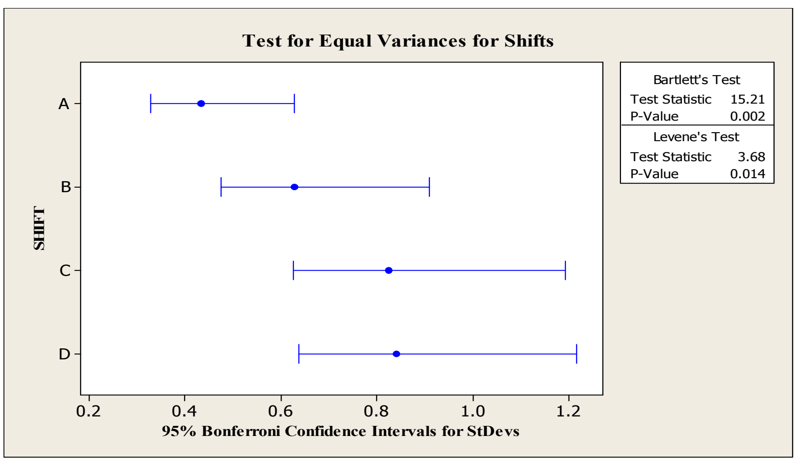

Figure 5. Equality of Variance Test for the Shifts

- For the drilling pressure in the equipment, lower levels are better, and for the improvement of the electrical performance without affecting other quality characteristics, such as the dimensions of width and length of the track, was determined that the best level for the pressure would be 95 psi.
- Regarding to the height of the drill, since it significantly affects the electrical performance and this is better when the tool is kept at 0.60 or 0.80 inches on the semiconductor. For purposes of standardization, the tool will remain fixed at a height of 0.60 inches.
- In relation to the cycle time, it showed to be a source of conflict between two quality characteristics (size of the track and percentage of electrical failures), although it is a factor with a relatively low contribution to the variation of the variable analyzed. Several experiments were run with the parameters that would meet the other characteristic of quality. Figure 5 shows the main effect. For the variable electrical performance, a factor behavior of the type smaller is better was introduced. While for the other variable output capacity of the process, a higher is better behavior was selected and for that reason, it was determined that this factor would be in a range from 7,000 to 8,000 milliseconds.
- Finally, with respect to the difference between the four-shift operations and electrical performance, results indicate that the "A" shift had better electrical performance, with the intention of standardization and reduction of the differences, a list of best practices was developed and a training program for all shifts was implemented.

In this stage was recommended an assessment of the benefits of the project (Impact Assessment of Improvement). Once implemented the proposed solutions, a random sample size 200 was taken from one week work inventory product and for all shifts. This sample was compared to a sample size 200 processed in previous weeks. Noticeable advantages were found in the average level of defects, as well as the dispersion of the data. Additionally, the results of the tested hypotheses indicate that the proposed changes reduced the percentage of defective units.

In Figure 8, Box diagrams are shown for the percentage of defects in the two populations. It is noted that the percentages of defects tend to be lower while maintaining the parameters of the equipment within the tolerances previously established, as the mean before implementation is 3.20%, against 1.32% after implementation.

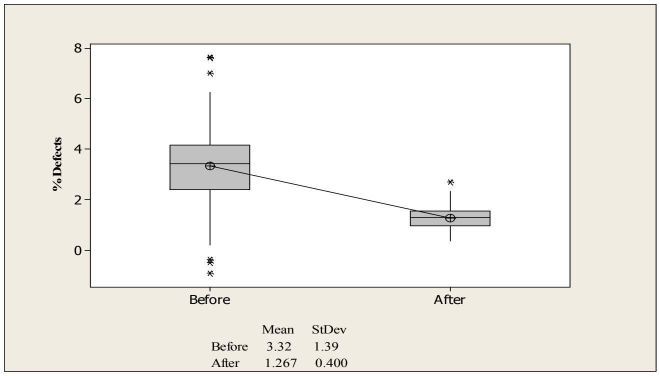

Figure 8. Box Diagrams Rejection Rate Before and After the Implementation

The test for equality of variances shows that in addition to a mean difference there was a reduction in the variation of the data (see Figure 9). Figure 10 shows a comparison of the distribution of defects before and after implementation. It can be seen that the defect called "Aluminum Oxide Residue" was considerably reduced by over 50%.

2.5. Phase: Control

In order to achieve a stable process, the pressure parameters were determined, as the height of the tool and cycle time within the limits set on the computer for Grit Blast.

Identification of Controls for KPIV's: Because these three parameters were considered to influence some equipment failures such as leaks or even, increase the cycle time, it was necessary to place devices that will facilitate the process control and avoid possible changes of the parameters. Additionally, to keep the machine operating, -easily-, within the parameters established, was essential to modify the maintenance plan of the equipment. Due to the current handles and control mechanisms and in order to assure the stability of the process, it was considered necessary their improvement. Based on the information generated, an action plan was devised and deployed, which resulted in a reduction in the percentage of electrical failures, as well as a reduction in the defect called "Residue of Aluminum Oxide". Table 10 shows the comparison before and after the implementation.

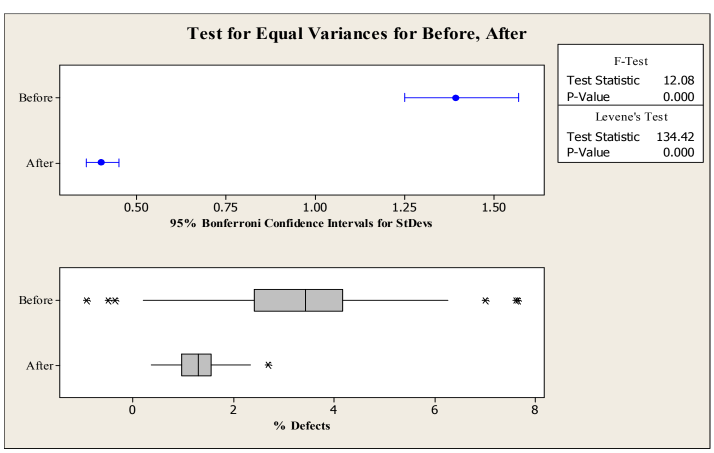

Figure 9. Test of Equality of Variances

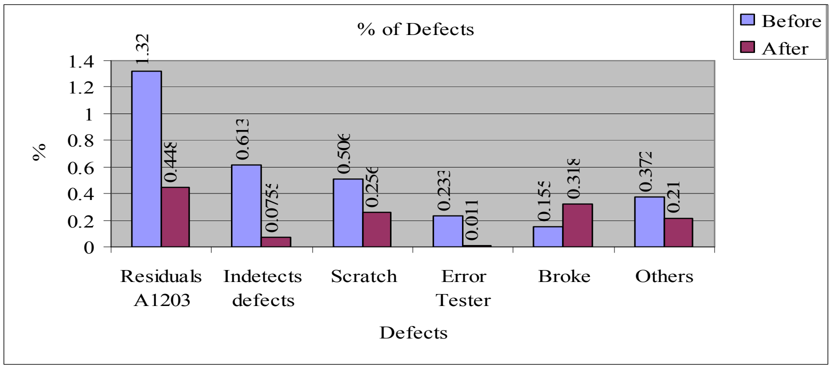

Figure 10. Distribution of Defects Before and After

Table 7. Comparative Before and After the Implementation of Six Sigma

	% Defects	Sigma Level	PPM's
Base Line	3.20	3.35	31982
Goal	1.60	3.64	16000
Evaluation	1.32	3.72	13194

4. CONCLUSIONS

The implementation of this project has been considered as successful because the critical factor for the process were found and controlled. Therefore the control plan was updated and new operating conditions for the production process. The base line of the project was 3.35 sigma level and the gain 0.37 sigma that represents the elimination of 1.88% of nonconforming units or 18,788 PPM's. Also, the maintenance preventive program was modified to achieve the goal stated at the beginning of the project. It is important to mention that the organization management was very supportive and encouraging with the project team. Finally, Six Sigma implementation can be helpful in reducing the nonconforming units or improving the organization quality and personal development.

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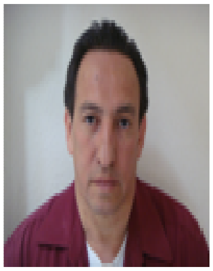
BIOGRAPHICAL SKETCH



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