

Development of SPC in the cutting plates process of AGM batteries

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Abstract

The present study took place at the battery manufacturing company, Exide Technologies, Lda, in Portugal, which aims to develop a SPC (Statistical Process Control) system in the process of cutting plates, which allows monitoring the quality of plates produced in this section.

In this study the DMAIC approach (Define-Measure-Analyze-Improve-Control) of Six Sigma methodology was applied to increase the effectiveness of the cutting plates process and, consequently, to improve their quality. In the define phase, the processes, products and defects with higher scrap production were identified and also the parameter (cutting height of plates) that will be analyzed in this study. In measure phase, a Measurement System Analysis (M.S.A.) was included through a Repeatability and Reproducibility (R&R) test to validate the measurement system that was chosen, and then, the capability and the behavior of the cutting plate's process were evaluated. In the analyze phase, the root causes that have significant impact in the cutting height were identified by a cause and effect diagram and, subsequently, each cause was individually analyzed by statistical tests. In the improve phase, several changes were implemented in the cutting process and the measurement system to eliminate the causes that revealed to have significant impact in the cutting height. Consequently, the measurement system became more suitable for measuring the height of the plates, the process capability was enhanced and the process behavior became controlled. Finally, in the control phase, several control strategies were recommended to sustain the improvements implemented previously.

Keywords: AGM battery, cutting height, DMAIC, M.S.A., Six Sigma, SPC.

1. Introduction

To survive the intense competition, organizations attempt to achieve the goals of effectiveness and customer satisfaction. The Six Sigma methodology is a project management approach to improve the quality of processes, products, services by reducing defects continuously. This methodology allowed many organizations to sustain a competitive advantage by integrating statistics, engineering and management.

From the statistical point of view, Six Sigma is defined as leading to less than 3.4 defects per million of opportunities. Therefore, Six Sigma represents the variation of the process parameters. On the other hand, from a business point a view, Six Sigma is defined as a strategy that aims to improve the effectiveness and efficiency of the processes to meet the customer's requirements.

The purpose of this article is to implement a system of SPC to monitor the cutting height of plates in a battery manufacturing organization. For the development of the SPC system the DMAIC approach was applied.

Initially, the process, the product and the defect with higher scrap production were identified. Then, some data was collected, which allowed the study of the cutting process behavior, in terms of control and capability.

This article also integrates: a M.S.A. study to validate the measurement system chosen; the development of a SPC software project to monitor the cutting height of plates in the shop floor; and an analysis of the root causes that revealed to have significant impact in the variability of cutting height. To eliminate these causes, several changes were made in the cutting process, the measurement system and the casting process. Afterwards, these changes were analyzed to prove that the measurement system and the cutting process have improved.

At last, some control procedures and a corrective actions chart were made to maintain the process capable and in control.

2. Background

Six Sigma is a quality methodology introduced by the engineer and scientist Bill Smith of Motorola in 1980. Bill Smith claimed that, by manufacturing high quality products, the cost of production would decrease. The Six Sigma concept has emerged due to the fact that they were facing the threat of Japanese competition in the electronics sector. Motorola set the quality goal of 3.4 ppm obtained by Eq.1 and the process variability of ± 6 S.D (Standard Deviation) from the mean (Breyfogle, Cuppelo, & Meadows, 2001). Furthermore, they assumed that the process was subject to disturbances that could produce a shift in the process mean by 1.5 S.D off the target. Therefore, this shift in the process mean results in the goal of 3.4 ppm, which represents 99.9997% of process yield (Montgomery, 2001).

$$PPM = \frac{\text{Defectives}}{\text{Production}} \quad (1)$$

The implementation of this method at Motorola increased the profit of 2.3 billion dollars in 1978, to 8.3 billion dollars in 1988 (Taghizadegan, 2006).

In the mid-90s, Jack Welch, CEO of General Electric, also adopted this methodology to fulfill the requirements imposed by the customers. This company spent half a billion in Six Sigma initiatives and received over two billion in benefits each fiscal year, since 2002. (Pande, Neuman, & Cavanagh, 2000). Thus, Six Sigma has been successfully applied in other manufacturing organizations, such as Boeing, DuPont, Toshiba, Kodak, Sony, etc. and became a well-established methodology in the manufacturing sector (Weiner, 2004). Furthermore, services providers have adopted this method, in particular, health and financial services.

Six Sigma is an organized structure, whose main purpose is to satisfy the customers' requirements by increasing the performance and profitability of companies by continuous improvement of the products and processes. To achieve this goal, organizations must reduce the variability of the critical parameters of the product or process by elimination of special causes. The Six Sigma level reflects the process performance, i.e., the ability to meet the specification.

To accomplish this goal it is necessary to involve everyone in the organization and use an extensive set of rigorous tools, such as statistical analysis, hypothesis tests, total management tools and statistical process control techniques (SPC).

In Portuguese companies, Six Sigma has still little expression (Cunha & Dominguez, 2015), therefore this article aims to explain the DMAIC procedure to improve the effectiveness and efficiency of a battery manufacturing process.

3. Methodology of the case study

The study took place at an AGM battery manufacturing company in Portugal in the cutting plates' process.

In this type of batteries, the electrolyte is completely absorbed in separators of fine fiberglass mat to prevent spill of electrolyte and the penetration of lead dendrites that might be formed at the negative plates. Figure 1 shows the main components in AGM battery.

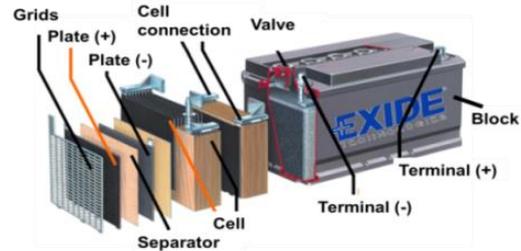


Figure 1 – The composition of AGM battery.

Plates are composed by grids and paste, which has the active material responsible for converting electrochemical to electrical energy. The plates are positive or negative according to their paste. Positive paste contains PbO_2 , while the negative consists in Pb.

AGM batteries also have fiberglass separators that are wrapped around the positive plates to prevent short-circuits and damages, and provide better contact between the electrolyte and the active material of the plates.

A cell or element is a set of positive and negative plates with separators and each one produces 2 V.

For a suitable transference of energy along the battery, the lugs of the plates must be aligned according to the polarity of each plate. Then, these lugs are welded together, which allow a uniform transfer of electrical current.

4. DMAIC approach

Six Sigma can follow three systematic data-driven approaches: DMAIC (Define-Measure-Analyze-Improve-Control) which improves existing processes, DMADV (Define-Measure-Analyze-Design-Verify) and DFSS (Design for Six Sigma), which are applied in reengineering or in new processes (De Feo & Barnard, 2005).

In this study, the DMAIC system, which has derived from Deming's PDCA cycle (Plan, Do, Check, Analyze) (Shewhart, 1931), aims to reduce the variability of the plates cutting height. This approach is defined by these five phases:

- (1) Define: identify the process, product, defects which have more scrap production and the parameter which will be analyzed;

- (2) Measure: includes the validation of measurement system and the data which allows to know the process behavior and capability;
- (3) Analyze: find the root causes that have more impact in the variability of cutting height;
- (4) Improve: develop solutions to eliminate the causes identified in the previous phase;
- (5) Control: implement control systems to maintain the process behavior in a long term.

4.1 Define phase

The Six Sigma project begins by defining the scope and the project variables. In this phase, the processes, products and defects with higher scrap production were identified through Pareto charts.

In the cutting process, there are many types of cutting machines due to the variety of plates that are produced in the curing process and sent to be cut. The Pareto charts in Figure 2 reveals that TBS 1 represents the process with higher scrap production (22% of total scrap production). TBS 1 is an automatic cutting machine that performs the cut of plates and lugs through discs and the cleaning of lugs by rotary brushes. After cutting the plates, operators remove the excess of lead and paste and also perform a visual inspection to detect nonconformities.

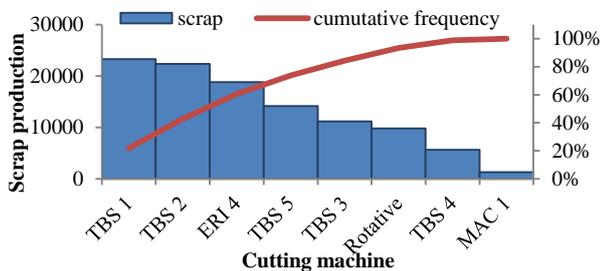


Figure 2 – Pareto chart of scrap production by cutting machine

The SIPOC (Suppliers, Inputs, Process, Outputs, Customers) diagram presented in Figure 3 is a data-collection form that assists in gathering information about the process. (ASQ, 2009)

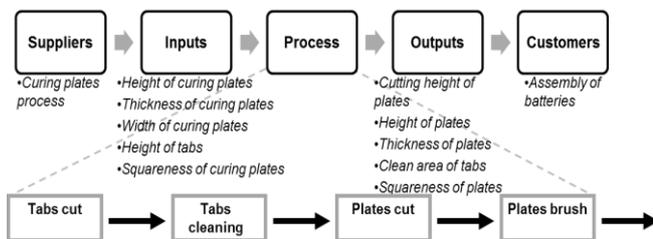


Figure 3- SIPOC diagram of cutting plates process.

In this case, the supplier is the curing process, in which after pasting, the plates are introduced in chambers with controlled temperature and humidity to convert the paste in active material. During the curing process, it is produced crystals that provide cohesion and adhesion properties to the paste.

The inputs of the cutting process represent the characteristic of curing plates that should be fulfilled by the suppliers. These inputs include height, thickness, width and the right-angled of plates.

In the cutting process, firstly the lugs are cut and cleaned, and then, the plates are cut through a central disc and brushed by operators. After a visual inspection, the plates are sent to be assembled.

The outputs include the main characteristics of plates that must be accomplished before the assembly process. These characteristics are the cutting height, thickness, right-angled of the plates and clean area of lugs.

The customer corresponds to the next process, in this case the assembly process, in which the plates form elements that are welded together to transfer electrical current along the battery.

The Pareto chart displayed in Figure 4 shows the scrap production by the type of unformed plates.

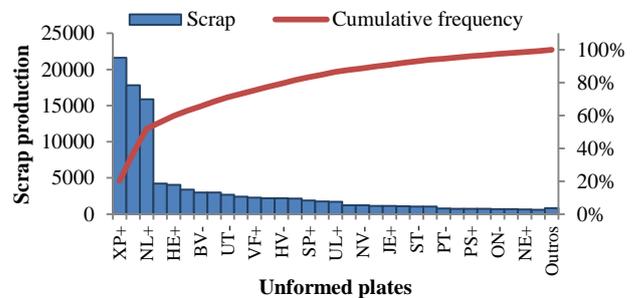


Figure 4-Pareto chart of scrap production by type of unformed plates.

The type of plates that produces more scrap is XP+, which represents 21% of the total scrap production. This type of plates comes from a double panel plate, therefore, one panel produces two plates.

After cutting the plates, operators do a visual inspection to detect non-conformities. The defective units that may not be repairable are introduced in boxes for subsequent registration in the SPC software. On the other hand, if the defects are repairable, some rework is performed at the end of the cut lines, and then the plates are sent to the assembly.

The Pareto Chart in Figure 5 shows the type of defects detected in XP+ plates.

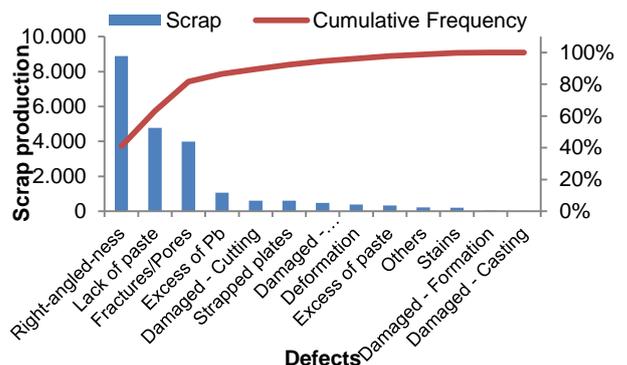


Figure 5 –Pareto chart of scrap production of XP+ plate by the type of defects.

The right-angled-ness of grids and the lack of paste are the most frequent defects in XP+ plates with 63% of the total rejection rate in the cutting section. Both nonconformities came from previous processes, in particular, the casting and the pasting of grids. The right-angled-ness impedes the cell to fit in the battery block, and also affects the cutting height of plates that, consequently, affects the welding of cells.

The cutting height presented in Figure 6, represents the total height of plates, which includes the height of the plate with the lug.

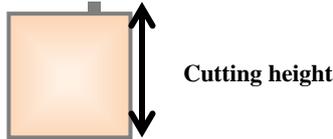


Figure 6 - Cutting height of plates.

The cutting height of plates is a critical parameter that should be monitored in the cutting process, because in AGM battery each cell is composed by separators and plates with lugs aligned by polarity. For this reason, the cutting height of plates must be the same according to their polarity, so the electrical current can be transferred along the battery. If there is a deviation, the cell construction and welding can be affected, therefore the transfer of energy is affected, inhibiting the battery performance. In Figure 7 a scheme of an AGM battery cell is presented.

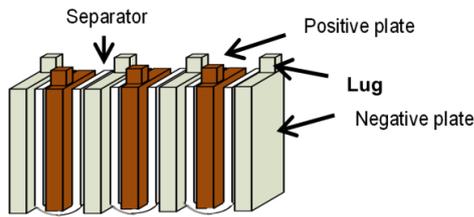


Figure 7 - Scheme of a AGM battery cell.

4.2 Measure phase

In the measure phase, some data was collected to allow the evaluation of the cutting process performance.

The XP+ plates are obtained from double-panel, therefore, each one produces two plates. The plates from the left and the right side of the cutting machine must be measured and analyzed separately, since the lugs are cut by different cutting discs.

The cutting height was measured by the digital caliper presented in Figure 8, which is connected to the SPC software that displays the results in form of control charts for a quick interpretation.

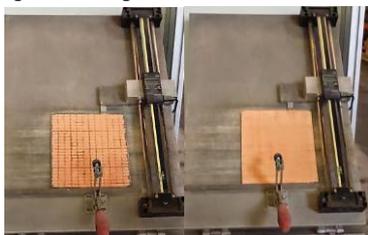


Figure 8 - Measurement method of cutting height plates.

The measure phase also incorporates a measurement system validation through a M.S.A. study that estimates the variation produced by the measurement equipment (digital caliper) and method. Therefore was performed a R&R test, which calculates the variation associated to reproducibility, repeatability and the differences between plates. Repeatability is the ability of an operator to consistently obtain the same measures with the same sample, using the same gage, under the same conditions. On the other hand, reproducibility is the ability of multiple operators to obtain the same measure of the same sample under the same conditions.

According to AIAG (Automotive Industry Action Group) guidelines, the measurement system to be acceptable must have (Automotive Industry Action Group, 2010):

- less than 30% of process's variation,
- less than 9% of contribution of variance components;
- at least 2 categories must be distinct.

The total variation of the R&R test and the total variation of the measurement system were calculated by Eqs. (2) and (3), respectively. (Minitab, 2015)

The study variation (Study Var) is the amount of variation caused by the measurement system and the differences between plates. The Study Var was obtained by Eq.(4) and its percentage by Eq. (5), which allows the evaluate the contributions of each component in the total variation (Minitab, 2015).

The number of distinct categories by the measurement system was obtained by Eq. (6). (Minitab, 2015). The results obtained in the M.S.A. study are represented in Table 1.

$$\sigma_{R\&R} = \sqrt{\sigma_{Repeat}^2 + \sigma_{Reprod}^2} \quad (2)$$

$$\sigma_{Total} = \sqrt{\sigma_{R\&R}^2 + \sigma_{part-to-part}^2} \quad (3)$$

$$Study\ Var = 6\sigma_i \quad (4)$$

$$\%Study\ Variation = \frac{\sigma_i}{\sigma_{Total}} \quad (5)$$

$$N^{\circ}\ distinct\ categories = NINT\left(\frac{\sigma_{part-to-part}}{\sigma_{R\&R\ total}} \times \sqrt{2}\right) \quad (6)$$

The variation of R&R test obtained was 18.6% and 23.1% for the plates of the left and the right side, respectively. The measurement system distinguishes 5 to 7 categories, which fulfill the requirements set by AIAG. In this case, the measurement system is acceptable for measuring the cutting height of plates, however it should be improved to reduce the variation, mainly the variation associated to the repeatability.

The repeatability represents the variation related to the measurement equipment (caliper). Therefore, the most suitable conditions for measuring the cutting height must be achieved to decrease the variation of gage R&R.

Table 1 – Percentage of study variation.

Source	Study Variation (%)	
	Plates from left side	Plates from right side
Total Gage R&R	18,61	23,12
Repeatability	18,21	23,02
Reproducibility	3,85	2,20
Part-to-part	98,25	97,29
Total Variaton	100	100
N° of distinct categories	7	5

Afterwards, some data was collected to evaluate the performance of the pretreatment process. The behavior of this process was analyzed by \bar{X}/R control charts and the capability was estimated by its indexes.

The control charts of cutting height from each side are presented in Figure 9 and Figure 10. Both control charts revealed that the cutting process was out of control and didn't fulfill the specification limits, since some plates had lower cutting heights than the specification limit (LSL). Moreover, the lower control limit (LCL) is below the lower specification limit (LSL), which indicates that the process behavior was not suitable for this specification.

The histograms of cutting height from each side are displayed in the Figure 11 and Figure 12. The process capability represents the ability of the process to obtain products according to specification. The capability compares the output with the specification limits by forming the ratio of spread between the process specifications and the spread of process values (6σ). The capability was estimated by the its indexes C_p , C_{pk} and C_{pm} that were calculated by Eqs. (7), (8) e (9), respectively. The results obtained for each side are described in Table 2.

$$C_p = \frac{USL - LSL}{6\sigma} \quad (7)$$

$$C_{pk} = \min\left(\frac{USL - \bar{x}}{3\sigma}; \frac{\bar{x} - LSL}{3\sigma}\right) \quad (8)$$

$$C_{pm} = \min\left(\frac{USL - Target}{6\sigma}; \frac{Target - LSL}{6\sigma}\right) \quad (9)$$

USL – Upper Specification Limit; LSL – Lower Specification Limit; σ – Standard deviation; \bar{x} – Population's mean.

The cutting process of the left side is capable to produce plates according to the specification ($C_p > 1$). However, the distribution of values was not centered on the mean, neither the target (C_{pm} , $C_{pk} < 1$), as is presented in Figure 11

On the other hand, the process of the right side is not capable to produce plates, since several plates have cutting heights lower than the specification (Figure 12).

Table 2 – Capability indexes for cutting height of plates from left and right side of the cutting machine.

Capability indexes	Plates from left side	Plates from right side
C_p	1,22	0,95
C_{pk}	0,28	0,28
C_{pm}	0,41	0,43

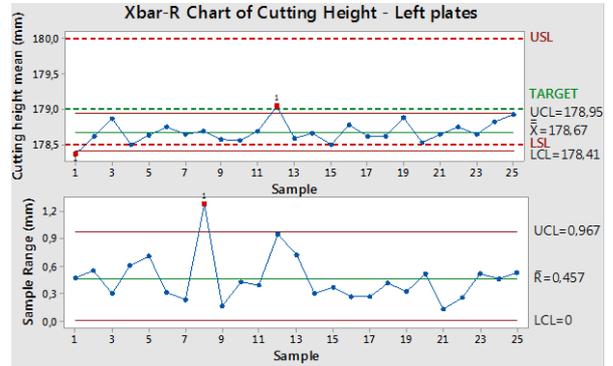


Figure 9 - Control chart of cutting height of plates from the left side of the cutting machine.

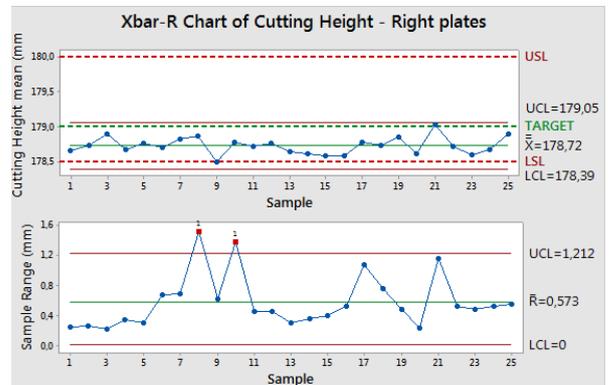


Figure 10 - Control chart of cutting height of plates from the right side of the cutting machine.

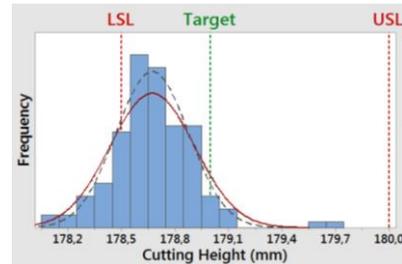


Figure 11 – Histogram of cutting height of plates from left side.

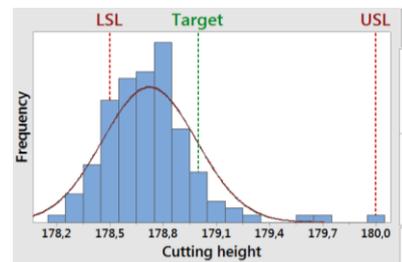


Figure 12 - Histograms of cutting height of plates from right side.

4.3 Analyze phase

The results obtained in the previous phase revealed that the performance level of the process was unsatisfactory, so it must be improved.

In Analyze phase, the root causes that increase the variability of the cutting height were identified by a cause and effect diagram presented in Figure 13. In this diagram, the causes were separated into six categories: Manpower, Environment, Material, Machine, Measure and Method. Then, the main causes were selected to be subsequently analyzed individually. In this case, the selected causes includes: the right-angled-ness of grids, the incorrect adjustment of cutting discs, the lack of operators training and cleaning procedure, the incorrect or lack of caliper calibration and the clearance between the plates and the caliper.

In Define phase was concluded that the most frequent defect was the right-angled-ness of grids, which can affect the cutting height of plates and, consequently, the transference of electrical current along the battery.

In Measure phase, several plates had lower cutting height than the lower specification limit due to the incorrect adjustment of the cutting discs. The cutting machine is composed by three discs: one central and two sideways that performed the cut of lugs. These discs should be spaced according to the specification.

Moreover, operators without proper training are inconsistent in the measuring procedure so they cause discrepancies in the cutting height.

During measurement, some Pb powder is deposited in the fix part of the caliper that also causes deviations in the cutting height.

Finally, some variability of the cutting height is produced by the measurement equipment. For instance, the incorrect or lack of calibration and the clearance between the caliper and the plates.

Afterwards, those selected causes were analyzed

individually by hypothesis tests, mainly by paired-test. The hypothesis test estimates the p-values that help to understand if the causes have significant impact in the cutting height. If a cause has a p-value lower than 0.05 (significant level), it is considered to be relevant to the cutting height.

The right-angled-ness of grids was analyzed by an attribute test, using a mold that has the dimensions described in the specification. Each sample was formed by 5 plates and the results were converted in the p control chart presented in Figure 14. This chart revealed this defect was out of control and also, the mean proportion of grids produced with this defect was 11.9%.

To understand if the right-angled-ness of grids was also detected in the cutting plates section, a test by variables was performed. In this test, the heights were measured in two distinct points for each plate and then were compared by a paired-test. The p-values obtained (0,000) led to conclude that there were significant differences between the two heights of each plates.

To analyze the adjustment of the cutting discs, some plates were measured to compare their heights to the specification limits. This analysis revealed that several plates were nonconforming and the average of cutting heights had a deviation of ~ -0.6 mm from the target. The cutting height of negative plates should be equal to the cutting height of positive plates plus the separator thickness. In this analysis, the positive plates exhibited to have more 0.5 mm than the negative plates, so it were reduced from 178,5-180 mm to 178-179,5 mm.

The deviations caused by the operators' lack of training were analyzed through the behavior of the measures range (~ 0.6 mm). The measurement method includes some crucial details that must to be accomplished to produce values approximately to the real ones, such as the calibration of the caliper, the position of plates, the measurement sequence, etc.

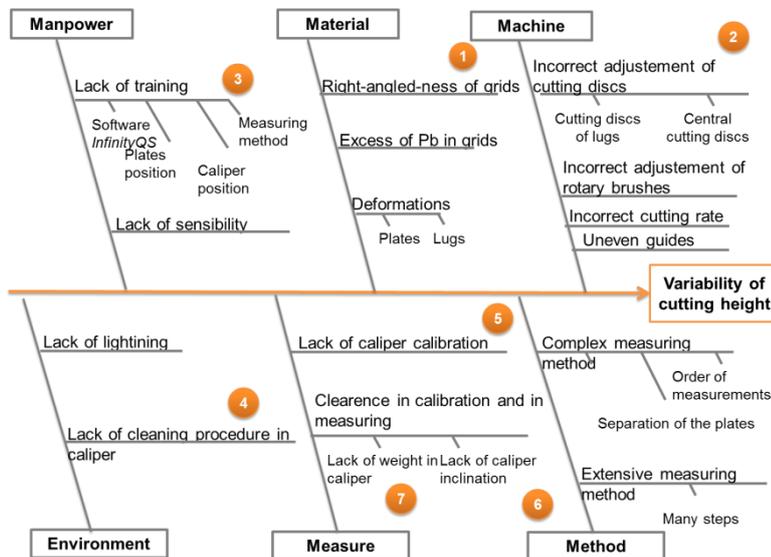


Figure 13 - Cause and effect diagram of cutting height variability

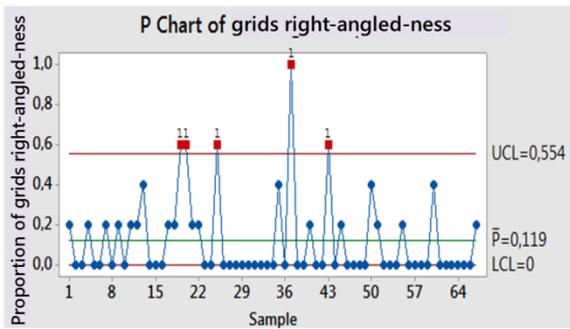


Figure 14 - Proportion control chart of grid right-angled-ness.

At the beginning of each measurement test, the caliper calibration must be performed to validate the measures heights. However, if the calibration is incorrectly or not performed, the values may not correspond to the real ones.

As discussed before, the measurement test releases Pb powder that causes a deviation of the cutting heights. To understand if a cleaning procedure reduces the variability of cutting heights, two tests were performed: with versus without the cleaning procedure, and another with cleaning at the beginning of each test versus cleaning between measurements. The p-values obtained in each test led to conclude that the cleaning procedure is required at least one time for test.

The clearance between the caliper and the plates can affect the caliper calibration and the measurement of the plates. To eliminate this failure, the inclination and the weight of the caliper were increased.

Firstly, the inclination of the caliper was increased from 50° to 70° and the cuttings of plates were compared by a paired-test that returned low p-values for each side (0.004 and 0.002). Therefore, the increase of caliper's inclination has significant impact in the cutting height.

The increase of the caliper weight caused a decrease in the clearance between the plates and the caliper. The heights were then compared by a paired-test, which demonstrated that the weight of caliper had significant impact in the measurement of the plates from the right side of the cutting machine. In the Table 3 are represented the p-values obtained in each hypothesis tests that allowed to identify the causes with higher impact in the cutting height of the plates.

In analyze phase, it was concluded that the right-angled-ness of grids, the cleaning procedure, the

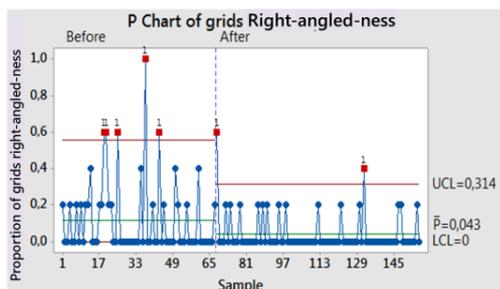


Figure 15 - Proportion Control chart of grids right-angled-ness.

Table 3 – p-values obtained in each test.

Test	p-value	
	Plates of left side	Plates of right side
Height of plates	0,000	0,000
Calibration of caliper	0,933	0,056
Measures with/without cleaning procedure	0,000	0,000
Caliper cleaning in the test's beginning or in every measure	0,185	0,752
Caliper's inclination	0,004	0,002
Caliper rule weight	0,533	0,006

increase of inclination and weight of the caliper caused significant differences in cutting height of the plates.

4.4 Improve phase

This phase describes the actions implemented in the cutting process and in the measurement system. These actions aim to eliminate the root causes that have higher impact in the cutting height. The condition of optimization is achievable by conducting experiments and analyzing the results with statistical tools.

Several changes were applied in the casting process to reduce the amount of right-angled-ness grids:

- A control of calcium content in the lead alloy, which promotes the grids' hardness;
- Changing the amount of cooling water to ensure fast solidification of grids;
- Changing the clearance between the guillotine and the transport rollers to avoid damaging;
- Adding a plastic o-ring on the transport rollers;
- Reducing the molds temperature.

In order to verify if those actions reduced the production of defective grids, an attributes test was performed, similar to the one described in Analyze phase. The results obtained are presented in the p control chart displayed in Figure 15. In this chart, there are some points out of control, although the process behavior has become more stable and the proportion of defective grids has decreased from 12% to 4%.

In Figure 16 is presented the scrap production of grids right-angled-ness, in order to verify if the changes in the casting process have reduced the scrap production in the cutting section, considering that these changes were implemented in March.

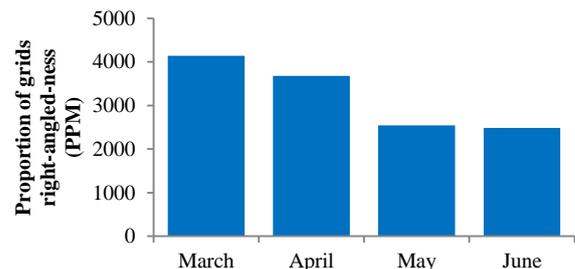


Figure 16 - Proportion of grids right-angled-ness in cutting area

The evolution of grids right-angled-ness presented in Figure 16 revealed that the scrap production has reduced 60% in the cutting section between March and June.

The next step to minimize the production of plates out of specification was the adjustment of the cutting discs. Once the specification has modified, the adjustment of discs has also changed accordingly to the new specification. The histograms of cutting height of plates collected from the left and right side of the cutting machine are represented in Figure 17 and Figure 18, respectively. The process capability was evaluated by the C_p , C_{pk} and C_{pm} indexes described in Table 4. In both sides, the cutting process capability has increased and the distribution became more centered on the specification limits and on target.

In Analyze phase, the operators training revealed to have impact in the cutting height. In order to implement a more consistent measurement method, training was provided to the operators. The control charts before and after training are displayed in Figure 19 and Figure 20 for each side. After training, the average of cutting height has increased, which indicated the caliper calibration was performed correctly. On the other hand, the range of measures has decreased, which proves that the measurement method became more consistent.

To remove the amount of Pb powder accumulated in the fix part of the caliper, in the beginning of the SPC tests, operators perform a cleaning procedure using a brush. During this implementation the cutting process was incapable to produce plates according to specification, however, after introducing the cleaning procedure, the capability increased, mainly in the right side, which has become capable to produce plates. The results obtained before and after the implementation of the cleaning procedure are presented in Table 5.

The clearance in the caliper was minimized by increasing the inclination and the weight of this equipment. These changes results in a better sliding of the caliper and also a better approach to the plate and to the fix part of the caliper. In this way, the cutting heights of plates increased, because the clearance in the calibration has more impact in the determination of this

parameter. Therefore the cutting heights are closer to the real values.

The process capability improved due to the increase of the cutting height caused by the change on the caliper inclination from 50° to 70° , as it is described in Table 6. In the left side, the cutting process has optimum capability to produce plates according to the specification. Although the right side is capable, the capability has greatly increased ($C_p > 2$), which indicates that the specification tolerance is very large to describe this process.

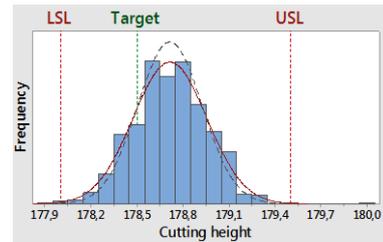


Figure 17 - Process capability for the plates of left side with new specification.

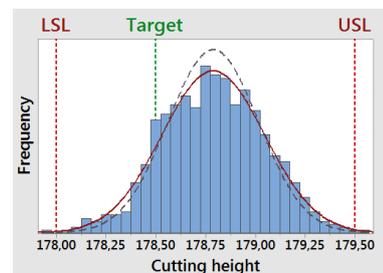


Figure 18 - Process capability for the plates of the right side with new specification.

Table 4 – Capability indexes of the plates cutting height obtained from the left and the right side of the cutting machine.

Capability Índexes	Before		After	
	Plates from left side	Plates from right side	Plates from left side	Plates from right side
C_p	1.09	0.99	1.18	1.09
C_{pk}	0.18	0.15	1.13	1.04
C_{pm}	0.34	0.33	0.51	0.43

Table 5 – Capability indexes in cutting process before and after implementing a cleaning procedure to the caliper.

Capability Índexes	Before		After	
	Plates from left side	Plates from right side	Plates from left side	Plates from right side
C_p	0.57	0.99	0.81	1.43
C_{pk}	0.31	0.88	0.54	0.96
C_{pm}	0.31	0.51	0.28	0.31

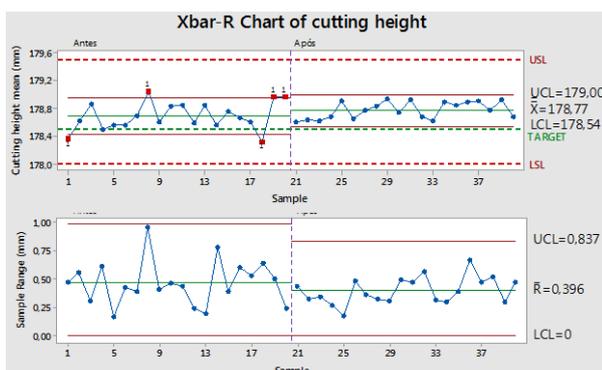


Figure 19 - Control Charts of Cutting Height of the left side with and without training.

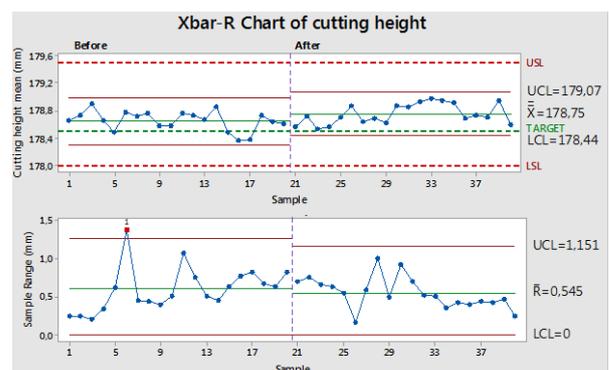


Figure 20 - Control Charts of Cutting Height of right side with and without training.

Table 6 – Process capability obtained with caliper inclination at 50° and 70°.

Capability Indexes	50°		70°	
	Plates from left side	Plates from right side	Plates from left side	Plates from right side
C_p	1.01	1.71	1.34	2.31
C_{pk}	0.99	1.47	0.74	1.36
C_{pm}	0.44	0.56	0.26	0.28

Furthermore to reduce the clearance of the caliper, its weight was also increased by adding a metal piece presented in Figure 21.



Figure 21 – a)Before, b)After adding the metal piece on the caliper.

The increase of weight has mainly reduced the clearance in the calibration and, consequently, has produced higher cutting heights that affected the process capability. In the Table 7 is described the capability indexes obtained before and after the increase of weight.

The process capability in both sides has decreased with the increase of calipers weight. The right side became incapable to produce plates according to specification. This decrease of the process capability indicates that the measurement system has become more accurate after adding the metal piece, revealing that the cutting process was not capable at that moment.

Table 7 – Process capability with and without the increase of calipers' weight.

Capability indexes	Before		After	
	Plates from left side	Plates from right side	Plates from left side	Plates from right side
C_p	1.26	1.16	1.17	0.98
C_{pk}	1.13	1.07	0.89	0.85
C_{pm}	0.56	0.40	0.33	0.37

After the changes have been implementing, another M.S.A. study was conducted to check if the variation associated to the measurement system has reduced. The results obtained for this R&R test are described in Table 8.

Comparing the results obtained in each M.S.A. studies, (Table 1 and Table 8), the variation of the R&R

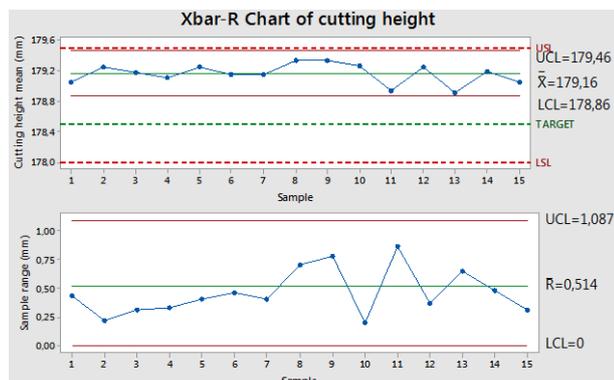


Figure 22 - Control charts of plates cutting height from the left side of the cutting machine

test has decreased. In the left side, the variation reduced from 18% to 13%, while in the right side decreased from 23% to 18%. This change was mainly due to the repeatability of values, indicating that the measurement equipment became more suitable for measuring cutting heights.

Table 8 –The variation and the contribution of components in the measurement system.

Variation source	Left side			Right side		
	σ (mm)	Contrib. (%)	Study Var (%)	σ (mm)	Contrib. (%)	Study Var (%)
Repeat	0,06	1,4	11,7%	0,06	3,2	18,0%
Reproduct	0,03	0,5	6,8%	0,01	0,1	3,8%
Test R&R	0,06	1,8	13,6%	0,06	3,4	18,4%
Part-part	0,47	98,2	99,1%	0,32	96,6	98,3%
Total Var	0,48	100,0	100,0%	0,32	100,0	100,0%
Distinct categories		10			7	

4.5 Control phase

In the Control phase several actions were suggested to maintain the process in control, such as corrective actions charts, visual aids, quality control instruction plans, etc.

The corrective actions chart helps operators to know how to act in the presence of nonconformities or failures.

The quality control instruction plan describes the SPC test of cutting heights, such as, the sample dimension, frequency, measurement equipment, etc.

The visual aids aim to assist the operator during the SPC test, which includes warnings and images in the software and the shop floor, where the SPC test is performed. When the cutting height exceeds the control limits or the specification limits, the background of control charts turns to yellow or red to alert the operators.

In Figure 22 and Figure 23 are demonstrated the profile of cutting height in control after every single improvement actions described previously. The average of cutting heights is higher than the target, therefore the discs must be adjusted again to produce plates with lower cutting heights.

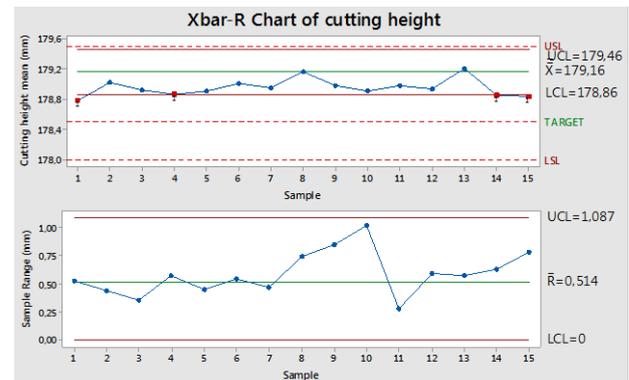


Figure 23 - Control charts of plates cutting height from the right side of the cutting machine.

5. Conclusion

This article describes the development of a Six Sigma project in the plates cutting process, which aims to reduce the variability of the cutting height. A deviation in this parameter affects the assembly of batteries and, consequently, their performance.

This study was developed by the DMAIC approach formed by five phases: Define, Measure, Analyze, Improve and Control. In this study the cutting height of XP+ plates produced by TBS 1 was analyzed and measured by a digital caliper. To validate the measurement system, a M.S.A. study was performed and revealed that it was acceptable for measuring the cutting height of plates.

Initially, the process revealed to be incapable to obtain plates according to the specification, since several had lower heights than the lower specification limit.

Subsequently, the root causes responsible for the variability of cutting height were identified and the more important were selected and analyzed individually. The right-angled-ness represents the main defect detected in the cutting section, therefore some changes were made in the casting process, which led to the reduction of the scrap production from 12% to 4%.

Moreover, the specification of cutting height was changed because there was a deviation between the total height of positive and negative plates. Thus, the cutting discs were adjusted according to this new specification, which led to an improvement of the process capability.

In order to reduce the variance caused by the measurement system, training to operators and better conditions for measuring the cutting height were provided. Firstly, a daily training to operators was conducted, which increased the consistency of the measurement method. Subsequently, a cleaning caliper procedure was introduced to remove the powder that causes deviations in cutting height. Finally, the inclination and the weight of the caliper were both increased to minimize the clearance in the caliper during calibration and measurement.

After all changes in the measurement system were implemented, the cuttings heights have increased mainly due to ease in calibration provided by the increase of calipers' inclination and weight. The range also has decreased because the measurement method became more consistent. For these reasons, the cutting heights are closer to the real values.

The overall effectiveness improved by identifying and analyzing the critical components of the cutting process and of the measurement system. The increase of the process capability has to be continuously pursued to achieve the goal of 3.4 ppm.

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