Application of Six Sigma Methodology to Reduce Defects of a Grinding Process

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Six Sigma is a data-driven leadership approach using specific tools and methodologies that lead to fact-based decision making. This paper deals with the application of the Six Sigma methodology in reducing defects in a fine grinding process of an automotive company in India. The DMAIC (Define–Measure–Analyse–Improve–Control) approach has been followed here to solve the underlying problem of reducing process variation and improving the process yield. This paper explores how a manufacturing process can use a systematic methodology to move towards world-class quality level. The application of the Six Sigma methodology resulted in reduction of defects in the fine grinding process from 16.6 to 1.19%. The DMAIC methodology has had a significant financial impact on the profitability of the company in terms of reduction in scrap cost, man-hour saving on rework and increased output. A saving of approximately US$2.4 million per annum was reported from this project. Copyright © 2011 John Wiley & Sons, Ltd.

Keywords: Six Sigma; Kappa statistic; process capability evaluation; chi-square test; ANOVA; Taguchi methods

1. Introduction

Six Sigma is a well-structured methodology that focuses on reducing variation, measuring defects and improving the quality of products, processes and services. Six Sigma methodology was originally developed by Motorola in 1980s and it targeted a difficult goal of 3.4 parts per million defects[1]. Six Sigma has been on an incredible run over 25 years, producing significant savings to the bottom line of many large and small organizations[2]. Leading organizations with a track record in quality have adopted Six Sigma and claimed that it has transformed their organization[3]. Six Sigma was initially introduced in manufacturing processes; today, however, marketing, purchasing, billing, invoicing, insurance, human resource and customer call answering functions are also implementing the Six Sigma methodology with the aim of continuously reducing defects throughout the organization's processes[4].

According to Harry and Schroeder[5], Six Sigma is a powerful breakthrough business improvement strategy that enables companies to use simple and powerful statistical methods for achieving and sustaining operational excellence. It is a business strategy that allows companies to drastically improve their performance by designing and monitoring everyday business activities in ways that minimize waste and resources while increasing customer satisfaction[6]. The Six Sigma approach starts with a business strategy and ends with top-down implementation, having a significant impact on profit, if successfully deployed[3]. Numerous books and articles provide the basic concepts and benefits of the Six Sigma methodology. These publications cover topics, such as What is Six Sigma[3]? Why do we need Six Sigma[7]? Six Sigma deployment[8]; critical success factors of the Six Sigma implementation[4]; Hurdles in the Six Sigma implementation[9]; the Six Sigma project selection[10] and organizational infrastructure required for implementing Six Sigma[11]. Numerous articles are available in different aspects of Six Sigma over the past 10 years[12–17]. The Six Sigma approach has been widely used to improve performances and reduce costs for several industrial fields[18–22].

This paper presents the step-by-step application of the Six Sigma DMAIC (Define–Measure–Analyse–Improve–control) approach to eliminate the defects in a fine grinding process of an automotive company. This has helped to reduce defects in the process and thereby improve productivity and on time delivery to customer. During the measure and analyse phases of the project, data were collected from the processes to understand the baseline performance and for validation of causes. These data were studied through various graphical and statistical analyses. Chi-square test, ANOVA[23], Design of Experiments (DOE) [24], Control Charts[25], Taguchi methods[26], etc. were used to make meaningful and scientifically proven conclusions about the process and the related causes.

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The structure of this article is as follows. The research methodology adopted for this study is explained in Section 2. Section 3 explains an introduction to the case study, Section 3.1 indicates the define phase, Section 3.2 details the measure phase with baseline performance. The Analyse phase is explained in Section 3.3 with details of potential causes and its validation followed by the Improvement phase in Section 3.4 with details of solutions implemented. Section 3.5 explains the controls introduced to ensure sustainability of the results. Section 4 provides information about the lessons learned followed by Section 5, the managerial implications of the initiative. Section 6 presents the concluding remarks and discusses the benefits and limitations of the study.

2. Research methodology

This section explains the methodology adopted for this case study. Scientific investigation on innovating a system or improvement to the existing one needs to begin with some structure and plan. This structure and plan of investigation were conceived so as to obtain answers to research questions in the research design[27]. The researcher worked with the company to provide support for the project in the Six Sigma techniques, whilst recording data about the exercise from which to develop a case study. A literature review was undertaken with an objective of identifying the past history of various improvement initiatives carried out to address process-related problems.

The methodology is divided into four major sections namely problem definition, literature survey, case study design and data analysis. Based on the available data on the process, the team studied the baseline status of the process and drafted a project charter, which explains the details of the problem. A detailed literature review was undertaken in Six Sigma with an objective of identifying the type of improvements carried out by different people in various organizations to address process-related problems.

A case study entails the detailed and intensive analysis of a single case—a single organization, a single location or a single event[28]. Yin[29] describes a case study as an empirical inquiry that investigates a contemporary phenomenon within its real-life context. According to Lee[30], the unit of analysis in a case study is the phenomenon under study and deciding this unit appropriately is central to a research study. In this paper, a case study is designed to study the underlying process problem so that solutions can be implemented for process improvement. The collected data were analysed using descriptive and inferential statistics. Measurement system analysis, chi-square test, ANOVA, DOE with Taguchi methods, etc. were used for analysing the data and inferences were made. Graphical analyses, such as histogram and control chart, were also utilized for summarizing the data and making meaningful conclusions. Minitab statistical software was used to analyse the data collected at different stages in the case study.

3. Case study

This case study deals with the reduction of defects in the fine grinding process in an automobile part manufacturing company in India. The company with manpower of approximately 2550 people is manufacturing common rail direct injection (CRDI) system pumps for vehicles. These pumps were used in cars, trucks and buses throughout the world. An injector primarily consists of nozzle and nozzle holder body. A schematic view of fuel injector is given in Figure 1. The components used in fuel injector and
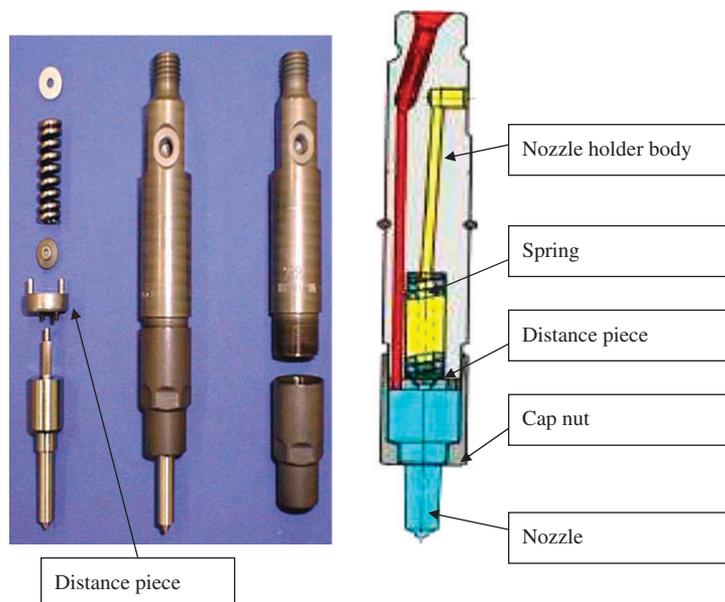

Nozzle holder body

Spring

Distance piece

Cap nut

Nozzle

Distance piece

Figure 1. Schematic view of fuel injector

their functions are as follows. Distance piece aligns the high-pressure fuel lines of nozzle holder body and nozzle. Its both sides are fine ground precisely to ensure sealing of the high-pressure fuel coming from holder body to nozzle. Cap nut retains the nozzle and distance piece with the holder body with sufficient torque to ensure sealing. Spring and pressure bolt ensures the functioning of injector with set opening pressure and timely delivery of fuel.

The current project was undertaken in the distance piece fine grinding process, which is done by fine grinding machine. Different types of distance pieces were fine ground in this machine. This is a sophisticated and very expensive CNC fine grinding machine. It finishes both faces of distance pieces in batches precisely with sub-micron flatness values.

After fine grinding, distance pieces were inspected visually to find various defects. Since the production of distance pieces were in thousands per shift, it was not practically possible to do 100% inspection of these components by objective methods. Hence visual inspection was carried out for all the components with reference to master pieces and visual limit samples. Since the rejection level of distance pieces after fine grinding process was very high and the function of the component in the product was highly critical, it was essential to do 100% inspection. Under these circumstances, the project was of highest priority to the management as it was clear that an effective solution to this problem would have a significant impact in reducing rework/rejection and improving productivity. Also, it was clear to the team members and champion of the project that the elimination of this problem will help the organization to cater to the increasing demand of market. In the past, many attempts were made to solve this problem by using different methodologies, which were unsuccessful. The Six Sigma problem solving methodology (DMAIC) was recommended when the cause of the problem is unclear[3]. Hence, it was decided to address this problem through the Six Sigma DMAIC methodology.

3.1. Define phase

This phase of the DMAIC methodology aims to define the scope and goals of the improvement project in terms of customer requirements and to develop a process that delivers these requirements. The first step towards solving any problem in the Six Sigma methodology is by formulating a team of people associated with the process. The team selected for this project includes the Senior Manager—Manufacturing as the Black Belt (BB). The other members of the team were Planning Manager, Maintenance Manager, Quality Control Senior Engineer and one Machine Operator. BB acts as the team leader, and was responsible for the overall success of the project. In this particular project, BB himself was the process owner. The primary responsibility of team members was to support BB in executing the project-related actions. The Head of manufacturing department was identified as the Champion and the Head of Business Excellence department as master black belt (MBB) for this project. The team along with the Champion and MBB developed a project charter (Appendix 1) with all necessary details of the project. This has helped the team members to clearly understand the project objective, project duration, resources available, roles and responsibilities of team members, project scope and boundaries, expected results from the project, etc. This creates a common vision and sense of ownership for the project, so that the entire team is focused on the objectives of the project.

The team had several meetings with the Champion and MBB to discuss various aspects of the problem, including the internal and customer-related issues arising because of this problem. The team decided to consider the rejection percentage of distance pieces after fine grinding process as the Critical to Quality (CTQ) characteristic for this project. The goal statement was defined as the reduction in rejection of distance pieces by 50% from the existing level, which should result in large cost saving for the company in terms of reduction in rework and scrap cost.

Since there was a cross-functional team for executing this project, the team felt that it was necessary to perform a SIPOC (Supplier–Input–Process–Output–Customer) analysis to have a better understanding of the process. This is a method similar to process mapping for defining and understanding process steps, process inputs and process outputs[3]. The team with the involvement of people working with the process prepared a SIPOC mapping along with a basic flowchart of the process. This SIPOC has given a clear understanding of the process steps needed to create the output of the process. Through this exercise, the team got the clarity of the project in terms of the scope of the project, inputs, outputs, suppliers and customers of the process. The team focused on the fine grinding process for improvement that is defined as the scope of the project. The process mapping along with SIPOC is presented in Appendix 2.

3.2. Measure phase

The objective of the measure phase is to understand and establish the baseline performance of the process in terms of process capability or sigma rating. The CTQ considered in this case was the rejection percentage of distance pieces after the fine grinding process. These rejections were mainly due to the occurrence of different types of defects, such as burr, shades, deep lines, patches and damage, on the component after machining. The schematic representation of these defects is presented in Figure 2. These defects create an uneven surface in the component that could lead to fuel leakages in pumps. After machining, the components were visually inspected for these defects. Master samples were provided for identifying each of these defects and inspectors did the inspection. Since there was no instrument involved in the inspection process and only visual inspection was performed, before going ahead with further data collection, the team decided to carry out Attribute Gage Repeatability and Reproducibility (Gage R & R) study to validate the measurement system. In such studies, intra-inspector agreement measures repeatability (within inspector), inter inspector agreement measures the combination of repeatability and reproducibility (between inspectors)[31]. The non-chance agreement between the two inspectors, denoted by *Kappa*, defines as

$$\kappa = \frac{\text{Number of observed agreements} - \text{Number of expected agreements}}{\text{Total number of observations} - \text{Number of expected agreements}}.$$
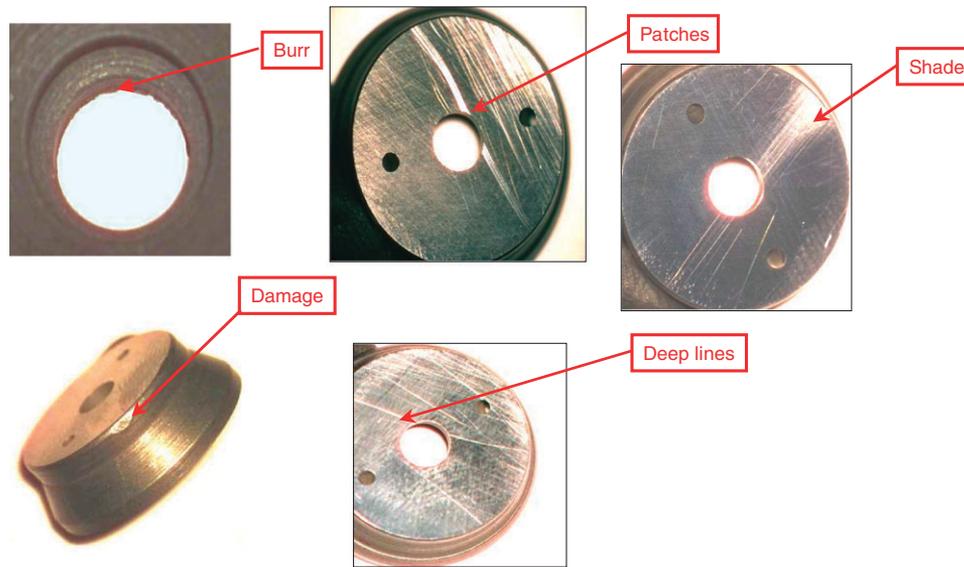
Figure 2. Schematic representation of defects

Table I. Data collection plan				
Characteristic	Data type	How measured	Sampling notes	Related conditions
Rejection percentage of distance pieces after the fine grinding process	Attribute	Visual checking by comparing with visual limit samples	100% of units in all the three shifts for two months	Shift wise and defect type wise

For conducting the study, 100 components were selected and they were classified as good or bad independently by two inspectors. From the resulting data, the *Kappa* value was calculated and was found to be 0.814 with a standard error of 0.0839. Since the *Kappa* value was more than 0.6, the measurement system was acceptable[31].

After the measurement system study, a data collection plan was prepared with details of types of data, stratification factors, sampling frequency, method of measurement, etc. for the data to be collected during the measure phase of this study. The data collection plan thus prepared is presented in Table I. The data were collected as per the plan to understand the baseline status of the process. During the defined period of data collection, 368 219 components were inspected and 61 198 components were rejected due to various defects. Each one of the rejected components was having one or more defects. The detailed data on the type of defects were collected and the same was graphically presented as a pareto diagram (Figure 3). The collected data shows that the rejection in the process was 166 200 PPM. The corresponding *sigma rating* of the process can be approximated to 2.47.

For any improvement initiative in this organization, the general goal set by the management was to reduce the rejection by 50% from the existing level. Based on this policy, the target set for the study was to reduce the rejections at the fine grinding process to 83 100 PPM from the existing level of 166 200 PPM.

3.3. Analyse phase

After mapping the process, the team proceeded to analyse the potential causes of defects. A cause and effect diagram was prepared after conducting a brain storming session with all the concerned people from the process along with the project team, Champion and MBB. The output of the cause and effect diagram depends on a large extent on the quality and creativity of the brain storming session[32]. Figure 4 illustrates the cause and effect analysis prepared during the brain storming session.

The next step in this phase was to gather data from the process in order to obtain a better picture of the potential causes, so that the root cause/s can be identified. The team had detailed discussion with the process personnel to identify the possible data that can be collected on the potential causes in the cause and effect diagram. After getting the detailed picture of availability of data on causes, the team discussed with MBB to identify the type of analysis possible on these causes. Based on this discussion, a cause validation plan was prepared to detail the type of data to be collected and the type of analysis possible for each of these causes. The potential causes, such as 'variation in input parts', 'supplier material variation' and 'program parameters not OK', can be validated by statistical analysis on the data collected from the process. But potential causes, such as 'improper cleaning after dressing' and 'repair batches mix up', have to be validated only by observing the process (gemba). Hence for few causes, detailed data were collected and statistical analyses were planned, and for the remaining causes *gemba* was planned to validate the causes. Table II summarizes the potential causes and the type of analysis planned for each cause.
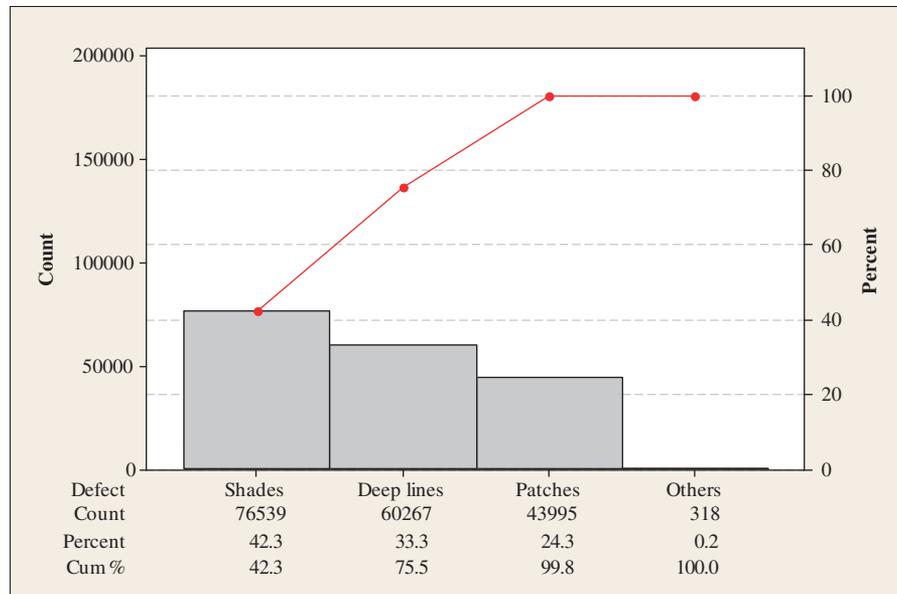
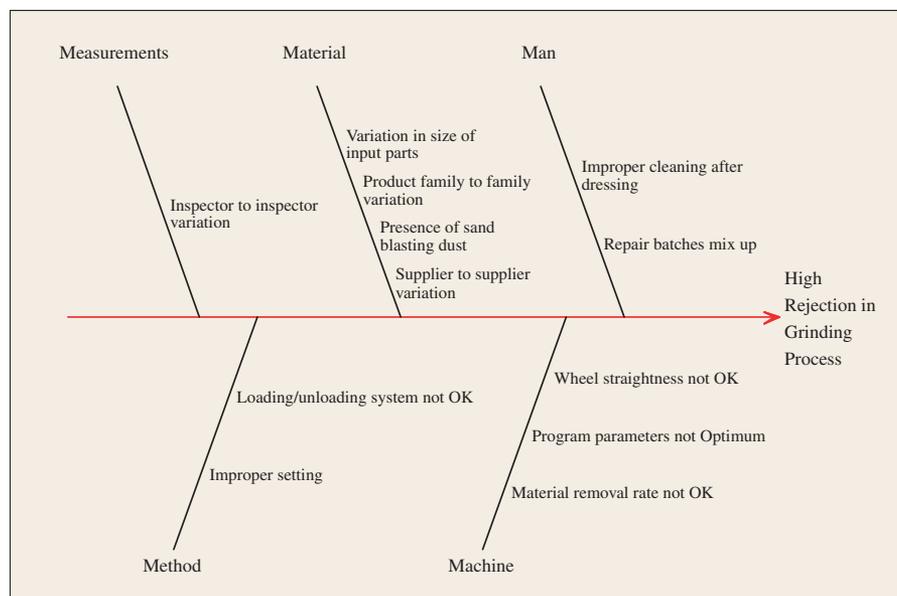**Figure 3**. Pareto diagram for visual defects

Figure 4. Cause and effect diagram for rejection in grinding process

As three different suppliers provided the raw material, it was suspected that there was possibility of supplier-to-supplier variation with respect to the thickness of input raw material. To study this variation, the data on the thickness of components from all the three suppliers were collected and ANOVA (A statistical procedure used to determine the significant effect of a variable under study[23].) was performed in the data and *p-value* was observed. *P*-value is a means for judging the significance of a statistical test. The smaller the *p-value*, the more significant the results are. Typically values below 0.05 are considered indicative of a significant test outcome[25]. In this case, *p-value* was found to be 0.407, ruling out the possibility of significant difference between the suppliers[23]. Further to validate the potential cause of variation in size of input parts, a batch of 57 *distance pieces* were selected and thickness measured. The data were subjected to *Anderson Darling* Normality test, and found to follow normal distribution[23]. Process capability study was carried out on this data and found to be capable, confirming that the thickness variation in input part was not a root cause[33]. The Process capability study is a comparison of the process output with customer requirements to determine whether a process is capable of meeting customer expectations[25]. The Minitab statistical software output of process capability evaluation is presented in Figure 5.

Table II. Cause validation plan

Sl. no	Cause	Plan for validation
1	Improper cleaning after dressing	GEMBA
2	Repair batches mix up	GEMBA
3	Variation in size of input parts	Process capability analysis
4	Product family to family variation	Chi-square test
5	Presence of sand blasting dust	GEMBA
6	Supplier to supplier variation	ANOVA
7	Material removal rate not OK	ANOVA
8	Process parameters not Optimum	Design of experiments (DOE)
9	Improper setting	DOE
10	Loading/unloading system not OK	GEMBA
11	Wheel straightness not OK	GEMBA
12	Inspector to inspector variation	Gauge R & R

Process Capability Analysis for Thickness

Process Data	
USL	3.16000
Target	*
LSL	3.11000
Mean	3.13937
Sample N	57
StDev (Overall)	0.0045027

Overall Capability	
Pp	1.85
PPU	1.53
PPL	2.17
Ppk	1.53
Cpm	*

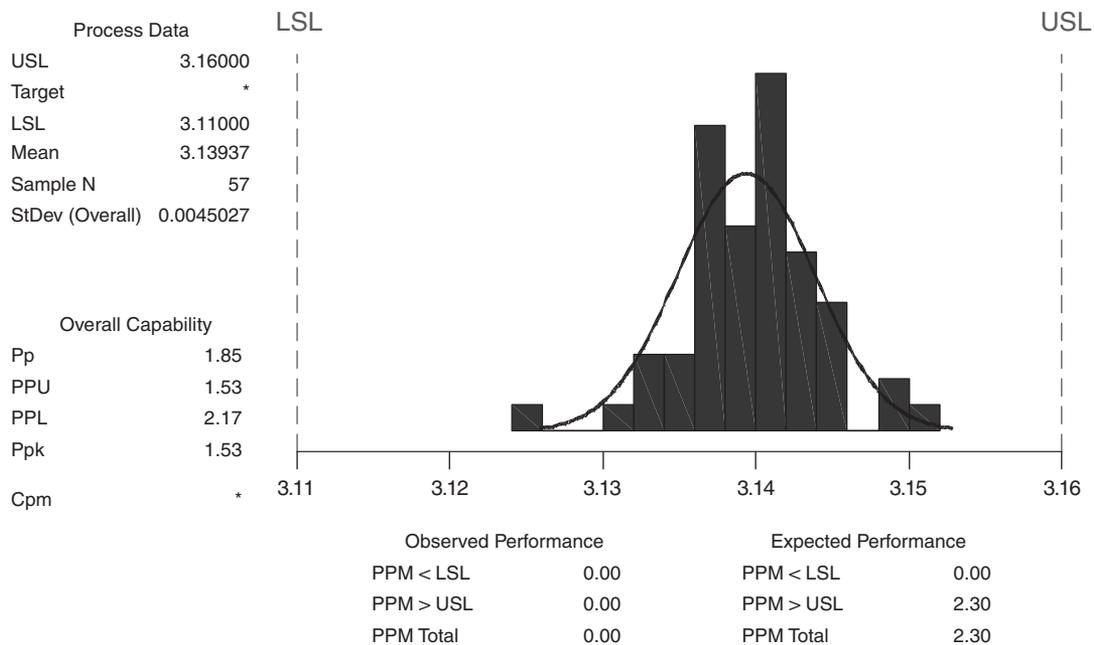| Observed Performance		Expected Performance	
PPM < LSL	0.00	PPM < LSL	0.00
PPM > USL	0.00	PPM > USL	2.30
PPM Total	0.00	PPM Total	2.30

Figure 5. Process capability analysis

Since different families of products were produced, data were collected for material removal rate (MRR) as well as defects with respect to various families of components to test their significance. Data on MRR were collected on three types of components to study the effect of type of component on MRR. Based on the quantity of material removed from the component during machining, the MRR value was calculated by an inbuilt software program in the machine. These MRR data were recorded in millimeter/minute. ANOVA was performed on this data and *p-value* was found to be 0.085, not showing significance at 5% level[23]. To test whether product family-to-family variation affects the defects, a chi-square test was carried out between defect type and family of components[23]. For each of the defect types, *viz.*, patches, shades and deep lines, separate chi-square test was done with three different families of components. The details of chi-square test are given in Table III. From Table III, it was clear that except for shades, family-to-family variation does not affect visual defects. The machining program and machine parameters for each family and type were different. The team thought, it was better to have a uniform machining program and parameters for all the family components so that the process can be better managed. Hence for validating the process parameters and identifying the optimum operating conditions, the team decided to conduct a DOE during the improve phase. DOE is a technique for understanding variability, in which factors are systematically and simultaneously manipulated while the variability in outputs (responses) is studied to determine which factors have the biggest impact[24].

The other causes listed in the cause and effect diagram were validated by gemba analysis. Some of the details are presented in Table IV. The details of validation of all causes in the cause and effect diagram are summarized in a tabular format and is given in Table V.

Table III. Test statistic values for Chi-square test

Defect type	Chi-square statistic	Degrees of freedom	*p*-value
Patches	2.509	2	0.285
Deep lines	2.398	2	0.301
Shades	452.256	2	0.000

Table IV. Gemba observations

Sl. no.	Cause	Observation/conclusion
1	Improper cleaning after dressing	It was observed that cleaning done after dressing. Not a root cause.
2	Repair batches mix up	Repair batches were found mixed with other batches during the random visit to the process. Root cause.
3	Presence of sand blasting dust	Traces of shot blasting dust found in the input batch during inspection. Root cause.
4	Loading/unloading system not OK	Loading table wear out observed at the edges. Root cause.
5	Wheel straightness not OK	Wheel straightness found OK. Checking frequency followed as per procedure. Not a root cause.

Table V. Summary of validation of causes

Sl. no.	Cause	Tools used for validation	Results
1	Improper cleaning after dressing	GEMBA	Not a root cause
2	Repair batches mix up	GEMBA	Root cause
3	Variation in size of input parts	Process capability analysis	Not a root cause
4	Product family to family variation	Chi-square test	Root cause
5	Presence of sand blasting dust	GEMBA	Root cause
6	Supplier to supplier variation	ANOVA	Not a root cause
7	Material removal rate not OK	ANOVA	Root cause
8	Process parameters not optimum	DOE	Root cause
9	Improper setting	DOE	Root cause
10	Loading/unloading system not OK	GEMBA	Root cause
11	Wheel straightness not OK	GEMBA	Not a root cause
12	Inspector to inspector variation	Gauge R & R	Not a root cause

3.4. Improve phase

This phase of the Six Sigma project is aimed at identifying solutions for all the root causes identified during the Analyse phase, implementing them after studying the risk involved in implementation and observing the results.

At this stage, as decided earlier, a DOE was planned for optimizing the process/machine parameters. The team along with champion, MBB, the production supervisor and operators of the process conducted a series of brain storming sessions to identify the important parameters for experimentation. The parameters selected through these discussions were *load applied*, *initial load setting*, *coolant flow rate*, *upper wheel rpm*, *lower wheel rpm* and *cage rpm*. Since the relationship between these parameters and MRR was not known, it was decided to experiment all these parameters at three levels[26]. The existing operating level was selected as one level for experimentation. The team based on various operational feasibilities selected the other two levels. The parameters and levels selected for experimentation are presented in Table VI. Also, the team felt there is a possibility of interaction between *load applied* with *upper wheel rpm*, *load applied* with *lower wheel rpm* and *load applied* with *cage rpm*. Hence it was decided to estimate the effect of these three interactions also. Six parameters at three levels and three interactions with replications require a huge number of components for conducting a full factorial experiment, which would be a costly and time-consuming exercise[24]. It was possible to estimate the effect of these selected parameters and interactions using the 27 experiments with the help of Orthogonal Array (OA). Hence for conducting an experiment with six parameters and three interactions, $L_{27}(3^{13})$ orthogonal array was selected[34]. As the name suggests, the columns of this array are mutually orthogonal. Also, experiments using orthogonal arrays play a crucial role in achieving additivity of the model effects[34]. The design layout prepared as per $L_{27}(3^{13})$ orthogonal array is given in Table VII. The response of the experiment was decided as material removal rate (MRR).

As per the design layout given in Table VII, the experiments were conducted after randomizing the sequence of experiments, and the data were collected[32]. The experimental data were analysed by Taguchi's *Signal-to-Noise (S/N)* ratio method[35]. The S/N ratio is advocated in the Taguchi method to maximize the performance of a system or product by minimizing the effect of noise[36]. The S/N ratio can be treated as a response (output) of the experiment, which is a measure of variation when uncontrolled

Table VI. Process parameters and their levels

Sl. no.	Factor	Levels		
1	Load applied	170	200*	230
2	Initial load setting	Minimum	Medium	Maximum*
3	Coolant flow rate	8 LPM	12 LPM	16 LPM*
4	Upper wheel RPM	70*	90	110
5	Lower wheel RPM	50*	60	70
6	Cage RPM	20*	30	40

*Existing levels.

Table VII. Design layout for experimentation

Exp. no.	Load	Setting	Coolant	UW RPM	LW RPM	C RPM
1	170	Min.	8 LPM	70	50	20
2	170	Min.	8 LPM	90	60	30
3	170	Min.	8 LPM	110	70	40
4	170	Med.	12 LPM	70	60	40
5	170	Med.	12 LPM	90	70	20
6	170	Med.	12 LPM	110	50	30
7	170	Max.	16 LPM	70	70	30
8	170	Max.	16 LPM	90	50	40
9	170	Max.	16 LPM	110	60	20
10	200	Med.	16 LPM	70	50	20
11	200	Med.	16 LPM	90	60	30
12	200	Med.	16 LPM	110	70	40
13	200	Max.	8 LPM	70	60	40
14	200	Max.	8 LPM	90	70	20
15	200	Max.	8 LPM	110	50	30
16	200	Min.	12 LPM	70	70	30
17	200	Min.	12 LPM	90	50	40
18	200	Min.	12 LPM	110	60	20
19	230	Max.	12 LPM	70	50	20
20	230	Max.	12 LPM	90	60	30
21	230	Max.	12 LPM	110	70	40
22	230	Min.	16 LPM	70	60	40
23	230	Min.	16 LPM	90	70	20
24	230	Min.	16 LPM	110	50	30
25	230	Med.	8 LPM	70	70	30
26	230	Med.	8 LPM	90	50	40
27	230	Med.	8 LPM	110	60	20

noise factors are present in the system[34]. Since the requirement of this process was to remove materials in a uniform rate from distance pieces to achieve specified dimension, the *S/N ratio* of *nominal-the-best* type was selected for analysis[36]. The S/N ratio for nominal the best type characteristic was defined as $10*\log((\bar{Y}^2)/s^2)$, where $\bar{Y}$ is the average and s, the standard deviation for each experiment[26]. The S/N ratio values were estimated for all the 27 experiments and ANOVA was performed on these S/N values to identify the significant parameters and interactions. From the ANOVA table (Table VIII), it was clear that the interaction effect between *load applied* and *upper wheel rpm* was significant at 5% level of significance. Also, parameters *setting* and *lower wheel rpm* were significant at 10% level of significance. The main effect (the change in average response produced by a change in the level of the factor[24]) and interaction (a measure of the degree to which the effect on the response of one factor is dependent upon the settings of one or more other factors[24]) plots of the S/N ratio values were made with the help of Minitab statistical software and are presented in Figures 6 and 7. From these plots, the best levels for parameters were identified as the level corresponding to highest value of *S/N* ratio[35]. Thus, the best levels for *load applied* and *upper wheel rpm* were selected from the interaction plot and the best levels for the other parameters were selected from the main effect plot. The optimum combination for process parameters thus arrived at is given in Table IX. One important point to be noted here is that for the factor *load applied*, the best level from the main effect plot was 230 daN and that from the interaction plot was 170 daN. This shows the importance of estimating interaction effect during the DOE study.

| Table VIII. ANOVA table for S/N ratio						
Source	DF	Seq. SS	Adj. SS	Adj. MS	F	p-value
Load	2	0.0031630	0.0031630	0.0015815	07.00	0.125
Setting	2	0.0073185	0.0073185	0.0036593	16.20	0.058
Coolant	2	0.0020963	0.0020963	0.0010481	04.64	0.177
UW RPM	2	0.0005852	0.0005852	0.0002926	01.30	0.436
LW RPM	2	0.0050296	0.0050296	0.0025148	11.13	0.082
C RPM	2	0.0018296	0.0018296	0.0009148	04.05	0.198
Load*UW RPM	4	0.0198815	0.0198815	0.0049704	22.00	0.044
Load*LW RPM	4	0.0057037	0.0057037	0.0014259	06.31	0.141
Load*C RPM	4	0.0062370	0.0062370	0.0015593	06.90	0.131
Error	2	0.0004519	0.0004519	0.0002259		
Total	26	0.0522963				
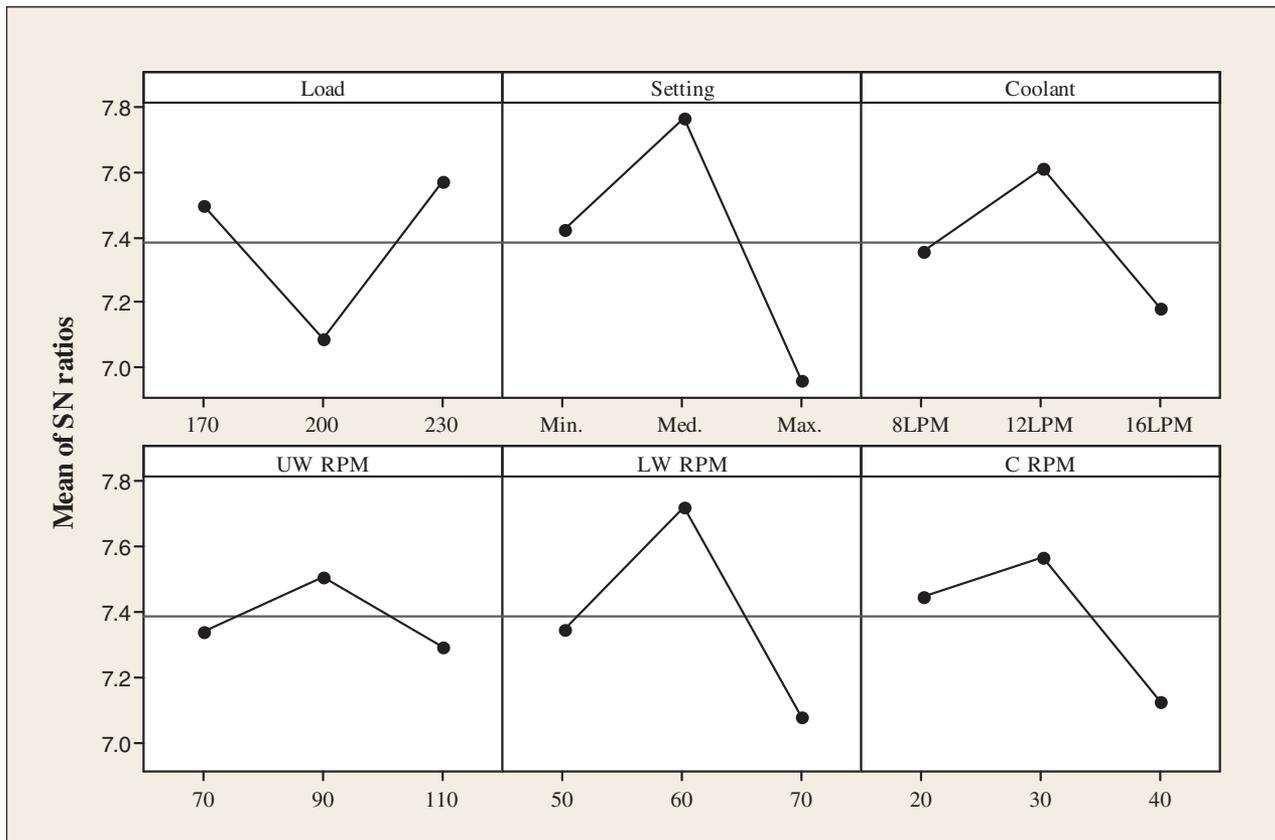
Figure 6. Main effects plot (data means) for S/N ratios

These optimum levels in Table IX were taken as solutions for the causes related to process parameters. Finally, the list of selected solutions is presented in Table X. A risk analysis was carried out to identify any possible negative side effects of the solutions during implementation. The team concluded from the risk analysis that there were no significant negative impacts associated with any of the selected solutions. Hence, an implementation plan was prepared for the above solutions with responsibility and target date for completion for each solution. A time frame of two weeks was provided for implementing these solutions. All the solutions were implemented as per the plan and the results were observed. A graphical presentation of the comparison of results before and after the project is provided in Figure 8.

3.5. Control phase

The real challenge of the Six Sigma implementation is the sustainability of the achieved results. Due to variety of reasons, such as people changing the job, promotion/ transfer of persons working on the process, changing focus of the individual to other process-related issues elsewhere in the organization and lack of ownership of new people in the process, quite often maintaining
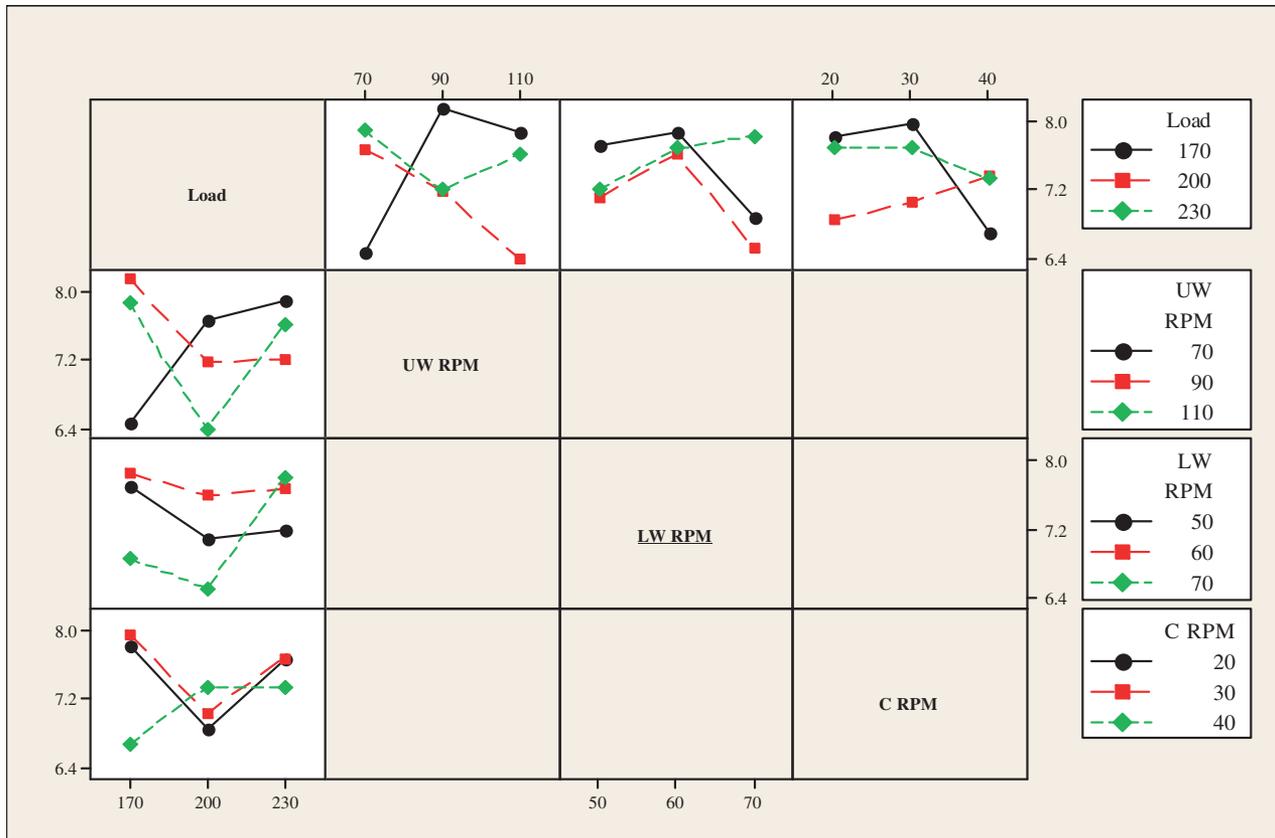
Figure 7. Interaction plot (data means) for S/N ratios

Table IX. Optimum combination for process parameters		
Sl. no.	Factor	Optimum level
1	Load applied	170
2	Initial load setting	Medium
3	Coolant flow rate	12
4	Upper wheel RPM	90
5	Lower wheel RPM	60
6	Cage RPM	30

Table X. Cause–Solution matrix		
Sl. no.	Cause	Solution
1	Repair batches mix up	New storage system for repair parts introduced in the process
2	Product family to family variation	Process parameters were optimized as per result of DOE
3	Presence of sand blasting dust	Cleaning method after sand blasting introduced
4	Material removal rate not OK	Reference table prepared for adjusting load
5	Process parameters not OK	Optimum factor level combination from DOE
6	Improper setting	Optimum factor level combination from DOE
7	Loading/unloading system not OK	Conditioning of grinding wheel-loading table is done.

the results are extremely difficult[9]. Sustainability of the results requires standardization of the improved methods and introduction of monitoring mechanisms for the key results achieved. It also requires bringing awareness among the personnel performing the activities.

Standardization of the solutions was ensured by affecting necessary changes in the process procedures that was a part of the quality management system of the organization. The quality plans and control plans were revised as per the solutions
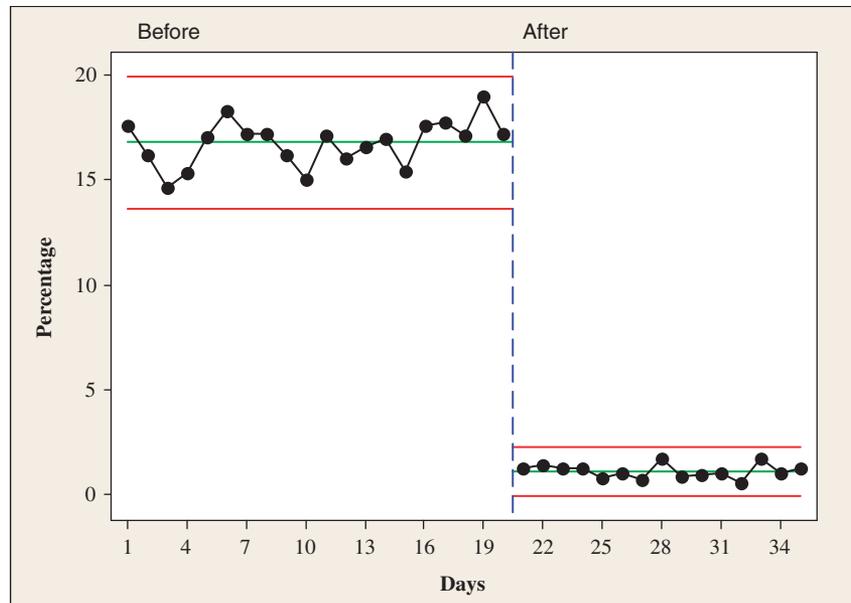
Figure 8. Rejection percentages—before and after the project

implemented and issued to the corresponding users. As a part of ISO 9001 implementation, once in three months internal audits were carried out in the process. The CTQs of the projects were added to the internal audit checklist so that verifications can be performed during the audits. Control chart is a statistical tool used to monitor a process over time to determine whether special causes of variation occur in the process[37]. Implementing appropriate control chart can do future monitoring of the process for assignable causes. Since there was a possibility that different types of defects, such as shades, deep line and patches, can appear after grinding, a control chart needs to be introduced for monitoring the process. Since the defect-related data were collected from the process, the most appropriate control chart for this situation was the *u chart*[37]. Hence, the *u* chart was introduced for monitoring the process along with a reaction plan. For every shift, data on number of defects observed during 100% visual inspection were collected and these values were plotted on the *u* chart by the quality control inspector attached with this process. When any signal for assignable cause appears in the control chart, the quality control inspector discusses this issue with the operator and immediate action was initiated on the process. The reaction plan displayed near to the machine gives direction for identifying the action required for addressing the assignable cause. Also, training was provided for the people associated with the process about the improved operational methods so that they are able to manage the process effectively.

After implementation, the data were compiled from the fine grinding process with respect to the defects for one month and the rejection percentage was found to be 1.19. Hence, as a result of this project, the rejection percentage of the distance pieces at the fine grinding process reduced from 16.6 to 1.19%. The corresponding approximate sigma level was estimated as 3.76. Thus, the sigma level of the process has improved from 2.47 to 3.76. This shows significant improvement in terms of sigma rating as well as defect percentage.

4. Lessons learned

Prior to the implementation of Six Sigma, this organization used to practice process improvement methods, such as Statistical Process Control, Quality Circles, Kaizen, 5S, Poka yoke and Shainin techniques[38, 39]. Small issues in various processes were addressed through these approaches. The usage of data and its analysis were mostly absent in this method of improvement practiced in the organization. The success in this Six Sigma case study has given confidence to the people of the organization in data-based decision making. During data analysis, few hidden problems in the process got uncovered. People started understanding the power of statistical thinking and its impact on processes. The learning of statistical software like Minitab has given them opportunity to apply different types of analysis to the collected data and it helped them to come out of the traditional 'experience and intuition' based actions on the process. One critical success factor in the Six Sigma implementation was found to be the management support for the initiative[17]. Because of the management support, the resistance at the operating level in the organization was easily taken care. Otherwise, there used to be initial resistance in terms of providing accurate data from the processes. The systematic usage of statistical techniques in Six Sigma was found to be very powerful in analysing the process data. Also, statistical software was essential for the analysis. However, these packages can be used by people with the correct training. The results obtained by this project will provide start-up data for further implementations in future. We hope that this case will encourage people to use the Six Sigma method to deal with difficult problems, especially where causes are not obvious.

5.   Managerial implications

There were isolated efforts in the organization in the past to implement initiatives, such as statistical process control, quality circles, continuous improvement programs, Kaizen, 5S and Autonomous maintenance. During the implementation of these initiatives, no systematic effort was made to identify the improvement opportunities in line with business priorities or customer requirements. As a result, the impact of these initiatives was not very visible in the organization whereas in Six Sigma, projects were identified with respect to the voice of the business/customer, and the problems addressed were of highest priority to the organization. Due to success in this project, the management decided to use the Six Sigma methodology for all future improvement initiatives. For monitoring of the Six Sigma initiatives, a core group was formed with all functional heads of the organization. The responsibility of this team was selection of projects and monitoring the execution of projects. All issues related to implementation were also reported to this team for further action. Thus, Six Sigma was introduced as a system in the organization to address any type of problems in the processes. The ultimate objective of the management was to bring a cultural change in the organization by involving everyone in the organization in this movement towards excellence.

6.   Concluding remarks

The Six Sigma method is a project-driven management approach based on the theories and procedures to reduce the defects for a specified process. This paper presents the step-by-step application of the Six Sigma methodology for reducing the rejection level of the fine grinding process. Several statistical tools and techniques were effectively utilized to make inferences during the project.

As a result of the project, the rejection level of distance pieces after the fine grinding process has been reduced to 1.19% from 16.6%. Once the results were observed, with the help of the finance department, the team carried out a cost–benefit analysis for the project. Due to improvement in the process, cost associated with rejection, repair, scrap, re-inspection and tool came down drastically. The annualized savings resulted from this project were estimated and found to be about US$2.4 million. This has given an encouragement for the management to implement the Six Sigma methodology for all improvement initiatives in the organization. Also to encourage the people for participating in the Six Sigma projects, the management declared incentive schemes for the successful teams. In addition to this, during the annual appraisal due weighting was given for individuals who actively participated in the Six Sigma implementation.

Like any other initiative, in Six Sigma also there were inherent difficulties in executing this project. Availability of people for attending training during their busy schedule of day-to-day work was very difficult. Getting support of the people at the lower levels in the organization for participating in the implementation of the solutions was not easy. Since the organization did not have any software for capturing data automatically, collection of data from the process during different phases of the Six Sigma project implementation was also very difficult. The team, by involving people at all levels in the organization, achieved the expected results. Finally, the significant achievement of this project has created many followers for Six Sigma in the organization.

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Appendix A: Project Charter

Project Title: Reducing rejection in distance pieces after fine grinding process	
Background and reasons for selecting the project: The rejection of distance pieces in the fine grinding process was as high as 16.2%. Approximately 4200 components are machined during every shift. The cost of components rejected due to defects was approximately $US1.6 million per annum. In addition to this, there was loss associated with tool, machine and man-hour related to rejection of components.	
Aim of the project: To reduce the rejection of distance pieces by 50% after the fine grinding process.	
Critical to Quality characteristic: Rejection percentage of distance pieces after fine grinding process.	
Project Scope	Fine grinding process
Project Champion:	Head - Manufacturing
Project Leader:	Senior Manager - Manufacturing
Team Members:	Planning Manager, Maintenance Manager, Quality Control Senior Engineer, Machine Operator.
Expected Financial Benefits:	A saving of approximately $US one million in terms of reduction in rejection and tool cost.
Expected Intangible Benefits:	Reduction in rejection will lead to increased output to meet the market demand and thereby increase in turnover and reduction in operational expenses.
Expected customer benefits:	Improving on time delivery.
Schedule:	Define: 2 Weeks, Measure: 2 weeks Analyze: 3 weeks, Improve: 4 weeks Control: 4 weeks.

Appendix B: SIPOC

Supplier	Input	Process	Output	Customer
Supplier	Pre finished parts		Finished parts	Assembly Shop
Sand Blasting Process	Shot blasted parts			
Planning Department	Setting Parameters		Production Reports	Manufacturing Department
Planning Department	Dressing Method	Fine Grinding Process		
Planning Department	CNC Program		Quality Reports	Quality Department
Planning Department	Visual Limit Sample			
Planning Department	Tooling			

Process Steps

Pre-Grinding	→	Sand Blasting	→	Fine Grinding	→	Cleaning & Arranging	→	Visual Inspection
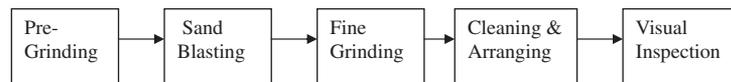
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