Quality improvement by reducing variation: a case study

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ABSTRACT *This article describes a systematic approach for solving a problem of high rejection and rework due to variation in the machining process. Two critical characteristics of a component under study were identified by risk analysis. The process capability of these characteristics was calculated and found to be very low. For improving the process capability, a step-by-step method was adopted by applying several statistical and quality tools, such as multivari chart, cause-and-effect diagram, gauge repeatability and reproducibility, design of experiments etc. After reducing the variation through continuous process improvements, the process capability has improved drastically.*

Background of the study

The production personnel in some of the key sections of a machine shop in an engineering industry in India were facing severe problems for the following reasons.

(1) Due to dimensional variations, rejections and rework were very high.
(2) Repeatability of the readings were not found for many of the critical dimensions.
(3) Complaints from the assembly shop were increasing day by day.

Consequently, it was decided to evaluate the process capability of different machining processes with respect to some of the critical characteristics and take remedial measures so that consistent quality is maintained. To start this mission, one of the machines was identified for an initial process capability study.

About the process

One of the machines thus identified for the study was a CNC machine, which was commissioned around 15 years ago. During commissioning it was a turn mill centre for complete turning, drilling and tapping of cast iron end shields. Now the machine is operating only as a turning centre. It is operated under a direct numerical control network. The machine has a hydraulic chuck for holding the workpiece with a variable clamping pressure. The clamping pressure can be varied from 0 to 100 kg/sq. cm. The machine has two axes, X and Z, in which the Z-axis is parallel to the axis of the chuck and the X-axis is perpendicular to the axis of the chuck. The tool turret has eight stations or tool holders and each tool holder can be loaded with the required tools. The tools, which are currently in use, are titanium carbide tools. A high-pressure coolant facility is available with the machine. For collecting and transferring the chips to pallet, a chip conveyor is also attached to the machine.

Objective of the study

The objective was to evaluate the existing process capability indices for critical characteristics and to make suitable actions to improve process capability and thereby reduce rejections through continuous process improvements.

Approach

The approach of the study was decided as follows.

- Identification of critical dimensions.
- Evaluation of present status.
- Cause and effect analysis.
- Detailed study.
- Experimentation and data collection.
- Analysis, results and conclusions.
- Confirmatory trial.
- Implementation and process control measures.

Identification of critical dimensions

The machine identified for study was used for machining the cast iron end shields of alternators. A typical sketch of the end shield is given in Fig. 1. There are a total of seven dimensions to be machined in the casting during the machining operation. All these dimensions are not equally critical with respect to the final assembly of the alternator. Hence, it was decided to conduct a Risk Analysis for identifying the critical characteristics from the seven dimensions. The details of the risk analysis results are given in Table 1.

From the risk analysis table, it is clear that the Risk Priority Number (RPN) for spigot diameter and bore diameter are very high. Hence, by considering the criticality of these two dimensions, it was decided to select them for process capability evaluation.

Evaluation of present status

For assessing the existing level of process capability, it was decided to carry out a planned data collection with the existing operating conditions for a batch quantity of 25 end shields for the two selected dimensions. The specification limits for bore and spigot diameters were (159.98–160.01 mm) and (469.95–470.00 mm) respectively. Data were collected for spigot and bore diameters for 25 components after machining. Dimensions were measured at three points (at 120° apart) for each end shield. The collected data were plotted on a multivari chart and are given in Figs 2 and 3.

From the multivari chart, it is clear that there is a lot of variation from component to component. Even the diameters measured at three points within a component were found to vary. This shows the presence of a high level of ovality in diameter. The process capability indices were evaluated and the C_{pk} values of bore and spigot diameters were found to be 0.19 and 0.16 respectively.

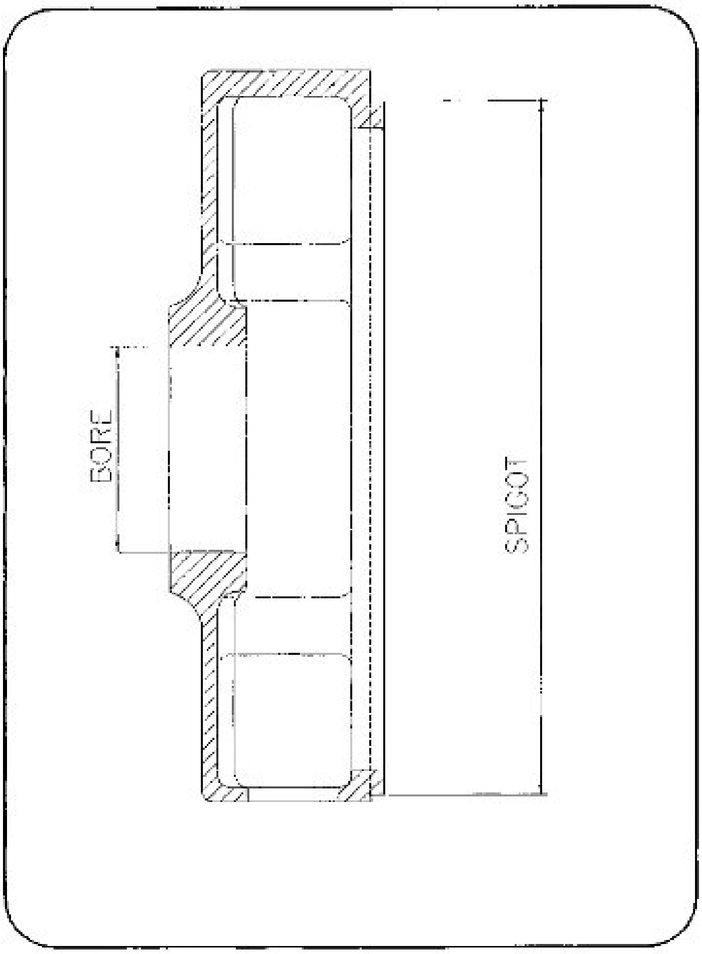

Figure 1. *Typical sketch of end shield.*

Table 1. *Risk analysis*

Key characteristic	Potential causes of variation*	Effect of variation	Occur-rence	Detect-ability	Severity	RPN
Spigot diameter		Fitment problem	9	4	8	288
Spigot depth	Casting related problem	Fan loading problem	3	4	3	36
Spigot inside dia		Fan loading problem	2	4	3	24
Bearing bore diameter	Machine parameters	Bearing failure, fitment problem	9	4	9	324
Bearing boss width	Machine geometrical accuracy	Mismatch with the shaft	3	3	1	9
Mounting depth	Tools used	Mismatch with the shaft	4	4	2	32
Outer diameter		Only cosmetic	2	4	1	8

* The potential causes of variation for all the characteristics are the same.

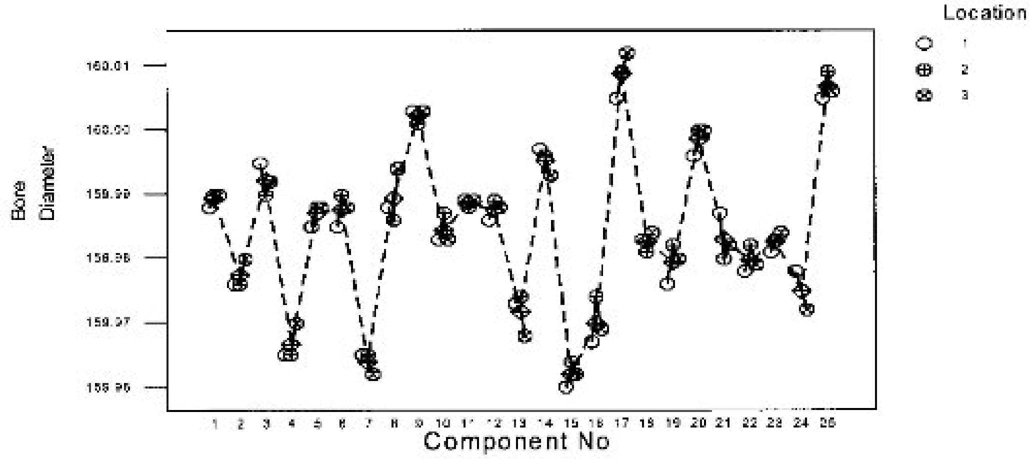

Figure 2. *Multivari chart for bore diameter.*

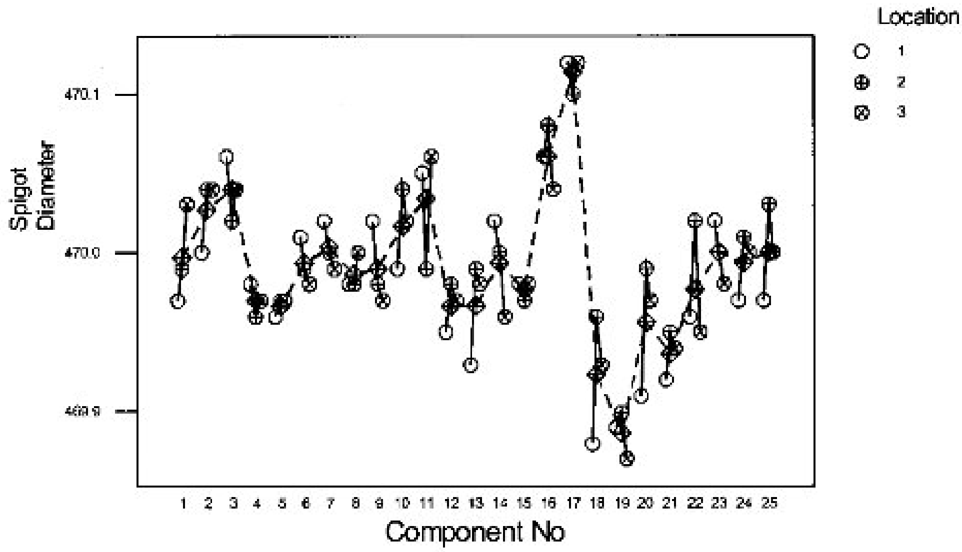

Figure 3. *Multivari chart for spigot diameter.*

Cause and effect analysis

Since the process capability values show that the process is incapable of meeting the specifications, it was decided to conduct an in-depth investigation for identifying the assignable causes. Based on the information obtained from the preliminary study, a brainstorming session was conducted with the personnel concerned for identifying the possible causes for dimensional variation. As a result of the brainstorming session, a cause-and-effect diagram was prepared. The cause-and-effect diagram is given in Fig. 4.

Detailed study

All the causes listed in the cause-and-effect diagram were verified by 'gemba' investigation. Few potential causes in the cause-and-effect diagram were found not to affect the dimensional

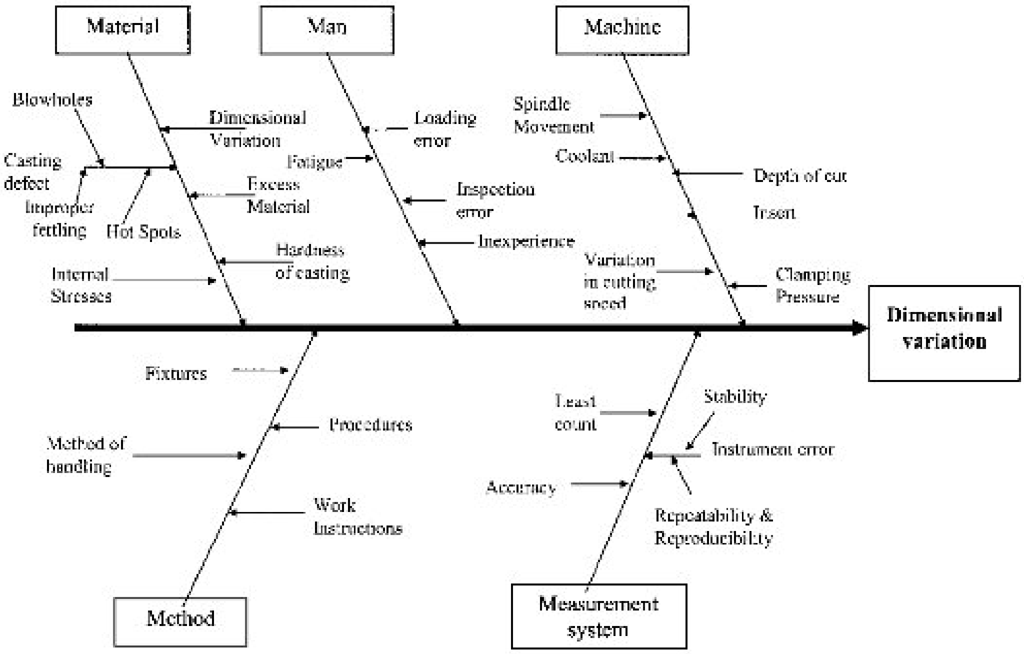

Figure 4. *Cause and effect diagram.*

Table 2. *Results of gauge R&R study*

	Bore gauge	Outside micrometer
Percentage equipment variation	25.41	19.95
Percentage appraiser variation	10.96	13.50
Percentage repeatability and reproducibility	27.73	24.09

variation. Some of the causes, like spindle run out, axes repeatability etc, were corrected on the spot. The remaining causes, which are suspected of causing high variation, were shortlisted.

Instruments used for measuring the two critical characteristics, bore diameter and spigot diameter, were 'bore gauge' and 'outside micrometer' respectively. The smallest measurements of these instruments are 0.001 mm and 0.01 mm respectively. To avoid any possibility of high variation due to measuring instruments, a gauge repeatability and reproducibility study was planned for these two instruments. Two inspectors were selected for the study and both of them measured the dimensions of ten components twice, randomly. The data were analysed as per the methodology suggested in the '*Measurement System Analysis*' manual of QS-9000 standard. The results obtained from the study are given in Table 2. Since the percentage Repeatability and Reproducibility (%R&R) is less than 30, it was decided to continue the measurements with the existing instruments.

Experimentation and data collection

After initiating the above-described actions, a batch of 25 components was again followed during machining. After machining, the measurements were recorded with the component

Table 3. *Factors and levels for experimentation*

SI. No.	CODE	Factors	Levels		
			1	2	3
1	A	Casting type	Stress relieved	Not stress relieved*	—
2	B	Hardness (BHN)	170–190*	191–210	—
3	C	Clamping pressure	14	17	20*
4	D	Feed rate (mm/rev.)	0.08	0.16*	—

* Present level.

on the machine (clamped position) and after removing from the machine (unclamped position). It was observed that the spigot diameter shows a highly erratic fluctuation in the unclamped condition compared with the clamped condition. This pattern indicated doubts about the pressure used for clamping the components, the hardness of the components as well as the internal stresses developed during the foundry process. Hence, it was decided to conduct an experiment by taking stress-relieved components and non-stress relieved components with hardness controlled at two different ranges and using a clamping pressure of two lower levels in addition to the existing one. Also, a very high feed rate may generate stresses on the component. Hence, in addition to the existing feed rate, a lower level of feed rate was also selected for experimentation. The factors and levels thus selected for experimentation are given in Table 3. All other parameters, other than the experimental factors, were maintained at fixed levels.

Four factors, one at three levels and the remainder at two levels, requires $3^1 \times 2^3 = 24$ trials to conduct a full factorial experiment (Montgomery, 1991). But the main effects of all these factors can be easily estimated by conducting nine trials by using the orthogonal array L_9 (3^4). Since the behaviours of the interaction effects of these factors were unknown, it was decided to select an orthogonal array L_{18} ($2^1 \times 3^7$) to conduct the experiment. In L_{18}, the effect of interaction is equally distributed in all columns. The physical layout of the experiment is given in Table 4.

The experiment was conducted by varying different parameters as per the requirement of the experimental layout. For each experimental combination, one end shield was machined and the dimensions were measured. The measurements were taken at three locations 120° apart.

Analysis, results and conclusions

Since each diameter was measured at three locations, the average and range (ovality) of these values were calculated for each component. The average and ovality values are given in Table 5. Now, the requirement of the process is to reduce ovality and bring the average to the specification target. The average and ovality values were subjected to analysis of variance (ANOVA). The contribution percentage (ρ%) for the significant factors were also calculated (Phadke, 1988). The ANOVA tables are given in Tables 6 to 8.

From the ANOVA tables, it was clear that none of the factors significantly affect the bore ovality (hence the table is not given here). The significant factors for different cases and their respective optimum levels are summarized and given in Table 9. From Table 9, it can be seen that factor D does not significantly affect either the average or the ovality. Factor B is found to affect only the spigot ovality and the best level of B was found to be B2. Hence, the optimum level of factor B is fixed at B2. Even though factor C significantly affects all

Table 4. *Physical layout for experimentation*

	Control factors			
Exp. No.	Casting type (1)	Hardness (BHN) (2)	Clamping pressure (kg/cm^2) (3)	Feed rate (4)
1	SR*	170–190	14	0.08
2	SR	170–190	17	0.16
3	SR	170–190	20	0.08
4	SR	191–210	14	0.08
5	SR	191–210	17	0.16
6	SR	191–210	20	0.08
7	SR	191–210	14	0.16
8	SR	191–210	17	0.08
9	SR	191–210	20	0.08
10	NSR*	170–190	14	0.08
11	NSR	170–190	17	0.08
12	NSR	170–190	20	0.16
13	NSR	191–210	14	0.16
14	NSR	191–210	17	0.08
15	NSR	191–210	20	0.08
16	NSR	191–210	14	0.08
17	NSR	191–210	17	0.08
18	NSR	191–210	20	0.16

* SR: Stress relieved; NSR: Not stress relieved.

Table 5. *Data of the experiment (average and ovality)*

	Bore diameter		Spigot diameter	
Exp. No.	Average	Ovality	Average	Ovality
1	159.9990	0.002	470.0333	0.03
2	159.9910	0.002	469.9333	0.04
3	160.0213	0.007	469.9917	0.08
4	160.0060	0.008	470.0133	0.02
5	159.9940	0.003	469.9500	0.04
6	159.9893	0.002	469.9967	0.01
7	159.9950	0.006	469.9567	0.01
8	159.9987	0.002	469.9300	0.02
9	160.0033	0.008	469.9767	0.05
10	159.9993	0.006	470.0400	0.07
11	159.9897	0.005	469.9267	0.05
12	159.9680	0.000	470.0367	0.06
13	160.0067	0.005	470.0567	0.05
14	159.9760	0.003	469.9333	0.06
15	159.9910	0.003	469.9900	0.03
16	159.9907	0.002	470.0467	0.02
17	159/9687	0.002	469.9467	0.08
18	160.0067	0.005	470.0167	0.09

except bore ovality, the highest contribution percentage is for spigot average. Hence, the corresponding best level, C3, was fixed as the optimum. With similar arguments, the best level of A is identified as A1. Since factor D had no significant effect on the response, it was decided to keep that factor at the current operating level. Hence, the optimum combination becomes: (A1 B2 C3 D2).

Table 6. *ANOVA table for average (bore)*

Source	D.F.	S.S.	M.S.	ρ%
A	1	5.6430E-4	5.6430E-4	13.80
B	1	3.0524E-6	3.0524E-6	
C	2	5.6937E-4	2.8468E-4	9.44
D	1	2.8946E-6	2.8946E-6	
Error (pooled)	14	0.00195	1.3929E-4	
Total	17	0.00308		

Table 7. *ANOVA table for average (spigot)*

Source	D.F.	S.S.	M.S.	ρ%
A	1	0.00249	0.00249	5.85
B	1	3.3565E-4	3.3565E-4	
C	2	0.02486	0.01243	69.80
D	1	1.5681E-4	1.5681E-4	
Error (pooled)	14	0.00686		
Total	17	0.03421		

Table 8. *ANOVA table for ovality (spigot)*

Source	D.F.	S.S.	M.S.	ρ%
A	1	0.00245	0.00245	19.14
B	1	0.0009	0.0009	4.35
C	2	0.0013	0.00065	3.92
D	1	0.0001	0.0001	
Error (pooled)	13	0.00579	0.000445	
Total	17	0.01054		

Table 9. *Significant factors and their optimum levels*

Characteristic	Variable	A	B	C	D
Bore	Average	A2	—	C2	—
	Ovality	—	—	—	—
Spigot	Average	A1	—	C3	—
	Ovality	A1	B2	C1	—

— not significant

- Stress relieved end shields
- Hardness in the range 191 to 210 BHN
- Clamping pressure 20 kg/cm^2
- Feed rate: 0.16 mm/rev

Stress relieving of the covers will remove all the internal stresses developed in the foundry. The high hardness will provide more rigidity to the castings so they will not undergo deformation easily.

Confirmatory trial

As per the optimum combination obtained from the experiment, a trial run was conducted with 20 end shields. The process capability indices were calculated for the collected data. C_{pk} values of 1.10 and 1.267 were observed for the bore and spigot diameters respectively.

Implementation and process control measures

The management of the company has decided to implement the optimum combination. All procedures and work instructions were modified to implement the optimum combination. For the purpose of monitoring the process, an $\bar{X}$ and R control chart was established in the process. A reaction plan was also prepared and given to the operator to take immediate actions on the process in case assignable causes are observed.

References

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