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Application of Taguchi method in optimization of control parameters of grinding process for cycle time reduction

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Abstract— In this study, the control parameters for grinding process are optimized for reduction in cycle time while maintaining quality standards in a bearing manufacturing company. The Taguchi method which is a powerful tool to design optimization for quality is used to find the optimal control parameters. An orthogonal array, the signal-to-noise (S/N) ratio and the analysis of variance (ANOVA) are used to study the performance characteristics of grinding process of an outer ring of a taper roller bearing. Various control parameters consisting of feed parameters, position parameters, speed parameters were optimized and also the main parameters that affect the grinding process can be found out. Experimental results are provided to verify the effectiveness of this approach.

Keywords— Taguchi method, Grinding, Optimization, Cycle time, Size variation

I. INTRODUCTION

In modern manufacturing industry, companies are faced with increased challenges in terms of total throughput and quality of the product. These challenges are accompanied by shorter product life cycles, intensified cost pressure and rising quality requirements. To remain competitive in an increasingly competitive global market, manufacturing companies are forced to simultaneously optimize their production in terms of cost efficiency, lead time and quality. Automated manufacturing systems are used along with computerised numerical control (CNC) machines that are capable of providing low processing time while maintaining the quality standards.

In bearing manufacturing, grinding is one the important process employed to achieve the desired quality and dimensions of the parts. In grinding process, it is important to select control parameters such as feed, speed and position for achieving high quality performance in the least processing time. Usually, the control parameters are determined based on experience or by use of a handbook. These parameters are reflected on size (dimensions) of the part, ovality and cycle time of the grinding machining indirectly adding to the lead time and hence total production per unit time.

To select control parameters, the Taguchi method [4-6] can be used which provides a simple, efficient and systematic approach to optimize design for performance, quality and cost as compared to mathematical models based on regression techniques which require considerable knowledge and experience. Furthermore, the Taguchi method requires less number of experiments, low cost and less time than mathematical models which are costly and require large number of experiments to be performed and analysed to build them. Taguchi parameter design aids in optimizing the performance characteristics through setting of control parameters and reduce the sensitivity of system to source of variation. It also helps in reducing the cycle time of the process while maintaining the desired quality of the workparts.

The paper demonstrates a systematic procedure of using Taguchi parameter design to reduce cycle time and size variation of track diameter of outer ring in a taper roller bearing with a particular combination of control parameters in a grinding process. First the Taguchi parameter design method and the grinding process of outer ring of a taper roller bearing is introduced. Then the experimental details of using the parameter design to determine and analyze the optimal control parameters is described. The experimental results of identified optimal parameters are described. Finally, the paper concludes with the summary of this study and future work.

II. TAGUCHI METHOD

Taguchi has developed a methodology for application of design of experiments, including a practitioner's handbook [1] to provide clearer understanding of the variation nature and the economic consequences of quality engineering in the world of manufacturing [1, 2]. He introduced a three-step approach i.e. system design, parameter design, and tolerance design.

In system design, the scientific and engineering knowledge is applied to produce a basic functional prototype design including the product design stage and the process design stage. In product design stage and process design stage, the selection of materials, components, parameter value, selection of production equipment, tentative process parameter value etc. are involved. In parameter design [3], the goal is to optimize the setting of parameter values for improving quality characteristics. Also the optimal process parameter values obtained from parameter design are expected to be insensitive to variation caused by environment and other noise factor. Finally, tolerance design is used to determine and analyze tolerances around the optimal settings.

The experimental design methods were developed originally by Fisher [8] which were not easy to use and too complex. A large number of experiments have to be carried out when the number of process parameters increases. This problem was solved by Taguchi method that uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments only. Taguchi recommends the use of the loss function to measure the performance characteristic deviating from the desired value. The value of the loss function is further transformed into a signal-to-noise (S/N) ratio. Usually, there are three categories of the performance characteristic in the analysis of the S/N ratio, that is, the smaller-the-better, the larger-the-better, and the nominal is best. The S/N ratio for each level of process parameters is computed based on the S/N analysis. Regardless of the category of the performance characteristic, the larger S/N ratio corresponds to the better performance characteristic. Therefore, the optimal level of the process parameters is the level with the highest S/N ratio. Furthermore, a statistical analysis of variance (ANOVA) is performed to see which process parameters are statistically significant. With the S/N and ANOVA analyses, the optimal combination of the process parameters can be predicted. Finally, a confirmation experiment is conducted to verify the optimal process parameters obtained from the parameter design.

The parameter design of the Taguchi method consist of following steps [9]:

- Identify the performance characteristics and select process parameters to be evaluated.
- Determine the number of levels for the process parameters and possible interactions between the process parameters.
- Select the appropriate orthogonal array and assignment of process parameters to the orthogonal array.
- Conduct the experiments based on the arrangement of the orthogonal array.
- Calculate the total loss function and the S/N ratio.
- Analyze the experimental results using the S/N ratio and ANOVA.
- Select the optimal levels of process parameters.
- Verify the optimal process parameters through the confirmation experiment.

III. GRINDING PROCESS

Grinding is a material removal and surface generation process used to shape and finish components made of metals and other materials. The precision and surface finish obtained through grinding can be up to ten times better than with either turning or milling. Grinding employs an abrasive product, usually a rotating wheel brought into controlled contact with a work surface. The grinding wheel as is composed of abrasive grains held together in a binder. These abrasive grains act as cutting tools, removing tiny chips of material from the work. As these abrasive grains wear and become dull, the added resistance leads to fracture of the grains or weakening of their bond. The dull pieces break away, revealing sharp new grains that continue cutting. Wheel dressing and truing is done with special tools designed for that purpose. Although wheel dressing is often done manually between work cycles, some grinding machines perform the dressing task automatically.

Fig.1 Grinding Wheel

Internal grinding process is used in grinding of outer ring for a taper roller bearing. The principle elements of an internal grinding machine as shown in figure 1 are the workhead, which holds the work and has its own drive; and the wheelhead, which is the internal grinding spindle. In addition to the rotary motions of work and wheel, an internal grinder has a traverse movement to bring the wheel to and from the work zone, and a reciprocating spindle movement for both the wheel's approach to the work surface and for the feed movement of the wheel during grinding. Workpiece surfaces produced by grinding are influenced by the following factors:

- Workpiece material - harder materials allow finer finishes
- Type of wheel - fine grains yield finer finishes
- dressing procedure - improperly dressed wheels will mar the work surface
- Feed rate - finer finishes are obtained with slower feed rates
- Machine rigidity - older, worn machines yield a poor quality finish
- Wheel condition - clogged wheels cannot produce a good finish
- Lubricant cleanliness - coolant filtration removes waste that could damage workpiece surface

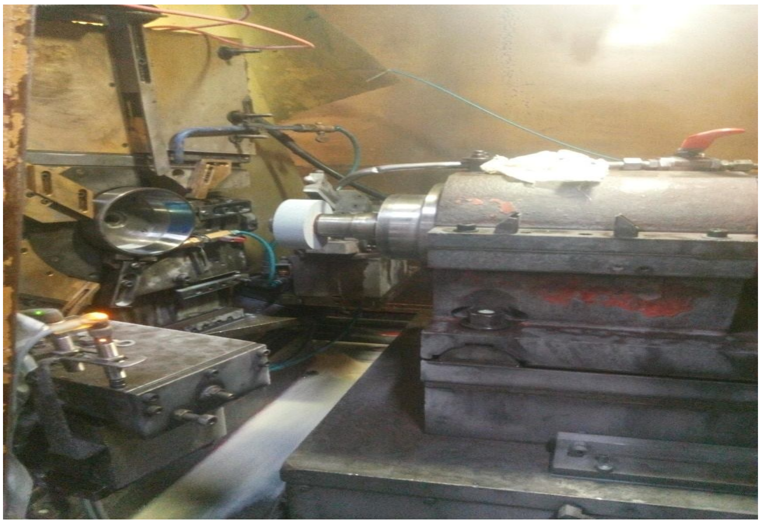

Fig. 2 Internal Grinding Machine

Fig. 3 Outer Ring of a Taper Roller bearing

Therefore, it is important to determine control parameters related to speed, feed rate, position of the internal grinder and dressing of the grinding wheel. All of these parameters have an influence on two main outputs; first, the variation in the size of track diameter of an outer ring and secondly, the cycle time of the grinding process.

A. Selection of control parameters and their levels

A typical grinding cycle is as shown in figure 4. The grinding experiments were carried out on an Outer Ring Track Grinding CNC machine using grinding wheel and outer rings same as used in the general production.
The control parameters selected are as follows:

- Speed Parameters

1. Workhead Spindle speed – It is the speed in rpm of the rotating spindle of the workpiece and is denoted by R142.

- Position Parameters

1. Knock off Position – It is the position of the slide at the start of finish cycle and is denoted by R104.
2. Incremental retreat 1 – It is the position of the slide as it retreats back before the start of finish cycle and end of rough cycle to reduce ring deflection and is denoted by R110.
3. Incremental retreat 2 – It is the position of the slide as it retreats back before the start of spark out and end of finish cycle to reduce ring deflection and is denoted by R111.

- Feed Parameters

1. Air grinding feed rate – It is the feed rate for grinding wheel in the air as it approaches the ring and is denoted by R127.
2. Rough 1 feed rate – It is the feed rate for grinding wheel during the initial rough stage for the removal of black surface (due to heat treatment) and is denoted by R128.

3. Rough 2 feed rate – It is the feed rate for grinding wheel during the rough stage for the removal of material. Both the rough stages account for 70-80 % of the desired material removal and is denoted by R129.
4. Fine feed rate – It is the feed rate for grinding wheel during the finish stage in which remaining desired material is removed to provide better quality and is denoted by R130.

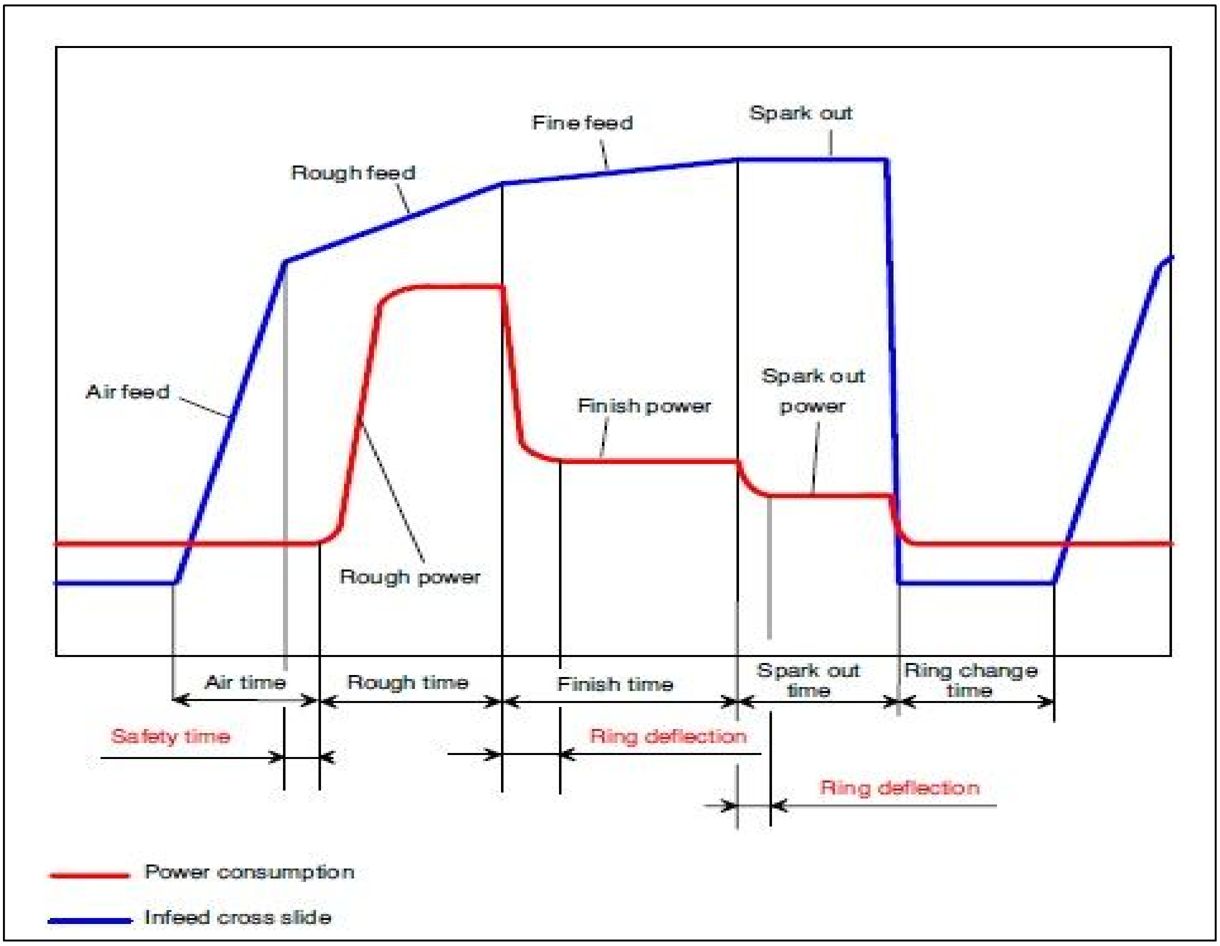

Fig. 4 Typical Grinding Cycle for Production

- Dressing and Time Parameters

1. Spark out time – It is the time after the finish stage for which the workpiece and the grinding wheel is rotated at fixed position for removal of chips and high point on track surface of outer ring and is denoted by R136.
2. Dressing Compensation – It is the amount of wheel material dressed during dressing of wheel and is denoted by R115.
3. Dress infeed speed – It is the feed rate at which wheel is dressed to obtain better quality and is denoted by R132.

The control parameters were varied in the range and their number of levels are as shown in Table I.

TABLE I
CONTROL PARAMETERS WITH THEIR RANGE and LEVEL

Sr. no.	Symbol	Control Parameters	Range	Level 1	Level 2	Level 3	Level 4
1	R142	Workhead Spindle Speed (rpm)	300-500	300	350	450	500
2	R104	Knock off position (µm)	80-120	80	120		
3	R110	Incremental retreat 1 (µm)	4-8	4	8		
4	R111	Incremental retreat 2 (µm)	4-8	4	8		
5	R127	Air grinding feed rate (µm/sec)	80-120	80	120		

6	R128	Rough 1 feed rate (µm/sec)	10-15	10	15
7	R129	Rough 2 feed rate (µm/sec)	10-15	10	15
8	R130	Fine feed rate (µm/sec)	7-11	7	11
9	R136	Spark out time (sec)	1-3	1	3
10	R115	Dressing compensation (µm)	20-40	20	40
11	R132	Dress infeed speed (µm/sec)	10-30	10	30

B. Performance Measure

The variation in the size of track diameter of outer ring and the cycle time of the grinding process are the two output parameters which were measured after grinding process. The variation in size of the ring was measured using Universal Dimension apparatus and Cycle time was measured based on as shown by the CNC machine User Interface. The baseline measurements were taken on the general production run and the output parameters were then compared before and after the experiments to analyse the stability of the grinding process and effects of various parameters on the size variation of the ring and cycle time of the grinding process.

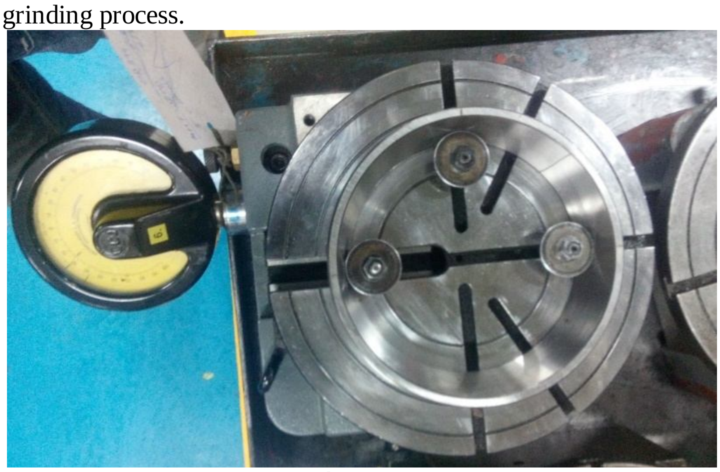

Fig. 5 Universal Dimension apparatus

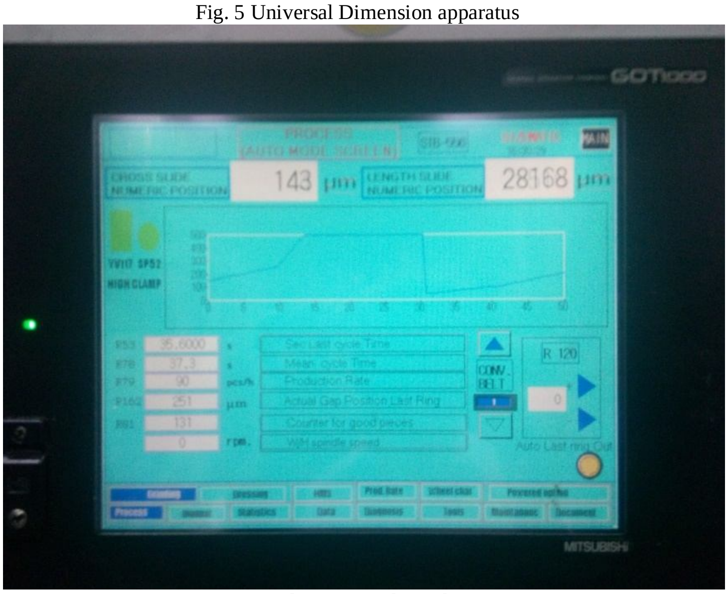

Fig. 6 Machine Control Display

IV. DESIGN and ANALYSIS of CONTROL PARAMETERS

In this section, the use of an orthogonal array to reduce the number of experiments for design optimization of the control parameters is described. Results of the experiments were studied and analysed using the S/N and ANOVA analyses. Based on the results, the optimal settings of the control parameters for reduced variation in size of track diameter of outer ring and cycle time both were obtained and verified.

A. Baseline measurements

The baseline measurements were taken to determine the stability of the grinding process during the general production. The grinding process was found to be stable based on the I-MR (Individual-Moving range) chart which showed the measurements within the control limits as shown in figure 7. An average size variation of track diameter within 23 microns (μ) was observed. Similarly cycle time was measured and an average cycle time of 36.3 sec was recorded as shown in figure 8. Baseline Control Parameters are given in table II.

TABLE II
CONTROL PARAMETERS in the GENERAL PRODUCTION

Sr. No.	R142	R104	R110	R111	R127	R128	R129	R130	R136	R115	R132
1	350	100	3	3	80	14	14	7	4	30	20

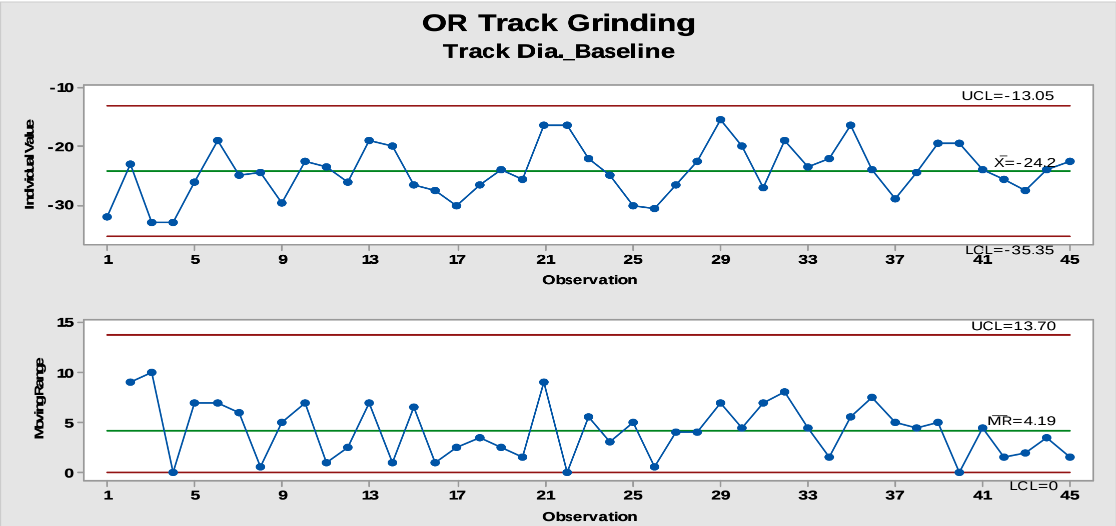

Fig. 7 I-MR chart for size of Track Diameter of Outer Ring

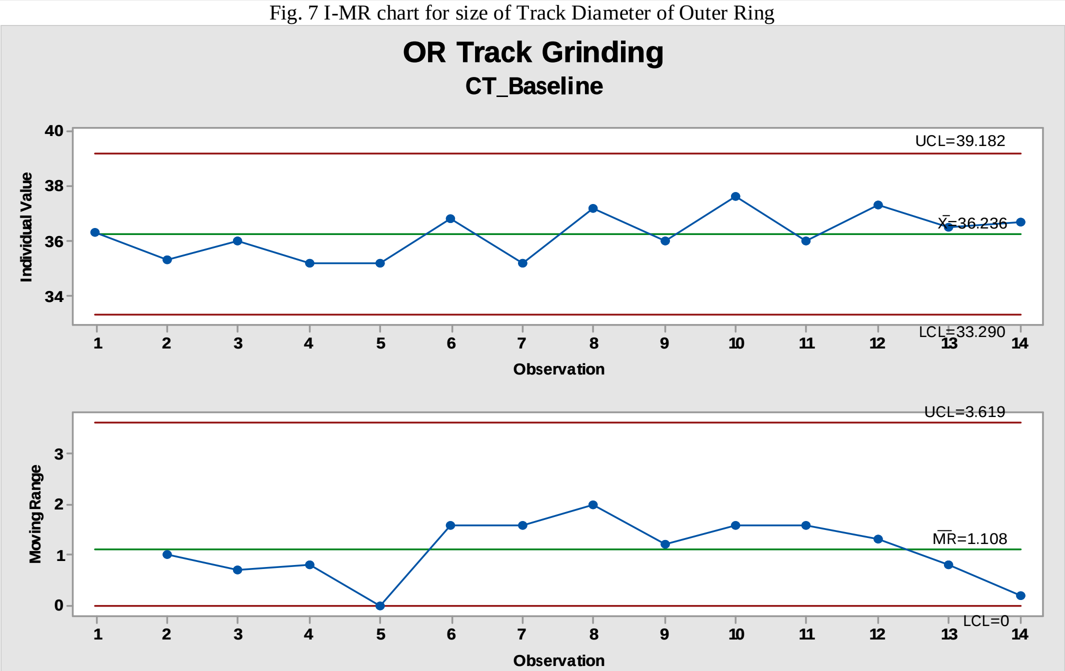

Fig. 8 I-MR chart for Cycle Time of Grinding process

B. Orthogonal array experiment

To select an appropriate orthogonal array for experiments, a Design – Expert software MINITAB was used for Taguchi's method. Based on the number of control parameters and their levels, an L16 orthogonal array design was selected. The experiments were carried out according to the selected Taguchi design of experiment.
The L16 orthogonal array is shown in Table III.

TABLE III
L16 ORTHOGONAL ARRAY

Sr. No.	R 142	R 104	R 110	R 111	R 127	R 128	R 129	R 130	R 136	R 115	R 132
1	300	80	4	4	80	10	10	7	1	20	10
2	300	80	4	4	80	15	15	11	3	40	30
3	300	120	8	8	120	10	10	7	1	40	30
4	300	120	8	8	120	15	15	11	3	20	10
5	350	80	4	8	120	10	10	11	3	20	10
6	350	80	4	8	120	15	15	7	1	40	30
7	350	120	8	4	80	10	10	11	3	40	30
8	350	120	8	4	80	15	15	7	1	20	10
9	450	80	8	4	120	10	15	7	3	20	30
10	450	80	8	4	120	15	10	11	1	40	10
11	450	120	4	8	80	10	15	7	3	40	10
12	450	120	4	8	80	15	10	11	1	20	30
13	500	80	8	8	80	10	15	11	1	20	30
14	500	80	8	8	80	15	10	7	3	40	10
15	500	120	4	4	120	10	15	11	1	40	10
16	500	120	4	4	120	15	10	7	3	20	30

C. Analysis of the S/N ratio

In the Taguchi method, the term 'signal' represents the desirable value (mean) for the output characteristic and the term 'noise' represents the undesirable value (S.D.) for the output characteristics. Therefore, the S/N ratio is the ratio of the mean to the S.D. Taguchi uses the S/N ratio to measure the quality characteristic deviating from the desired value. The S/N ratio η is defined as

$\eta = -10 \log (M.S.D.)$ – (1)

where M.S.D. is the mean-square deviation for the output characteristic.

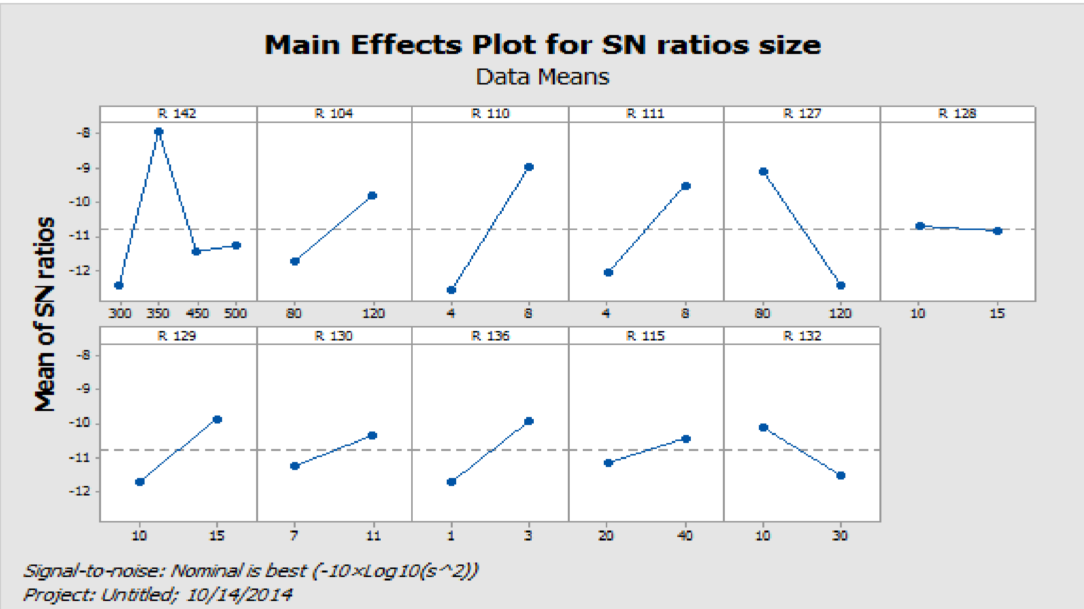

Fig. 9 S/N ratio graph for track diameter size

As mentioned earlier, there are three categories of performance characteristics, i.e., the smaller-the-better, the larger-the-better, and the nominal is best. To obtain optimal output performance, the nominal is best must be taken for size variation and the smaller-the-better must be taken for cycle time. The S/N ratio for these quality characteristic can be expressed as:

S/N (nominal is best) = -10(log (σ^2)) – (2)

S/N (smaller-the-better) = -10(log (ΣY^2 /n)) – (3)

where n is the number of tests and Y is the output response and σ is the mean-square deviation.

The results of the experiment were analysed using S/N ratio graphs for both the size of track diameter of outer ring and cycle time. Figure 3 shows the response graph of S/N ratio for size of track diameter of outer ring. Figure 4 shows the response graph of S/N ratio for cycle time of the grinding process.

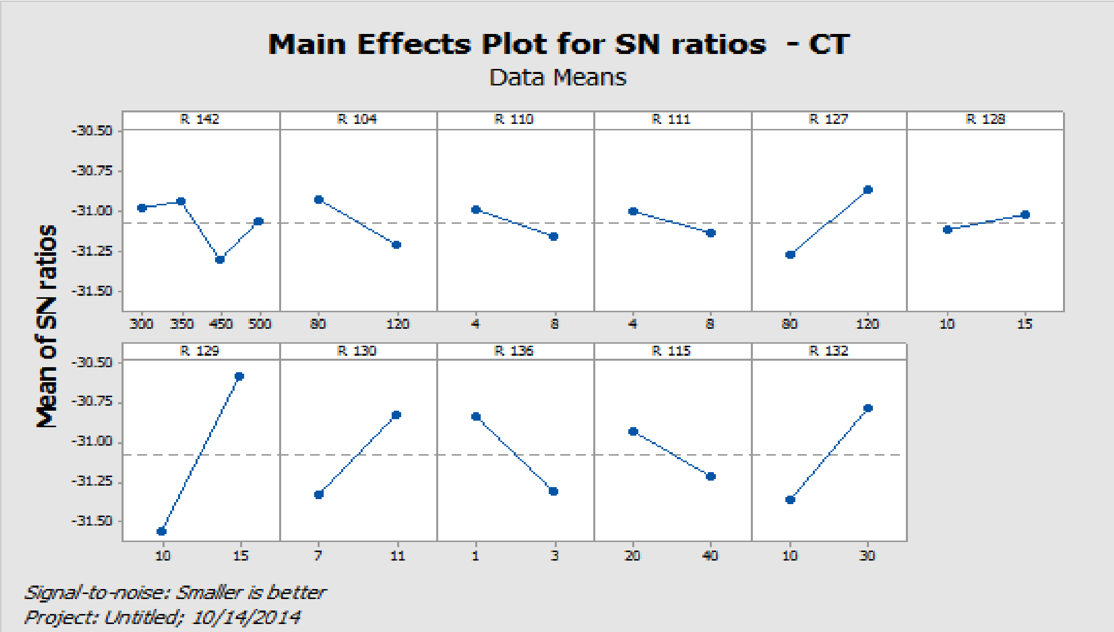

Fig. 10 S/N ratio graph for Cycle Time

Figure 9 shows the following significant parameters for track diameter size based on S/N ratio:
R142, R104, R110, R111, R127, R129, R130, R136 and R132
Figure 10 shows the following significant parameters for Cycle time based on S/N ratio:
R104, R127, R129, R130, R136 and R132
It should be noted that regardless of the nominal is best and the smaller-the-better quality characteristics, the greater S/N ratio corresponds to the smaller variance of the output characteristics around the desired value. The values of control parameters are to be selected on the levels which corresponds to the higher S/N ratio to obtain optimal output results.

D. Analysis of Variance (ANOVA)

The purpose of the ANOVA is to investigate which of the process parameters significantly affect the performance characteristics. This is accomplished by separating the total variability of the S/N ratios, which is measured by the sum of the squared deviations from the total mean of the S/N ratio, into contributions by each of the process parameters and the error. First, the total sum of the squared deviations SST from the total mean of the S/N ratio is calculated. The total sum of spared deviations SS_T is decomposed into two sources: the sum of squared deviations SS_d due to each design parameter and the sum of squared error SS_e. The percentage contribution by each of design parameter in total sum of squared deviations SS_T is a ratio of the sum of squared deviations SS_d due to each design parameter to the total sum of squared deviations SS_T.

Analysis of Variance (ANOVA) using MINITAB 17 software was performed to determine the contribution (in percentage) of the process parameters on the output responses namely track diameter size and cycle time of the process. Statistically, there is a tool called the F-test named after Fisher [8] to see which process parameters have a significant effect on the performance characteristic. Usually the larger the F-value, the greater the effect on the performance characteristic due to the change of the process parameter.

Table IV shows the results of ANOVA for track diameter size. It can be found that the control parameters R142, R104, R110, R111, R127, R129, R130, R136 and R132 are significant and account for 96 % of the total variation in track diameter size of the outer ring.

TABLE IV
ANOVA TABLE for TRACK DIAMETER SIZE of OUTER RING

Source	DF	Seq SS	Adj SS	Adj MS	F	P	%
R 142	3	46.69	46.69	15.5635	29	0.01	20%
R 104	1	14.705	14.705	14.7046	27.4	0.014	6%
R 110	1	52.826	52.826	52.826	98.44	0.002	23%
R 111	1	26.219	26.219	26.2193	48.86	0.006	11%
R 127	1	45.909	45.909	45.9086	85.55	0.003	20%
R 129	1	13.799	13.799	13.7991	25.71	0.015	6%
R 130	1	3.02	3.02	3.0196	5.63	0.098	1%
R 136	1	12.732	12.732	12.7322	23.73	0.017	5%
R 115	1	1.859	1.859	1.8585	3.46	0.16	1%
R 132	1	7.947	7.947	7.9469	14.81	0.031	3%
Residual Error	3	1.61	1.61	0.5367			
Total	15	227.315					

Table V shows the results of ANOVA for Cycle time of the process. It can be found that the control parameters R104, R127, R129, R130, R136 and R132 are significant and contribute to 82% of the total Cycle time of the grinding process.

TABLE V
ANOVA TABLE for CYCLE TIME of GRINDING PROCESS

Source	DF	Seq SS	Adj SS	Adj MS	F	P	%
R 104	1	0.3388	0.3388	0.3388	3.02	0.12	2%
R 127	1	0.6574	0.6574	0.6574	5.86	0.042	6%
R 129	1	3.8872	3.8872	3.8872	34.65	0	40%
R 130	1	1.0263	1.0263	1.0263	9.15	0.016	10%
R 136	1	0.8832	0.8832	0.8832	7.87	0.023	8%
R 115	1	0.3165	0.3165	0.3165	2.82	0.132	2%
R 132	1	1.3705	1.3705	1.3705	12.22	0.008	13%
Residual Error	8	0.8974	0.8974	0.1122			
Total	15	9.3771					

Therefore, based on the S/N ratio and ANOVA analyses, the optimal control parameters for reduction in cycle time while maintaining quality i.e. reduced size variation in track diameter are given in table VI.

TABLE VI
OPTIMAL PROCESS CONTROL PARAMETERS

R 142	R104	R110	R 111	R 127	R 128	R 129	R130	R 136	R 115	R 132
350	120	8	8	80	15	15	11	1	20	30

E. Confirmation tests

Once the optimal level of the process parameters is selected, the final step is to predict and verify the improvement of the performance characteristic using the optimal level of the process parameters. The estimated S/N ratio using MINITAB 17 software can be obtained and the corresponding cycle time and track diameter size can also be calculated using Eq. (3) and (2) respectively.

TABLE VII
RESULTS of CONFIRMATION TESTS

Sr. No.	Output Performance Characteristic		Values
1	Track Diameter Size Variation	Initial	25µ
		Predicted	15.06 µ
		Actual	17.97 µ
2	Cycle Time	Initial	36.3 sec
		Predicted	31.3 sec
		Actual	34.2 sec

Table VII shows the comparison of initial and actual results of the confirmation experiment for both output performance characteristics namely variation of track diameter size and cycle time of the grinding process. The variation in track diameter size was reduced 39.12 % and the cycle time was reduced by approximately 3 sec. which led to improvement in the throughput and overall lead time. Therefore, the experimental results show that the prior design and analysis done for optimizing the process control parameters has improved both the output performance characteristics.

V. CONCLUSIONS

This paper has described an application of the Taguchi method for optimizing the control parameters in grinding process. This study shows that the parameter design of the Taguchi method provides a simple, systematic, and efficient methodology for the optimization of the control parameters of a process. Experimental results demonstrate that the cycle time for a grinding process can be reduced simultaneously with reduction in variation of the size of track diameter of outer ring in manufacturing of bearing. The confirmation tests were conducted to verify the optimal parameters. This research demonstrates how the Taguchi parameter design can be used for optimizing process performance with minimum cost and time to industrial readers. Further study could consider more factors to see how they influence the output characteristics of a process. Future work can be done on application of Taguchi method for optimization of other processes in industries.

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