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QUALITY IMPROVEMENT IN MULTIRESPONSE EXPERIMENTS THROUGH ROBUST DESIGN METHODOLOGY

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Abstract: *Robust design methodology aims at reducing the variability in the product performance in the presence of noise factors. Experiments involving simultaneous optimization of more than one quality characteristic are known as multiresponse experiments which are used in the development and improvement of industrial processes and products. In this paper, robust design methodology is applied to optimize the process parameters during a particular operation of rotary driving shaft manufacturing process. The three important quality characteristics of the shaft considered here are of type Nominal-the-best, Smaller-the-better and Fraction defective. Simultaneous optimization of these responses is carried out by identifying the control parameters and conducting the experimentation using L9 orthogonal array.*
Keywords: *orthogonal array, control and noise factors, signal-to-noise ratio, multiple responses*

1. INTRODUCTION

Robust design methodology comes a great way in improving engineering productivity. The customer satisfaction can be ensured when one considers the cost of failure of a product along with the noise factors such as environmental variation, manufacturing variation and component deterioration. Robust design focuses on improving the fundamental function of the product or process, thus facilitating flexible designs and concurrent engineering (Michael Hamada, 1995). It is the most powerful method available to reduce product cost, improve quality and simultaneously reduce development interval. The aim of robust design is not to eliminate the cause of variation in the product performance, but to minimize the effect of such causes (Genichi Taguchi and Den Clausing, 1990). This can be achieved by proper choice of settings of the control factors, which can be easily controlled by the design engineer. Hence it is very much necessary to identify the settings of the control factors that yield insensitivity of the response to the noise factors.

The concept of robust design was pioneered by Genichi Taguchi in order to improve engineering productivity and the quality of manufactured goods. This approach to control and design engineering incorporates innovative statistical analysis as well as new approaches to the design of experiments (Genichi Taguchi and Den Clausing, 1990). The difference in the Taguchi method heavily relies on cost analysis of the product in the field, where it will ultimately be used, and the effect it will have on the consumer to increase end product satisfaction (Wu C.F.J & Michael Hamada, 2000). The two-step optimization technique utilizes the idea that improving the functionality of a process will reduce the variability, thus resulting in more precise control of the product quality (Naidu N V R and Dharani Gowda, 2001). The first step is to find the alternative or control factor setting that is least sensitive to noise (uncertainty) and the second step is to bring the design to its performance target (Phadke M S, 1989). Taguchi's point is that if one does not account for the effects of uncertainty from the beginning, one may end up with a product that is great if everything goes right, but that may behave poorly if there are any changes in the environment in which the product operates (George Box, 1988). Robust design involves five tools (Phadke M S, 1989):

- P-Diagram is used to classify the variables associated with the product into noise, control, signal (input), and response (output) factors.
- Ideal function is used to mathematically specify the ideal form of the signal-response relationship as embodied by the design concept for making the higher-level system work perfectly.
- Quality Loss Function is used to quantify the loss incurred by the user due to deviation from target performance.
- Signal-to-noise ratio is used for predicting the quality through laboratory experiments.
- Orthogonal arrays are used for gathering dependable information about control factors (design parameters) with a small number of experiments.

2. SPLINE HOBBING OPERATION

A rotary driving shaft used for power transmission in tiller is an important product, which had some customer complaints regarding its quality. Hence, this shaft is considered for the study. This shaft is made of EN19 and its total length is 450.3mm and its outside diameter is 30.3mm. Spline hobbing is a machining operation for making splines on this shaft and is a critical operation in the shaft manufacturing process. The hobbing machine is a special type of milling machine which consists of a chuck and a tailstock, to hold the shaft. The cutter or hob is installed on arbor for support which is joined with the column, traveling along the saddle. Hob axial feed is realized due to saddle traveling along the flat horizontal guides of the base. The splines are progressively cut into the shaft by the hob. 16 splines are cut to a length of 74 mm from the left end of the shaft. The rotary driving shaft after the spline hobbing operation is shown in figure 1.

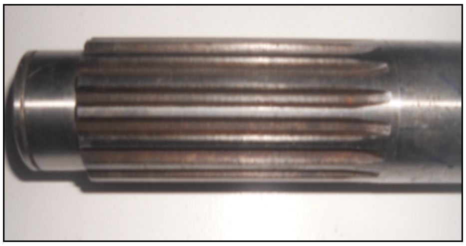

Figure 1 Rotary driving shaft

After the spline hobbing operation, the shaft is checked for the following quality characteristics:

- Diameter over pin (DOP)
- Root diameter at a point on the spline
- Root diameter along the length of the spline
- Length of spline
- Tooth depth
- Pitch circle diameter - run out
- Visual defects

3. METHODOLOGY

A discussion with the supervisor, quality control – head and inspector was conducted to identify the critical characteristics from the above list. The three characteristics namely, DOP, root diameter along the length of the spline (variation in root diameter) and visual defects (fraction defective) were identified to be critical.

The DOP is measured with digital micrometer using two pins, each with a diameter of 3mm. The specification limit for DOP is 32.615 mm ± 15 microns. As there is a target value of 32.615 mm with tolerances on both sides, this quality characteristic is considered as nominal-the-best type. The root diameter of the shaft should be same at all the points along the length of the spline. The root diameter specified is 26 mm. The root diameter is measured using two cones along with the digital micrometer. The variation in the root diameter along the spline on the shaft should be minimum; the ideal value being zero and hence it is a smaller-the-better type of quality characteristic. Visual inspection is carried out to identify the visible defects that are present on the surface of the shaft. The shaft can have different types of defects like improper addendum chamfer, profile chipping, burr, tooth damage etc. Such visual defects are attribute quality characteristics and are of fraction defective type.

The Signal-to-noise (SN) ratio for DOP for the existing conditions is found to be 82.66 dB, -28.303 dB for variation in root diameter and 7.381 dB for fraction defective.

Brainstorming sessions are conducted with Head – Quality Control, Engineers, Inspectors, Line Supervisors and Operators and four control factors having significant effect on the three responses are identified. The control factors are shaft spindle speed, hob speed, feed and depth of cut. To study the curvilinear effect, three levels are identified for each factor and are presented in table 1.

Table 1: Control Factors and their levels

Control Factors	Levels		
	1	**2**	**3**
Shaft spindle speed (A) rpm	200	250	300
Hob speed (B) rpm	150	200	250
Feed (C) mm/rev	1.5	2	2.5
Depth of cut (D) mm	1	1.5	2.5

Taguchi method emphasizes on making the product insensitive to noise factors by setting optimum levels to the control factors (Jiju Antony, 2001). Hence after discussion with the engineers and line supervisors, width of the hole on the shaft face is selected as a noise factor. A hole is drilled on the two faces of the shaft so that the shaft is held tightly between the chuck and tailstock. If the hole is narrow, the shaft is held rigidly during operation. If the hole is wide, the shaft would not be held tightly and it may vibrate during the operation and may become defective. However, a shaft with wide hole on its face is not rejected during inspection because it does not affect its function when assembled into the socket. Hence width of hole on shaft face is considered as a noise factor and two levels are identified for the same as shown in table 2.

Table 2: Noise Factor and levels

Noise Factors	Levels	
	N1	**N2**
Outer hole on shaft face	Narrow	Wide

With four control factors at three levels each, 9 experiments are required. The most appropriate orthogonal array identified for this experimentation is L_9 orthogonal array.

4. EXPERIMENTATION AND DATA COLLECTION:

The experimentation is carried out with nine runs for DOP, variation in root diameter and fraction defective simultaneously. For every experimental run, the DOP is measured for a sample of eight shafts; four shafts having narrow hole (N1) and four shafts with wide hole (N2) on the face. The observations of DOP are shown in excess of 32 mm and are expressed in micron. Also, on every shaft, the root diameter was measured at four points along the length of the spline and the mean root diameter is calculated for each shaft. The observations for variation in root diameter are expressed above or below the nominal value of 26mm. To identify the visual defects, fifty shafts with narrow hole (N1) and fifty shafts with wide hole (N2) are spline hobbed for every experimental run and visual inspection is carried out to find the fraction defective. The result of the experimentation is shown in table 3.

Table 3: Experimental results using L_9 orthogonal array

No	A	B	C	D	Responses																	
					DOP (in micron) at N1 for 4 different shafts				DOP (in micron) at N2 for 4 different shafts				Mean root diameter (in micron) at N1 narrow hole				Mean root diameter (in micron) at N2 wide hole				p* at N1	p* at N2
					1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4		
1	200	150	1.5	1	643	639	642	641	648	647	634	645	+012	+011	-187	+106	-216	-097	+113	-206	0.08	0.12
2	200	200	2	1.5	624	627	622	627	623	624	621	622	-17	-124	+103	-112	-236	-257	-202	-217	0.02	0.1
3	200	250	2.5	2.5	596	609	593	602	599	597	596	598	+112	+108	+104	+112	-27	-16	-117	+82	0.14	0.18
4	250	150	2	2.5	641	642	635	644	631	621	628	620	+183	-127	-104	+3	-16	+13	+23	-47	0.16	0.14
5	250	200	2.5	1	623	622	625	624	633	619	634	628	+10	+2	-114	-222	+3	+14	+3	+4	0.18	0.16
6	250	250	1.5	1.5	612	616	615	617	603	601	608	604	+112	+110	-16	+10	+112	-36	-208	-37	0.18	0.16
7	300	150	2.5	1.5	599	613	605	603	611	624	633	623	-59	+263	+262	-1	-54	-2	+113	+114	0.18	0.2
8	300	200	1.5	2.5	609	611	608	609	626	625	616	627	+104	+134	+109	+91	+93	+88	+59	+98	0.08	0.14
9	300	250	2	1	615	614	618	610	611	612	601	613	-31	+2	+101	+2	+3	+23	-6	-13	0.1	0.12

* p denotes fraction defective

The SN ratio is calculated for all the three output quality characteristics for every factor level and SN ratio graphs for DOP are shown in figure 2. The specimen calculation for SN ratio for DOP is shown below.

SN ratio for Nominal-the-best is given by $\eta = 10 \log_{10}(\mu^2/\sigma^2)$ decibels

$= 10 \log_{10} (32.642^2 / 0.004533^2) = 77.146$ dB

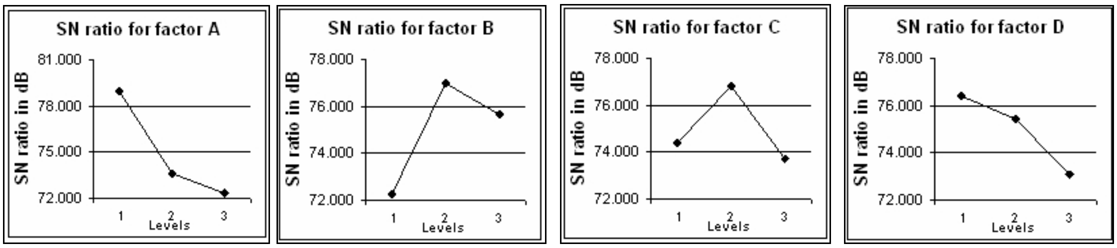

Figure 2 SN ratio graphs for DOP

The SN ratio graphs for variation in root diameter are shown in figure 3. The specimen calculation for SN ratio for variation in root diameter is shown below.

SN ratio for Smaller-the-better is given by $\eta = -10 \log_{10} 1/n \, \Sigma \, y_i^2$ decibels

$\eta = -10 \log_{10} 1/8 \, (26.012^2 + 26.011^2 + 25.813^2 + 26.106^2 + 25.784^2 + 25.903^2 + 26.113^2 + 25.794^2) = -28.280$ dB

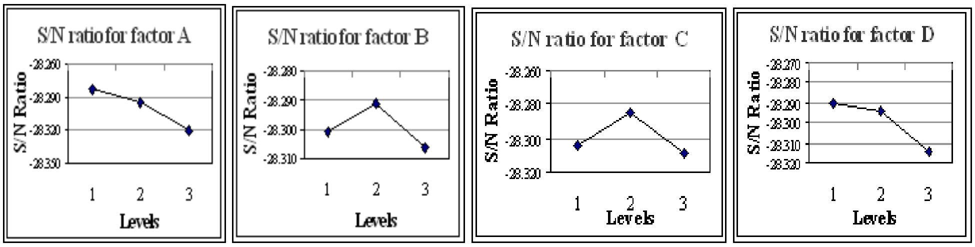

Figure 3 SN ratio graphs for variation in root diameter

The SN ratio graphs for fraction defective are shown in figure 4. The specimen calculation for SN ratio for fraction defective is shown below.

SN ratio for fraction defective = η = 10 log ((1/p) - 1) dB. p = (0.08 + 0.12) / 2 = 0.1

η = 10 log ((1/0.1) – 1) = 9.542 dB

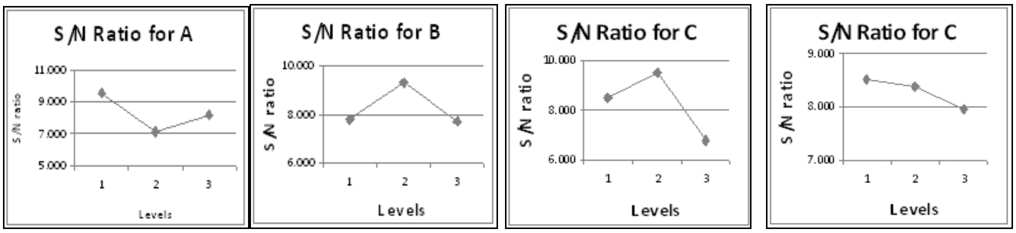

Figure 4: SN ratio graphs for fraction defective

From the SN ratio graphs, the optimal levels for the factors A, B, C and D are obtained as A1, B2, C2 and D1 which is shown in table 4.

Table 4: Optimal Levels for the Control Factors

Factors	Optimal level	Value
Shaft speed (A)	1	200 rpm
Hob speed (B)	2	200 rpm
Feed (C)	2	2 mm/rev
Depth of cut (D)	1	1 mm

The predicted SN ratio for DOP under optimal conditions is given below.

$\eta_{predicted} = m + m_{A1} + m_{B2} + m_{C2} + m_{D1} - 4m$

$\eta_{predicted}$ for DOP = 74.959 + 78.947 + 76.952 + 76.785 + 76.407 – 4 (74.959)

= 84.214 dB

The predicted SN ratio for variation in root diameter under optimal conditions is given below.

$\eta_{predicted}$ for DOP = (-28.3) + (-28.283) + (-28.291) + (-28.285) + (-28.290) – 4 (-28.3)

= - 28.249 dB

The predicted SN ratio for fraction defective under optimal conditions $\eta_{predicted}$ = 12.078 dB

5. CONFIRMATION EXPERIMENT

Confirmation experiment is carried out by measuring DOP for twenty subgroups with a subgroup size of five shafts by setting the control factors at their optimal levels. For variation in root diameter, the diameter at the root was measured for hundred shafts at four different points along the length of the spline. For fraction defective type, visual inspection is carried out for hundred shafts. The SN ratio for DOP during the confirmation experiment is obtained as 83.82 dB, -28.287dB for variation in root diameter and 13.80 dB for fraction defective. Gain in the SN ratio for the each of the three quality characteristics is given below.

Gain in SN ratio is given by

Gain = $\eta_{confirmation} - \eta_{existing}$

Gain (for DOP) = 83.82 - 82.66 = 1.16 dB

Gain (for variation in root diameter) -28.287 – (-28.303) = 0.016 dB

Gain (for visual defects) = 13.80 - 7.381 = 6.419 dB

6. CONCLUSION

Multiresponse experiments are conducted to improve the quality of the rotary driving shaft during spline hobbing operation using robust design methodology.

The three responses considered here are diameter over pin (Nominal-the-best), variation in root diameter (Smaller-the-better) and tooth damage (Fraction defective). L_9 orthogonal array is selected for experimentation; experimental runs are carried out with four control factors and one noise factor and SN ratio is calculated for each of the three responses.

SN ratio graphs are plotted and optimal levels are identified for the control factors. Confirmation run is carried out and the improvement is shown in table 5.

Table 5: Improvement in quality after applying robust design methodology

Response	Before experimentation	After experimentation
Diameter over pin	$\eta_{existing}$ = 82.66 dB	$\eta_{confirmation}$ = 83.82 dB Gain = 1.16 dB
Variation in root diameter	$\eta_{existing}$ = -28.303 dB	$\eta_{confirmation}$ = -28.287 dB Gain = 0.016 dB
Fraction defective	$\eta_{existing}$ = 7.381 dB	$\eta_{confirmation}$ = 13.80 dB Gain = 6.149 dB

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