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Optimization of In-feed Centreless Cylindrical Grinding Process Parameters Using Grey Relational Analysis

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ABSTRACT

This paper presents an effective approach for the optimization of an in-feed centreless cylindrical grinding of EN52 austenitic grade steel (DIN: X45CrSi93) with multiple performance characteristics based on the grey relational analysis. To study the effect of the entire space of the input variables, nine experimental runs, based on the Taguchi method of L_9 orthogonal arrays, were performed to determine the best factor level condition. The response table and response graph for each level of the machining parameters were obtained from the grey relational grade. In this study, the in-feed centreless cylindrical grinding process parameters, such as dressing feed, grinding feed, dwell time and cycle time, were optimized by taking into consideration the multiple-performance characteristics like surface roughness and out of cylindricity. By analyzing the grey relational grade, it was observed that dressing feed, grinding feed and cycle time had significant effect on the responses. The optimal multiple performance characteristics were achieved with dressing feed at level 1 (5 mm/min), grinding feed at level 2 (6 mm/min), dwell time at level 2 (2.5 s), and cycle time at level 2 (11 s). It is clearly shown that the above performance characteristics in the in-feed Centreless cylindrical grinding process can be improved effectively through this approach.

Keywords: **Centreless cylindrical grinding, surface roughness, out of cylindricity, grey relational analysis, optimization, multi-performance**

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INTRODUCTION

In-feed centreless cylindrical grinding is used to finish parts that have projections, variation in shapes, varying diameters, or shoulders. In the in-feed method, the shape variations are accommodated in the form of grinding wheel (or wheels) truing to form various part diameters and lengths that describe the part

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geometry. In this process, the part is fed to the wheels from above with no lateral movement of the piece while it is being ground. This makes the process well suited for profiles and multi-diameter components. Fig.1 illustrates the schematic diagram of the in-feed cylindrical grinding. Centreless cylindrical grinding process involves a large number of influencing factors that are non-linear, interdependent and difficult to quantify. It is the process of choice for high volume finishing of the surfaces of revolution shaped components. Despite all its merits, it is marked with instability problems.

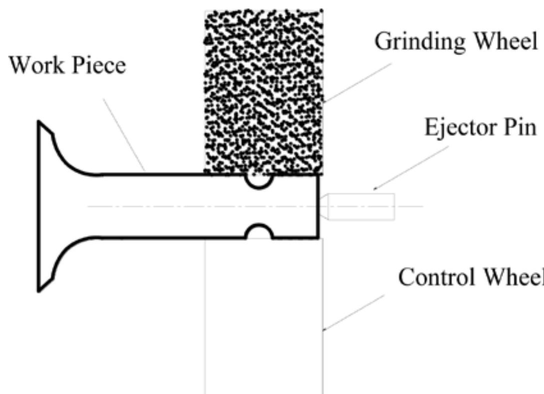

Fig.1: Schematic of In-feed Centreless Grinding Process

Furthermore, the characteristics of the machined surfaces, such as surface finish and roundness, are largely dependent on the machine's attributes, including its condition, dynamics, setup and also process parameters (Bueno *et al*., 1990; Hashimoto & Lahoti, 2004). Available literature also shows that such issues have been extensively studied and analytically addressed (Bueno *et al*., 1990). This has led to remarkable improvements in the technology of accurate machines. Yet, due to complexities related to the machine and its setup, the success of the process is dependent a large extent on the initial setup conditions and process parameters, which in many cases, are done by extensive trial and errors based on the operator's skills (Hashimoto & Lahoti, 2004). Thus, finding the optimum process parameters is still a challenge from the manufacturing process point of view.

In order to control the grinding process, it is necessary to quantify roundness and surface roughness, which are the most critical quality characteristics for the selection of cylindrical grinding process parameters. The roundness of a part is defined by the initial conditions, i.e. blade angle and part height (Hashimoto & Lahoti, 2004). The surface roughness of the finished component depends on the centreless cylindrical grinding gap set-up, the dressing condition and the significant process kinematical factors (Hashimoto & Lahoti, 2004).

It appears from the literature that grey relational analysis has been extensively used by the researchers in determining the optimal parameters for different machining processes. For example, grey relational analysis, coupled with principal component analysis, was used to optimize the process parameter of high-speed end milling of SKD61 tool steel (Lu *et al*., 2008). The grey relational analysis was employed for the optimization of the laser cutting process of

St-37 steel (Çaydaş & Hasçalık, 2008) so as to determine the optimal wire electrical discharge machining (WEDM) parameters for machining Al_2O_3 particle reinforced material with multiple-performance characteristics (surface removal rate and maximum surface roughness) (Chiang & Chang, 2006), optimize the drilling process parameters, such as feed rate, cutting speed, drill type and point angles of drill for the workpiece surface roughness and burr height (Tosun, 2006), optimize turning operations with multi-performance characteristics (tool life, cutting forces and surface roughness) (Lin, 2004), determine the cutting parameters for optimizing the side milling process with multi-performance characteristics (Chang & Lu, 2007), and determine the optimal machining parameter setting for the end-milling of high-purity graphite under dry machining condition (Yang, 2006).

A fuzzy based grey relational analysis was used to find the optimal process conditions of an injection-molded thermoplastic part with a thin shell feature (Ko-Ta, 2007). Turning parameters, such as cutting speed, feed rate, depth of cut and machining time, were also optimized based on the multiple-performance characteristics which included material removal rate, tool wear, surface roughness and specific cutting pressure by using grey relational analysis method (Palanikumar *et al*., 2006).

The out-of-roundness of a part is determined mainly by grinding speed. It also depends on the height of job axis above the centerline of the grinding and regulating wheels. The height is set so that the axis of the workpiece is above the centerline of the grinding and regulating wheels. The surface roughness of the finished component, on the other hand, is significantly dependent on the dressing condition and the process kinematical factors (Hashimoto & Lahoti, 2004). Meanwhile, the dimensional deviations of the finished part are established by work rest setting and feed. The feed affects all the quality attributes including out-of-roundness, surface roughness and dimensional accuracy.

The present study was carried out with the purpose to select the optimal in-feed centreless cylindrical grinding process parameters that would optimize the multiple-performance characteristics, namely, work piece surface roughness and out of cylindricity of internal combustion engine valve stems using grey relational analysis. The cylindrical grinding of valve stems was chosen owing to the fact that any error beyond permissible limits would progressively cause growing deposits of combustion residues and increase oil consumption, in addition to disturbed heat transmission and excessive wear. The valve stems were ground finished to very tight tolerances of shape, size and surface finish in order to obtain a consistent in-service performance.

The geometric characteristics of the valve stem (e.g. roundness, surface finish and out of cylindricity) are also important as these affect the specific operating load, noise, faster wear and overall performance of the part in an internal combustion engine. The valve stem is ground finished to the prescribed levels of surface finish as it affects material fatigue strength, corrosion resistance, sealing performance, friction, lubrication, force distribution, etc. The setting of in-feed centreless cylindrical grinding process parameters was accomplished using the Taguchi experimental design method. Moreover, the most effective factor and the order of importance of the controllable factors to the multi-performance characteristics in the in-feed centreless cylindrical grinding process were determined by using the grey relational grade.

EXPERIMENTAL PROCEDURE

The experiments were conducted on a centreless cylindrical grinding machine (HMT, model GCL-50 TG, CNC centreless grinding machine). A schematic diagram of the In-feed Centreless Cylindrical grinding Process is shown in Fig.1. The process involved a cylindrical grinding of an internal combustion (IC) engine valve stem made of EN52 austenitic grade steel with a 79.6 mm diameter. For this grade of steel and the size of the valve stem to be ground finished, an A80N5V45 grinding wheel rotating at 1440 rpm (giving a surface speed of 45 m/s) and an A80RR control wheel were used based on experience. The cylindrical grinding process was carried out over a length of 98 mm of valve stem (Fig.2) with a job height of 212 mm above the blade. The chemical composition of EN52 is given in Table 1.

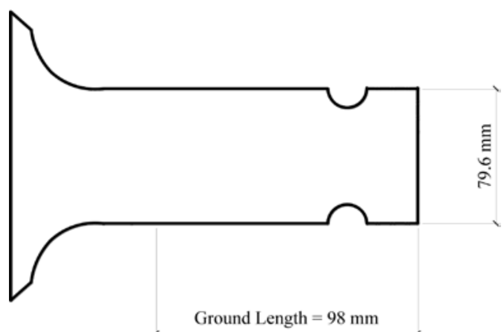

Fig.2: IC Engine Valve

Table 1: Composition of EN52 grade valve steel

VALVE STEELS Chemical Composition (average values in %)									
Grade	C	Si	Mn	P	S	Cr	Mo	Ni	N
EN52	0.40 – 0.50	2.70 – 3.30	0.80 max	0.04 max	0.03 max	8.0 – 10.0	--	--	-

As a large number of independent parameters control the in-feed centreless cylindrical grinding process, some preliminary experiments were conducted to determine the parameters to be taken into consideration for optimization. Four parameters (namely, grinding feed, dressing feed, dwell time and cycle time) were varied to obtain the optimum levels of parameters for acceptable quality. A summary of the experimental conditions is listed in Table 2. In order that the experiments were performed under chatter-free conditions, indirect parameters such as coolant flow rate (50 litre per minute), grinding depth (60 µm), blade angle (32^o), control wheel speed (25 rpm), blade height (212 mm), in-feed speed (20 rpm) and control wheel angle (1^o) were kept constant during experimentation.

MEASUREMENT OF THE RESPONSE PARAMETERS

In order to achieve the best cylindrical grinding quality, Taguchi's experimental design was used for conducting the experiments (Roy, 1990). The experimental results after the cylindrical

Table 2: Design factors and their levels

Trial No	Grinding Parameters	Notation	Units	Levels		
				Level -1	Level -2	Level - 3
1	Dressing Feed	A	mm/min	5	8	10
2	Grinding Feed	B	mm/min	2	6	10
3	Dwell Time	C	s	1.5	2.5	3
4	Cycle Time	D	s	10	11	12

grinding were evaluated in terms of the following measured cylindrical grinding performances: (1) surface roughness (R_a) and (2) out of cylindricity. Meanwhile, the surface roughness was measured with a surface roughness measuring instrument (Taylor Hobson, model SurfCom). The sampling length of each measurement was set to 6 mm as per the recommendations of ASME B-46.1-2002. In order to measure out of cylindricity, an indigenously made precision fixture was used, on which the ground valve-stem was held. Three equidistant sampling lengths of 6 mm each were taken on the valve-stem. At each end of the first sampling length, the probe of a dial-micrometer-gauge (Mitutoyo, AGD series 1010SB-11) was touched to the valve-stem. Subsequently, the valve-stem was given one complete rotation, while the minimum and maximum deflections in the pointer were recorded. The difference between the maximum and minimum deflections gave the valve's out of cylindricity over the sampling length. The above steps were repeated on the other sampling lengths and the average was taken as the valve's out of cylindricity for the ground valve-stem.

DETERMINATION OF THE IN-FEED CENTRELESS CYLINDRICAL GRINDING PROCESS PARAMETERS

In this section, the use of the grey-based Taguchi method to determine the in-feed centreless cylindrical grinding process parameters is reported. The optimal in-feed centreless cylindrical grinding process parameters, with considerations of the multiple performance characteristics are also obtained and verified.

Orthogonal Array Experiment

An L_9 orthogonal array, with 4 columns and 9 rows, is used. This array has eight degrees of freedom and it can handle three-level process parameters. Nine experiments are required to study the entire in-feed centreless cylindrical grinding process parameter space when the L_9 orthogonal array is used. The experiment layout for the in-feed centreless cylindrical grinding process parameters using the L_9 orthogonal array is shown in Table 3.

S/N Ratio for the Multiple Performance Characteristics

In the Taguchi method, the term "signal" represents the desirable value (mean) for the output characteristic and the term "noise" represents the undesirable value for the output. There are three categories of quality characteristics, namely, the-lower-the-better, the-higher-the-better,

Table 3: Experimental layout using an L9 orthogonal array

Experiment number	Grinding Parameter			
	Dressing Feed (mm/min)	Grinding Feed (mm/min)	Dwell Time (s)	Cycle Time (s)
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

and the-nominal-the better. Surface roughness and out of cylindricity are the lower-the-better performance characteristics, with the loss function can be expressed as (Hsiao *et al*., 2007):

$$L_{ij} = \frac{1}{n}\sum_{k=1}^{n} y^2 ijk \quad [1]$$

where L_{ij} is the loss function of the ith performance characteristic in the jth experiment, y_{ijk} is the experimental value of the ith performance characteristic in the jth experiment at the kth trial, and n is the number of trials. The loss function is further transformed into an S/N ratio to determine the deviation of the performance characteristic from the desired value. The S/N ratio η_{ij} for the ith performance characteristic in the jth experiment can be expressed as:

$$\eta_{ij} = -10\log(L_{ij}) \quad [2]$$

In the next section, the grey relational analysis is used to analyze the complicated inter-relationships among the S/N ratios, as shown in Table 4 and Table 5.

Grey Relational Analysis for the S/N Ratio

The grey relational generating (Deng, 1989), i.e. a linear normalization of the S/N ratio, is performed in the range between zero and unity. The normalized S/N ratio x_{ij} for the ith performance characteristic in the jth experiment can be expressed as:

$$x_{ij} = \frac{\eta_{ij} - \min_j \eta_{ij}}{\max_j \eta_{ij} - \min_j \eta_{ij}} \quad [3]$$

Table 6 shows the normalized S/N ratio for surface roughness and out of cylindricity. Basically, the larger normalized S/N ratio corresponds to the better performance and the best-normalized S/N ratio is equal to unity. The grey relational coefficient is calculated to express the relationship between the ideal (best) and actual normalized S/N ratio. Meanwhile, the

Table 4: Experimental results for surface roughness and its S/N ratio

Experiment number	A	B	C	D	Surface roughness (μm)	S/N Ratio (dB)
1	1	1	1	1	0.43	7.26
2	1	2	2	2	0.44	7.13
3	1	3	3	3	0.43	7.40
4	2	1	2	3	0.58	4.78
5	2	2	3	1	0.61	4.25
6	2	3	1	2	0.76	2.35
7	3	1	3	2	0.50	5.96
8	3	2	1	3	0.52	5.74
9	3	3	2	1	0.55	5.14

Table 5: Experimental results for out of cylindricity and its S/N ratio

Experiment number	A	B	C	D	Out of cylindricity (mm)	S/N Ratio (dB)
1	1	1	1	1	0.0007	63.52
2	1	2	2	2	0.0007	63.52
3	1	3	3	3	0.0010	60.00
4	2	1	2	3	0.0017	55.56
5	2	2	3	1	0.0010	60.00
6	2	3	1	2	0.0013	57.50
7	3	1	3	2	0.0033	49.54
8	3	2	1	3	0.0030	50.46
9	3	3	2	1	0.0037	48.71

grey relational coefficient ξ_{ij} for the ith performance characteristic in the jth experiment can be expressed as:

$$\xi_{ij} = \frac{\min_i \min_j \left| x_i^0 - x_{ij} \right| + \xi \max_i \max_j \left| x_i^0 - x_{ij} \right|}{\left| x_i^0 - x_{ij} \right| + \xi \max_i \max_j \left| x_i^0 - x_{ij} \right|} \qquad [4]$$

where x_i^0 is the ideal normalized S/N ratio for the ith performance characteristic, and ξ distinguishing coefficient which is defined in the range of $0 \leq \xi \leq 1$.

A weighting method is then used to integrate the grey relational coefficients of each experiment into the grey relational grade. The overall evaluation of the multiple performance characteristics is based on the grey relational grade (Hsiao *et al.*, 2007), as follows:

$$\gamma_j = \frac{1}{m}\sum_{i=1}^{m} w_i \xi_{ij} \qquad [5]$$

Assume $w_1 = w_2 = 0.5$ as it is required to be taken to be equal in grey relational analysis, where γ_j is the grey relational grade for the jth experiment, w_i is the weighting factor for the ith performance characteristic, and m is the number of the performance characteristics.

Table 6: Normalized S/N ratios

Experiment number	Surface roughness	Out of cylindricity
Ideal sequence	1.00	1.00
1	0.97	1.00
2	0.95	1.00
3	1.00	0.76
4	0.48	0.46
5	0.38	0.76
6	0.00	0.59
7	0.72	0.06
8	0.67	0.12
9	0.55	0.00

Table 7 shows the grey relational grade for each experiment using the L_9 orthogonal array. A higher grey relational grade indicates that the corresponding S/N ratio is closer to the ideally normalized S/N ratio. The findings revealed that experiment 1 obtained the best multiple performance characteristics among the nine experiments because it has the highest grey relational grade (*see* Table 7). In other words, the optimization of the complicated multiple performance characteristics can be converted into the optimization of a single grey relational grade.

Table 7: Grey relational grade and its order

Experiment number	Grey relational grade	Order
1	0.9745	1
2	0.9520	2
3	0.8386	3
4	0.4865	6
5	0.5612	4
6	0.4424	8
7	0.4918	5
8	0.4823	7
9	0.4306	9

The effect of each in-feed centreless cylindrical grinding process parameter on the grey relational grade at different levels can be independent because the experimental design is orthogonal. The grey relational grade for each level of the in-feed centreless cylindrical grinding process parameters is summarized and shown in Table 8.

In addition, the total mean of the grey relational grade for the 9 experiments is also calculated and presented in Table 8. Fig.3 shows the grey relational grade graph, where the dashed line is the value of the total mean of the grey relational grade. Basically, the larger the grey relational grade, the better the multiple performance characteristics will be. However, the relative importance among the in-feed centreless cylindrical grinding process parameters for the multiple performance characteristics still needs to be known, so that the optimal combinations of the in-feed centreless cylindrical grinding process parameter levels can be determined.

Table 8: Response table for the grey relational grade

Symbol	Process parameter	Grey relational grade			
		Level 1	Level 2	Level 3	Maximum- minimum
A	Dressing feed	0.92	0.50	0.47	0.45
B	Grinding feed	0.65	0.67	0.57	0.10
C	Dwell time	0.63	0.62	0.63	0.01
D	Cycle time	0.66	0.63	0.60	0.06
Total mean value of the relational grade = 0.63					

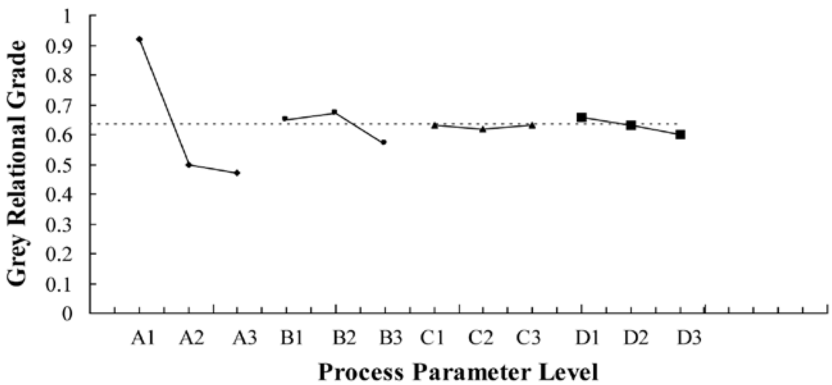

Fig.3: Grey Relational Grade Graph

Analysis of Variance

The purpose of the analysis of variance (ANOVA) is to investigate which in-feed centreless cylindrical grinding process parameters significantly affect the performance characteristics. This was accomplished by separating the total variability of the S/N ratios, which was measured by the sum of the squared deviations from the total mean S/N ratio into contributions by each of the design parameters and the error. First, the total sum of the squared deviations SS_T from the mean S/N ratio η_m was calculated (Hsiao *et al*., 2007) as follows:

$$SS_T \sum_{i=1}^{n} (\eta_i - \eta_m)^2 \quad [6]$$

where *n* is number of the experiments in the orthogonal array, and η_i is the mean S/N ratio for the *i* th experiment.

The total sum of the squared deviations SS_T is decomposed into two sources, namely, the sum of the squared deviations SS_d (due to each process parameter), and the sum of the squared error SS_e. The percentage contribution by each of the process parameters in the total sum of the squared deviations SS_T is a ratio of the sum of the squared deviations SS_d due to each process parameter to the total sum of the squared deviations SS_T.

Statistically, there is a tool called *F* test to determine which process parameters have significant effect on the quality characteristic. To perform the *F* test, the mean of squared deviations SS_m needs to be calculated due to each process parameter. The mean of the squared deviations SS_m is equal to the sum of the squared deviations SS_d divided by the number of degree of freedom associated with the process parameter. Then, the *F* value for each process parameter is simply the ratio of the mean of the squared deviations SS_m to the mean of squared error SS_e.

The results of ANOVA (Table 9) indicate that dressing feed, grinding feed and cycle time are the significant in-feed centreless cylindrical grinding process parameters that affect the multiple performance characteristics. Furthermore, the dressing feed is the most significant process parameter due to its highest percentage contribution among the process parameters. Based on the above discussion, the optimal in-feed centreless cylindrical grinding process parameters are dressing feed at level 1 (5 mm/min), grinding feed at level 2 (6 mm/min), dwell time at level 2 (2.5 s) and cycle time at level 2 (11 s).

Table 9: Results of analysis of variance (ANOVA)

Source of variation	Degree of freedom	Sum of squares	Mean square	Variance Ratio (F)	Contribution (%)	P-value
A, Dressing feed	2	0.387	0.194	2363	95.045	0.0004
B, Grinding feed	2	0.016	0.008	95.4	3.799	0.0104
C, Dwell time	2	(0.00016)	-	-	-	-
D, Cycle time	2	0.004	0.002	25.7	0.995	0.0375
Residual	2	0.00016	0.00008		0.161	
Total	8	0.407	0.051		100.000	

CONFIRMATION TESTS

Once the optimal level of the design parameters has been selected, the final step is to predict and verify the improvement of the quality characteristic using the optimum level of the design parameters. The estimated S/N ratio $\hat{\eta}$ using the optimal level of the design parameters can be calculated as follows (Yang & Tarng, 1998):

$$\hat{\eta} = \eta_m + \sum_{i=1}^{0} (\eta_i - \eta_m) \quad [7]$$

where η_m is the total mean S/N ratio, η_i is the mean S/N ratio at the optimal level, and *o* is the number of the main design parameters that affect the quality characteristic.

The estimated S/N ratio using the optimal level of the process parameters can be calculated from Table 7, considering only the process parameters that significantly affect the multiple performance characteristics. Table 10 shows the comparison of the experimental results using the initial and optimal in-feed centreless cylindrical grinding process parameters. It is important to note that the in-feed centreless cylindrical grinding performance has been greatly improved through this study. As shown in Table 10, the surface roughness is decreased from 0.55 to 0.44 μm, and the out of cylindricity is changed from 37.0×10^{-4} to 7.00×10^{-4} mm.

Table 10: Results of in-feed centreless grinding performance using the initial and optimal process parameters

	Initial Process Parameter	Optimal Process Parameters	
		Prediction	Experiment (Average)
Level	$A_3B_3C_2D_1$	$A_1B_2C_2D_2$	$A_1B_2C_2D_2$
Surface roughness, µm (Average)	0.55		0.44
Out of cylindricity, mm (Average)	37.0 x 10^{-4}		7.00 x 10^{-4}
Grey relational grade	0.4306	0.958	0.952
Improvement of the grey relational grade =	0.5214		

CONCLUSION

This study engaged in the testing of the surface roughness and the out of cylindricity of internal combustion engine valve stem that had been ground finished on the in-feed centreless cylindrical grinding machine. The following conclusions are derived at:

- The multiple performance characteristics of the lowest surface roughness and out of cylindricity were obtained from the process parameters and the greatest grey relation value of 0.9745.
- The optimal multiple performance characteristics were achieved with dressing feed at level 1 (5 mm/min), grinding feed at level 2 (6 mm/min), dwell time at level 2 (2.5 s) and cycle time at level 2 (11 s).
- Using ANOVA, the dressing feed, grinding feed and cycle time were found to have significant impacts on the multiple performance characteristics while dwell time have insignificant impact.
- The experimental outcomes indicated that based on the optimal parameter combination level of the multiple performance characteristics, the experimental values of the surface roughness and out of cylindricity have been reduced. The grey relation was improved by 0.5214. Meanwhile, the grey relation value of the optimal parameter level fits the predicted value of the optimal parameter level very well and this serves as a proof of the projection power of this study.

The optimization of the complicated multiple performance characteristics can be greatly simplified through this approach. The performance characteristics of the in-feed centreless cylindrical grinding process, such as the surface roughness and the out of cylindricity, have been found to be reduced together by using the proposed method. In addition, the use of the Taguchi method, through the grey relational analysis, has been shown to have greatly simplified the optimization procedure for determining the optimal process parameters with the multiple performance characteristics in the in-feed centreless cylindrical grinding process.

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