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Comparative Assessment of Cutting Inserts and Optimization during Hard Turning: Taguchi-Based Grey Relational Analysis

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Abstract: The present study aims to compare the conventional cutting inserts with wiper cutting inserts during the hard turning of AISI 4340 steel at different workpiece hardness. Type of insert, hardness, cutting speed, feed, and depth of cut are taken as process parameters. Taguchi's L18 orthogonal array was used to conduct the experimental tests. Parametric analysis carried in order to know the influence of each process parameter on the three important Surface Roughness Characteristics (R_a, R_z, and R_t) and Material Removal Rate. Taguchi based Grey Relational Analysis (GRA) used to optimize the process parameters for individual response and multi-response outputs. Additionally, the analysis of variance (ANOVA) is also applied to identify the most significant factor.

[**Keywords :** Hard turning; AISI 4340 steel; Surface Roughness Characteristics; Material Removal Rate; wiper ceramic insert; Grey Relational Analysis.]

1. INTRODUCTION

Present manufacturing industries are trying to establish the new methods for producing high-quality products with low machining costs. Quality aspect of the product is generally associated with its surface roughness characteristics, in turn, it is important to the functionality of machined components. Achievement of a fine surface is a big issue during the conventional machining for advanced hard engineering materials, which involves a series of operations, further it, leads high machining costs with low production rate. In this scenario, hard turning is the best alternative for steel to turn at hard state (45-65) as it has several benefits over conventional turning methods in the quality aspects. It reduces the machining time about 60% of conventional hard turning time, even at a lower depth of cuts and feed rates [1]. Surface quality and production rate are generally associated with the process parameters adopted during the machining. Kopac et al. [2] state that, production of fine surfaces possible by adopting higher cutting speeds during the machining with ceramic inserts. Noordin et al. [3] revealed that the feed was the important factor for surface roughness, while hard turning of AISI 1045 steel with carbide inserts. Thamizhmanii et al. [4] confirm that the depth of cut is the important parameter and cutting speed had less influence on surface roughness. Aouici et al. [5] reported that surface roughness is mainly influenced by the feed rate and workpiece hardness during the turning of AISI H11 steel with CBN cutting inserts.

With the introduction of the wiper insert in machining, surface finish characteristics are greatly modified and it competes with the grinding in fine surface generation aspect with the additional advantage of higher productivity. Addona [6] compares the wiper inserts with conventional inserts and reports the superiority of wiper inserts over conventional inserts. Wiper insert can produce same surface finish even though they are operated at double feed rate compared with conventional inserts [7]. Optimization of cutting conditions is generally carried to obtain best responses for the machining. Taguchi method is considered as the prime option for design of experiments (DOE) and single parameter optimization, as it locate the critical parameters and predict optimal levels for each process parameter [8]. However single response optimization technique (Taguchi method) cannot be used to obtain the best combination of machining parameters for multi-responses.

This paper present wiper and conventional inserts performance during hard turning of AISI 4340 steel at different hardness levels and carries Grey Relational Analysis (GRA) to obtain the multi-responses optimization. Type of insert, hardness, cutting speed, feed, and depth of cut are considered as process parameters.

2. Experimental Details

The material selected for this experimental study was AISI 4340 steel as it is widely used in manufacturing and its allied industries. The work pieces used for this study were 30 mm diameter and 150 mm axial length. To obtain different hardness values for the set of work pieces, primarily they were subjected to heat treatment at 830°C and then they quenched at different temperatures batch wise to attain three different hardness levels viz.45, 50 and 55 [9]. All the experiments were carried out using a CNC Jobber XL lathe. Cutting inserts used for this study are Conventional ceramic insert (CC6050) and Wiper ceramic insert (CC6050WH) and fig 1 and 2 shows the microscopic images of the inserts.

The surface roughness parameters studied in this work are Arithmetic Mean Roughness (R_a), Mean Depth of Roughness (R_z), and Total Roughness (R_t). The surface roughness characteristics were measured by Mitutoyo surface tester. Material removal rate (MRR) in was calculated using 1000*Vc*f*ap mm3/min. Taguchi's L18 Orthogonal Array (OA) is chosen as the experimental design in the present research as mixed levels were presented in the selected process parameters. Table 1 presents the selected parameters low-middle-high levels in the form of L18 OA and their corresponding responses of R_a,R_z,R_t, and MRR.

Table 1. Experimental Results

S.No	I	H HRC	V_c m/min	F mm/rev	A_p mm	R_a µm	R_z µm	R_t µm	MRR mm3/min
1	CON	45	140	0.1	0.1	0.94	4.04	4.52	1.4
2	CON	45	180	0.2	0.2	1.42	6.28	6.59	7.2
3	CON	45	220	0.3	0.3	1.61	6.91	7.96	19.8
4	CON	50	140	0.1	0.2	1.01	4.65	4.84	2.8
5	CON	50	180	0.2	0.3	1.1	4.66	4.96	10.8
6	CON	50	220	0.3	0.1	1.16	5.12	5.94	6.6
7	CON	55	140	0.2	0.1	0.95	4.52	5.02	2.8
8	CON	55	180	0.3	0.2	1.19	5.01	5.28	10.8
9	CON	55	220	0.1	0.3	0.97	2.21	3.06	6.6
10	WIPER	45	140	0.3	0.3	0.73	3.56	5.63	12.6
11	WIPER	45	180	0.1	0.1	0.67	3.12	4.11	1.8
12	WIPER	45	220	0.2	0.2	0.63	2.95	4.28	8.8
13	WIPER	50	140	0.2	0.3	0.62	2.88	4.71	8.4
14	WIPER	50	180	0.3	0.1	0.52	2.39	5.25	5.4
15	WIPER	50	220	0.1	0.2	0.18	0.93	1.32	4.4
16	WIPER	55	140	0.3	0.2	0.46	2.32	3.3	8.4
17	WIPER	55	180	0.1	0.3	0.34	1.95	3.06	5.4
18	WIPER	55	220	0.2	0.1	0.47	2.05	3.39	4.4

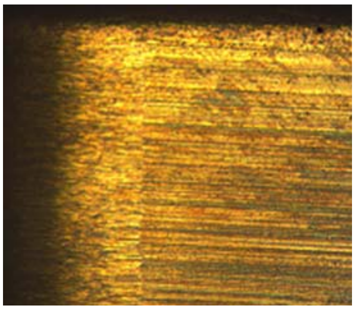

Fig 1 Conventional ceramic insert

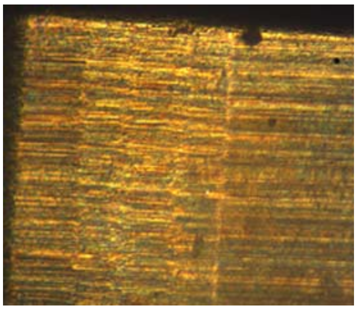

Fig 2.Wiper ceramic insert

3. Results and Discussions

ANOVA results from tables 2-4 used to establishing the significance of the process parameters on response parameters. Statistical significance of any process parameter on the response is considered only when its P-value is lower than 0.05. All this analysis is carried at 95% confidence level (α= 0.05). It is seen in Table 2 that the process parameters I, H, and F are significant sources on average R_a, as their P-value is less than 0.05. Type of insert is the most significant factor on R_a as its F-value is 109. From Fig.2, Main effects plot of data means reveals that wiper insert produces fine surface finish compared to the conventional inserts. It is also confirmed from the Table 2 and Fig 3(a), both H and F shows only moderate influence on R_a. However, cutting speed and depth of cut does not show any statistical significance on R_a as their

F-values are 0.71 and 1.16, the same is also confirmed from the Fig 6 as they produce almost horizontal lines on main effect plots of R_a.

ANOVA results for the R_z presented in Table 3 shows I, H and F are significant factors on R_z. Type of insert is the most significant factor and its F-values is 116.. Fig 3(b) shows main effects plot of data means for R_z, it is observed that wiper insert with lower feed rate produces lower R_z values. From the Table 3 and Fig 3(b), R_z is moderately influenced by H and it is lowered with increase in H. However, cutting speed and depth of cut does not show any statistical significance on R_z, however, lower R_z values are reported at higher levels of V_c and f.

Table 2 Analysis of Variance for R_a

Source	DF	Seq SS	Adj SS	Adj MS	F	P
INSERT	1	1.82405	1.82405	1.82405	109.50	0.000
H	2	0.25870	0.25870	0.12935	7.76	0.013
V_c	2	0.02363	0.02363	0.01182	0.71	0.520
F	2	0.21280	0.21280	0.10640	6.39	0.022
A_p	2	0.03880	0.03880	0.01940	1.16	0.360
Error	8	0.13327	0.13327	0.01666		
Total	17	2.49125				

Table 3 Analysis of Variance for R_z

Source	DF	Seq SS	Adj SS	Adj MS	F	P
INSERT	1	25.0868	25.0868	25.0868	41.81	0.000
H	2	6.8254	6.8254	3.4127	5.69	0.029
V_c	2	0.8784	0.8784	0.4392	0.73	0.511
F	2	6.4490	6.4490	3.2245	5.37	0.033
A_p	2	0.0931	0.0931	0.0466	0.08	0.926
Error	8	4.8005	4.8005	0.6001		
Total	17	44.1332				

ANOVA results for the R_t presented in Table 4 shows Type of insert is the most significant factor followed by feed and hardness. Fig 3(c) shows effects plot of data means for R_t, machining of higher hard workpieces with wiper insert at lower feed rate produces fine surfaces. However, cutting speed and depth of cut does not show any statistical significance on Rt.

Table 4. Analysis of Variance for R_t

Source	DF	Seq SS	Adj SS	Adj MS	F	P
INSERT	1	9.5630	9.5630	9.5630	15.57	0.004
H	2	8.4296	8.4296	4.2148	6.86	0.018
V_c	2	0.9271	0.9271	0.4635	0.75	0.501
F	2	13.2829	13.2829	6.6414	10.81	0.005
A_p	2	1.2444	1.2444	0.6222	1.01	0.405
Error	8	4.9145	4.9145	0.6143		
Total	17	38.3616				

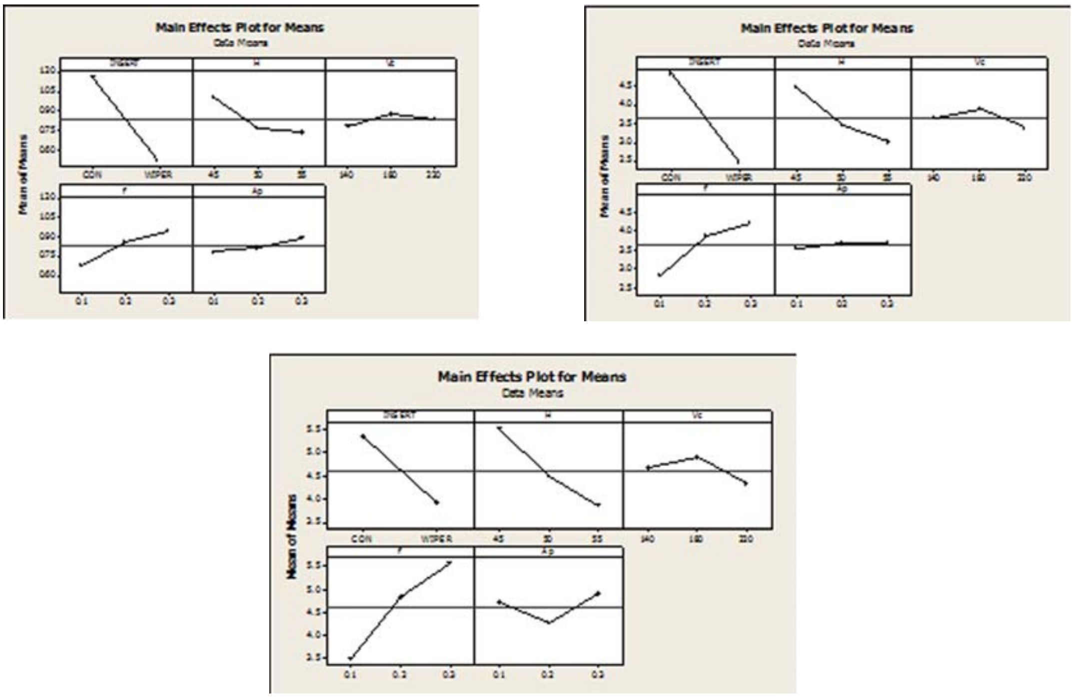

Fig. 3 Main Effects Plot of Data Means for a).R_a (b) R_z and (c) R_t

4. Multi-Response Parametric Optimization

In this study Grey relational analysis has been applied for the multi-response optimization. The following steps are followed in GRA [10].

a. Normalization of the Experimental data in the range between zero and one. Normalization of Experimental data is carried as "lower the better" for Surface Roughness by using equation (1) and 'higher is better' for MRR response using equation (2).

$$x_i^*(k) = \frac{x_{i\max}(k) - x_i(k)}{x_{i\max}(k) - x_{i\min}(k)} \quad (1)$$

$$x_i^*(k) = \frac{x_i(k) - x_{i\min}(k)}{x_{i\max}(k) - x_{i\min}(k)} \quad (2)$$

Where $X_i^*(k)$ and $X_i(k)$ are the normalised data and observed data, respectively, for i^{th} experiment using k^{th} response. The lowest and highest values of $X_i(k)$ in the k^{th} response are $X_{i\,min}(k)$ and $X_{i\,max}(k)$, respectively.

b. Calculating the Grey Relational Coefficient (ζ_i) from the normalized data. Grey Relational Coefficient (GRC) provides the relation between desirable and normalized data. Grey relational coefficient is defined as follows:

$$\zeta_i = \frac{\Delta_{\min} + \varphi\Delta_{\max}}{\Delta_i(k) + \varphi\Delta_{\max}} \quad (3)$$

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1. Where $X_o^*(k)$ represents the comparability sequence, $X_j^*(k)$ represents reference sequence, φ is the distinguishing coefficient, its range $0 \le \varphi \le 1$, Δ_i is the difference between absolute value of $X_o^*(k)$ and $X_j^*(k)$ i.e. $|X_o^*(k) - X_j^*(k)|$, Δ_{min} is least value of Δ_i and Δ_{max} is biggest value of Δ_i

c. Calculation of Grey Relational Grade (γ_i) by using the means of the weighted grey relational coefficients.

2. $$\gamma_i = \frac{1}{m}\sum_{k=1}^{n} w^* \zeta_i(k) \quad (4)$$

Where

n = the number of responses, m = the number of run and w = the weight assigned

d. Establishing the most influencing process parameters by analysis of variance (ANOVA) of grey relational grade.

e. Selection Optimal levels of process parameters.

f. Conformation tests.

Normalized values of Ra and MRR are calculated by equation 1 & 2 using the experimental results presented in Table 5. GRC's are calculated by equation 3 and GRG is determined by using GRC's of all Experimental trails using equation (4). The large value of GRG provides the optimum process parameters for high quality. Results Calculated for GRA from equation 1-4 are presented in table 6.

Table 5. Calculated Grey Relational Coefficient and Grade Values

Normalised data				GRC				
Ra	Rz	Rt	MRR	Ra	Rz	Rt	MRR	GRG
0.47	0.48	0.52	0.00	0.48	0.49	0.51	0.33	0.45
0.13	0.11	0.21	0.32	0.37	0.36	0.39	0.42	0.38
0.00	0.00	0.00	1.00	0.33	0.33	0.33	1.00	0.50
0.42	0.38	0.47	0.08	0.46	0.45	0.49	0.35	0.44
0.36	0.38	0.45	0.51	0.44	0.44	0.48	0.51	0.47
0.31	0.30	0.30	0.28	0.42	0.42	0.42	0.41	0.42
0.46	0.40	0.44	0.08	0.48	0.45	0.47	0.35	0.44
0.29	0.32	0.40	0.51	0.41	0.42	0.46	0.51	0.45
0.45	0.79	0.74	0.28	0.48	0.70	0.66	0.41	0.56
0.62	0.56	0.35	0.61	0.57	0.53	0.44	0.56	0.52
0.66	0.63	0.58	0.02	0.59	0.58	0.54	0.34	0.51
0.69	0.66	0.55	0.40	0.61	0.60	0.53	0.46	0.55
0.69	0.67	0.49	0.38	0.62	0.61	0.49	0.45	0.54
0.76	0.76	0.41	0.22	0.68	0.67	0.46	0.39	0.55
1.00	1.00	1.00	0.16	1.00	1.00	1.00	0.37	0.84
0.80	0.77	0.70	0.38	0.72	0.68	0.63	0.45	0.62
0.89	0.83	0.74	0.22	0.82	0.75	0.66	0.39	0.65
0.80	0.81	0.69	0.16	0.71	0.73	0.62	0.37	0.61

ANOVA results for the GRA presented in table 6 shows INSERT; H is the significant factors as their P-value is less than 0.05. Type of insert used for the hard turning is the most influencing parameter for this model and its F-value is 36. Fig. 4 is the main effect plot for GRG and this graph exposes that the optimal process parameters INSERT = Wiper, H=55HRC, V_c =220 m/min, f = 0.1mm/rev, A_p = 0.2mm. Fig. 4 and Table 6 indicate the influence of process parameters on the GRG for minimum surface roughness and maximum MRR.

Table 6 Analysis of Variance for GRG

Source	DF	Seq SS	Adj SS	Adj MS	F	P
INSERT	1	0.089768	0.089768	0.089768	20.50	0.002
H	2	0.013071	0.013071	0.006536	1.49	0.281
V_c	2	0.028027	0.028027	0.014014	3.20	0.095
F	2	0.023384	0.023384	0.011692	2.67	0.129
A_p	2	0.007596	0.007596	0.003798	0.87	0.456
Error	8	0.035034	0.035034	0.004379		
Total	17	0.196882				

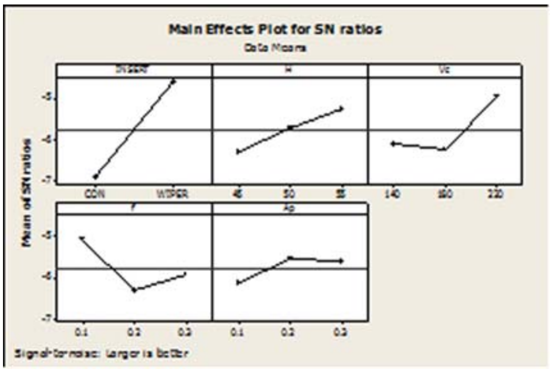

Fig. 4 Main Effects Plot of Data Means for GRG

3. Table 7. Results of the Confirmation Experiment

Machining Parameters	Initial Data	Optimum Machining Parameters	
		Predicted	Experimental
	I1 H1 Vc1 f1 Ap1	I2 H3 V_c3 f1 A_p2	I2 H3 V_c3 f1 A_p2
R_a	1.06		0.3
R_z	3.32		1.7
R_t	4.5		2.38
MRR	1.4		4.4
GRG	0.48	0.6513	0.7055
Percentage increase in GRG is 45.83%			

A. Confirmatory Experiments

4. Validation of the results, is the important step of this study, is carried by verification of results by conducting the confirmation run as the optimal process parameters identified from the GRG Main effects plot of data means. The identified optimal process parameters are used to determine the Estimated Grey Relational Grade ($\breve{\gamma}_1$) using equation 5.

5. $$\breve{\gamma}_1 = \gamma_m + \frac{1}{m}\sum_{i=1}^{q}(\bar{\gamma}_m - \gamma_m) \qquad (5)$$

6. Table 7 shows the comparison of the predicted Grey Relational Grade calculated at optimum process parameters from equation 5 and conformation experiments Grey Relational Grade. Good approximation exists between the predicted value (0.65) and experimental value (0.70). Percentage increase in GRG is 45.83% from initial data to confirmation run.

5. CONCLUSIONS

The Taguchi based Grey Relational Analysis optimization method was successfully used during the comparative assessment wiper insert and conventional insert to identify the optimal cutting parameters in the aspect of production and quality and the following specific conclusions are made from this work.

a. Type of insert is the most significant factor on all surface roughness characteristics (R_a, R_z, and R_t) and hardness and feed show moderate influence only.
b. Grey Relational Grade is increased from 0.48 to 0.7055 for initial process parameter combinations to optimal process parameter combination.
c. ANOVA results of GRG, for multi-response optimization Type of insert, is most significant controlled factor followed by Hardness.
d. From the analysis of Main effects plot of data means of GRG, use of wiper insert for higher hard workpieces (55 HRC) is recommended for the maximization of productivity with high surface quality.
e. Hard turning with wiper inserts provides lower values surface roughness which is comparable with the grinding, i.e. R_a = 0.18 µm , R_z = 0.93 µm and R_t = 1.32 µm

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