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Optimization of tool wear and surface roughness in ST-37 steel turning process with varying tool angles and machining parameters

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Abstract

The process of cutting low carbon steel (ST-37) typically utilizes High-Speed Steel (HSS) tools owing to their high hardness, affordability, and ease of shaping tool geometry. In machining, tool geometry plays a crucial role in the material cutting process and determines the quality of the final product, particularly surface roughness. The objective of this research is to achieve optimal surface roughness by varying the tool geometry and nose radius. This study employed an experimental approach using ST-37 and HSS tools. The variations in tool geometry include side rake angles of 12°, 15°, and 18°; side cutting edge angles of 85°, 80°, and 75°; and nose radii of 0 mm, 0.4 mm, and 0.8 mm. The machining parameters applied consist of a cutting depth of 1 mm and 2 mm, spindle rotation speeds of 185 rpm, 425 rpm, and 624 rpm, and a feed rate of 0.05 mm/rev, 0.075 mm/rev, and 0.1 mm/rev. Tool wear measurements were captured using a USB camera, whereas the surface roughness was assessed using a surface roughness tester. The impact of the tool geometry on the surface roughness was analyzed using the Taguchi-Grey Relational Analysis (Taguchi-GRA) and ANOVA methods. The optimal combination for ST-37 lathe machining with a sharpening tool is: A1 (cutting depth 1 mm), B1 (cutting speed 17.42 m/min), C3 (feed 0.05 mm/rev), D1 (corner radius 0 mm), E3 (side rake angle γ 18°), and F3 (side cutting edge angle γ 75°). According to the Analysis of Variance (ANOVA), three factors—cutting speed, tool tip angle, and chip angle—should be considered to achieve minimal tool wear and desirable surface roughness during machining.

Keywords:
ST-37 steel, turning process, tool geometry, machining parameter, optimization, Taguchi-GRA.

1 Introduction

Machining is a critical process in manufacturing. Manufacturing industries generally use machining processes to produce finished or semi-finished products. Machining with low-carbon steel materials is often carried out in manufacturing processes, particularly in the engine and automotive component manufacturing industries. Fabricating low-carbon steel parts frequently involves the use of High-Speed Steel (HSS) tools because of their affordability. HSS tools are readily available. These tools facilitate the shaping of the geometry relatively effortlessly compared to carbide tools, which, although formidable, are prone to breaking. HSS tools are high-alloy steels that can perform good cutting up to an operating temperature of 650°C [1]. HSS tools have high enough hardness so they can be used at high cutting speeds in machining low carbon steel materials [2].

The influence of the tool to the machining results includes the type of tool material, the geometry of the tool angle, and the position of the tool installation on the lathe. The geometric angle of the tool is typically adjusted according to the type of workpiece material and machining parameters [3], [4]. The angles contained in the tool blade are also called the tool geometry. On the tool, some angles come into direct contact with the cutting material, namely the back rake angle, side rake angle, end cutting edge angle, side cutting edge angle, and corner radius angle [5].

Research has shown that varying rotational speeds of the lathe during cutting produce different tool wear results [6], [7]. Turning with an engine speed of 330 rpm for iron and aluminum materials shows different results in tool wear; turning iron materials does not experience wear, whereas turning aluminum experiences wear of 0.01 mm. The 650 rpm engine speed for iron and aluminum materials shows the results of different tool wear differences, namely turning the iron material 0.03 mm while aluminum turning experiences wear 0.02 mm.

In a study, Mrihrenaningtyas and Prayad similarly stated that using coolant at cutting speed V = 25.01 m/min and chip angle $\gamma_o = -6°$, an average of 0.165 mm of tool edge wear (VB) was obtained [2]. In contrast, the average tool edge wear (VB) was obtained without the coolant was 0.187 mm. When cutting using a coolant at a cutting speed V = 39.30 m/min with a chip angle $\gamma_o = 10°$, an average of 0.347 mm of tool edge wear (VB) was obtained, whereas without using a coolant, an average of tool edge wear (VB) was obtained. The workpiece used in Mrihrenaningtyas and Prayad's research was carbon steel S54C. The greater the cutting chip angle, the greater the wear, and wear will occur more quickly compared to a smaller chip angle.

In addition to causing tool wear, the machining parameters and geometry also affect the quality of the machined surface. The weakness of Mrihrenaningtyas and Prayad's research is that the parameter variations need to be known to determine the wear that occurs during cutting. The variations in the above parameters are the cutting speed, machine rotation speed, and chip angle [2].

This study aims to address the limitations of previous studies that did not account for the impact of changing the machining parameters. This study aims to determine the influence of machining parameters and HSS tool geometry on HSS tool wear and surface roughness of ST-37 steel turning results. Then, we simultaneously look for optimal factors and parameter values for both dependent variables, namely, tool wear and surface roughness.

2 Materials and Methods

2.1 Materials and Equipments

Two types of materials were used in this study: work and tool materials. The working materials used for testing are ST-37 steel – work material round rod shape with dimensions ϕ 30 mm × 400 mm. The chemical composition and mechanical properties of ST-37 steel as shown in Table 1 and Table 2.

Table 1. Chemical composition of ST-37 steel [8]

C (%)	Mn (%)	P (%)	S (%)	Cu (%)
0.20	0.2-0.275	0.05	0.05	0.02

Table 2. ST-37 steel mechanical properties [9]

Young's modulus (*E*)	188 GPa
Density	7.33×106 kg/m^3
Static yield strength (σy)	187.0 MPa
Static ultimate strength (σu)	289.6 MPa

HSS tool material has 65 HRC hardness and can be used in cutting carbon steel. The tool material is in the form of a cube with dimensions of 20×20×200 mm. This material is then sharpened using a sharpening grinder with variations in cutting edge angle, side rake angle and nose radius. Nomenclature of tool is shown in Fig. 1.

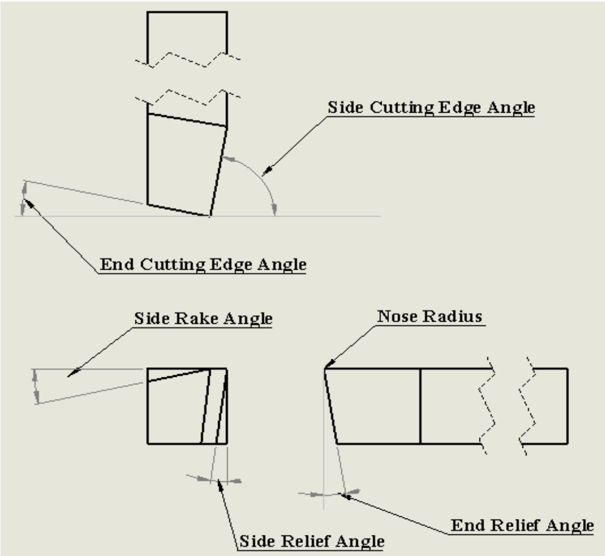

Fig. 1. Single-point cutting tool nomenclature [10].

Research on the impact of variations in machining parameters and tool geometry utilized a machine lathe conventional brand PINACHO type S-90/200. The machine has a table measuring 300 mm × 1200 mm. Spindle motor power 4 kW. Wear measurements were performed using a USB camera. Based on the tool wear, the tool life was determined for each trial. The workpiece surface roughness was measured using a Mitutoyo SJ-21 tester. The surface roughness was the roughness at the end of the experiment.

2.2 Experimental Methods and Analysis

This study employs a Taguchi experimental design involving six varied factors. Tool wear and surface roughness are influenced by the machining parameters and tool geometries. The machining parameters of the two factors have three levels: cutting speed and feed, and one factor has two levels: depth of cut. Meanwhile, there are three factors in the tool geometry: nose radius, side rake angle, and cutting-edge angle, all of which have three levels. Based on these factors and levels, an L18 mixed-orthogonal array was chosen for the experiments. Experiments were conducted at various depth of cutting (1 and 2 mm), cutting speeds (17.42, 40 and 58.87 m/min), feeding (0.05, 0.075 and 0.1 mm/rev), nose radius (0, 0.04 and 0.08 mm), side rake angle (12^o, 15^o and 18^o) and cutting edge angle (85^o, 80^o and 70^o). The experiments were conducted without replication. The parameters and levels used in this study are presented in Table 3.

Table 3. Experimental parameters and levels

Machining parameter (factor)	Level		
	1	2	3
Depth of cutting (a; mm)	1	2	
Cutting speed (Vc; m/min)	17.42	40	58.87
Feeding (f'; mm/rev)	0.05	0.075	0.1
Nose radius (r; mm)	0	0.4	0.8
Side rake angles (γ)	12^o	15^o	18^o
Side cutting edge angles (Kr)	85^o	80^o	75^o

After data were collected, they were analyzed using the Taguchi-Grey Relational Analysis (Taguchi-GRA) method. Grey relational analysis has been used to convert a multi-response optimization model into a single response grey relational grade. According to Pervez et. al [11], the Taguchi-GRA analysis steps are:

1. Determine and calculate the signal-to-noise (S/N) ratio
   The output responses are converted to signal-to-noise (S/N) ratios according to the quality objectives. The objective of this research is to prolong the tool life; hence, a larger better type is chosen (Eq. 1). The surface roughness is decreased; hence, the smaller, the better type is chosen (Eq. 2).

$$\textit{Larger the better}: -10log\frac{1}{n}\left(\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{1}$$

$$\textit{Smaller the better}: -10log\frac{1}{n}\left(\sum_{i=1}^{n}y_i^2\right) \tag{2}$$

2. Calculating the value of S/N ratio normalization
   Eq. 3 and Eq. 4 was used to calculate the normalization value:

$$\textit{Smaller the better}: x_i^*\,(k) = \frac{maxY_i^o\,(k) - Y_i^o(k)}{max\,Y_i^o(k) - \min Y_i^o\,(k)} \tag{3}$$

$$\textit{Larger the better}: x_i^*\,(k) = \frac{Y_i^o\,(k) - minY_i^o(k)}{max\,Y_i^o(k) - \min Y_i^o\,(k)} \tag{4}$$

3. Calculate delta value
   Calculates the distance $\Delta_{0i}(k\,)$ which is the absolute value of the difference between values maximum normalization $xo^*(k)$ results with data that has been normalized $xi^*(k)$ at point k (Eq. 5).

$$\Delta_{0i} = |x_0{}^*(k) - x_i{}^*(k)| \tag{5}$$

   where $\Delta_{0i}(k\,)$ is the deviation sequence of the reference sequence $xo^*(k)$ and the comparability sequence $xi^*(k)$.
4. Calculating the Grey Relational Coefficient (GRC) value
   GRC shows the relationship between the best conditions and the actual conditions of the normalized response. The Eq. 6 used to obtain the GRC value:

$$\xi_{oi} = \frac{\Delta min + \Psi\Delta maks}{\Delta\,oi(k\,) + \Psi\Delta maks} \tag{6}$$

   where Ψ is a distinguishing coefficient, $0 \leq \Psi \leq 1$.
5. Calculating Grey Relational Grade (GRG)
   The formula used is Eq. 7:

$$\gamma_i = \frac{1}{n}\sum_{i=1}^{0}\xi_i(k) \tag{7}$$

   where γ_i is the GRG for the i^{th} experiment and n is the number of performance characteristics.
6. Calculating predicted values
   Value of a combination of factors that are not in the Taguchi method run order combination can be predicted using Eq. 8 [12].

$$\gamma_{predicted} = \gamma_m + \sum_{i=1}^{q}(\gamma_i - \gamma_m) \tag{8}$$

   where γ_m is the mean GRG at the optimal level, and q is the number of process parameters that affect the responses.
7. Analysis of Variance test (ANOVA)
   ANOVA was used to investigate the influence of the process parameters on the performance characteristics. The ANOVA test was carried out using the ranking (grade) obtained previously.

3 Results and Discussion

The results of tool life and wear in this study are shown in Table 4. The highest tool life was in the 5^{th} experiment, namely 43 min, whereas the lowest surface roughness was observed in the 6^{th} experiment. These results showed that the best response was observed in a different experiment. This research aims to maximize tool life (T) and minimize surface roughness (Ra) using the Taguchi-GRA method.

Table 4. Data from measurements of tool life and workpiece surface roughness

Test	Factors						Response	
	A	B	C	D	E	F	Tool life (minute)	Surface roughness (μm)
1	1	17.42	0.05	0	12	85	31.52	2.35
2	1	17.42	0.075	0.4	15	80	22.2	2,3
3	1	17.42	0.1	0.8	18	75	31	2.12
4	1	40	0.05	0	15	80	14	3.13
5	1	40	0.075	0.4	18	75	43	2.41
6	1	40	0.1	0.8	12	85	5.8	1.59
7	1	58.8	0.05	0.4	12	75	9.75	1.62
8	1	58.8	0.075	0.8	15	85	18.55	2.31
9	1	58.8	0.1	0	18	80	13.3	3.44
10	2	17.42	0.05	0.8	18	80	22.6	1.62
11	2	17.42	0.075	0	12	75	9,11	3.33
12	2	17.42	0.1	0.4	15	85	15.5	3.23
13	2	40	0.05	0.4	18	85	20.73	1.67
14	2	40	0.75	0.8	12	80	5	2
15	2	40	0.1	0	15	75	0.92	5.32
16	2	58.8	0.05	0.8	15	75	0.8	1.16
17	2	58.8	0.075	0	18	85	1.9	3.15
18	2	58.8	0.1	0.4	12	80	1.8	2.78

3.1 Signal-to-Noise Ratio (S/N Ratio)

The collected response data were used as the S/N ratio. The S/N ratio is a transformation value from several repetitions of the data to represent the quality of the presentation. In this case, the response variables were tool life and surface roughness. For tool life, the larger is the better characteristic used, while for roughness, the smaller is a better characteristic. The results of the S/N ratio calculations are listed in Table 5.

Table 5. S/N ratio calculation results for tool life and surface roughness

S/N tool life	S/N roughness (Ra)	S/N tool life	S/N roughness (Ra)
29.972	-7.421	27.082	-4.190
26.927	-7.235	19.190	-10.449
29.827	-6.527	23.807	-10.184
22.923	-9.911	26.332	-4.454
32.669	-7.640	13.979	-6.021
15.269	-4.028	-0.724	-14.518
19.780	-4.190	-1.938	-1.289
25.367	-7.272	5.575	-9.966
22.477	-10.731	5.105	-8.881

3.2 GRG Computing

After calculating the S/N ratio, it was normalized using Eq. 3 and Eq. 4. The results of the normalization of the S/N ratio are shown in Table 6. The results of this normalization are then processed again into deviance sequence and Grey Relational Coefficient (GRC). The deviance sequence and Grey Relational Coefficient (GRC) calculation results can be seen in Tables 7 and 8. Then, the GRC values for tool life and surface roughness for each experiment were added and divided by two to obtain the Grey Relational Grade (GRG) values, as listed in Table 9.

Table 6. Normalized values of S/N ratio for tool life and surface roughness

Tool life	Roughness (Ra)	Tool life	Roughness (Ra)
0.922	0.464	0.839	0.219
0.834	0.449	0.611	0.692
0.918	0.396	0.744	0.672
0.718	0.652	0.817	0.239
1.000	0.480	0.460	0.358
0.497	0.207	0.035	1.000
0.628	0.219	0.000	0.000
0.789	0.452	0.217	0.656
0.705	0.714	0.204	0.574

Table 7. Delta values

Tool life	Roughness (Ra)	Tool life	Roughness (Ra)
0.078	0.536	0.161	0.781
0.166	0.551	0.389	0.308
0.082	0.604	0.256	0.328
0.282	0.348	0.183	0.761
0.000	0.520	0.540	0.642
0.503	0.793	0.965	0.000
0.372	0.781	1.000	1.000
0.211	0.548	0.783	0.344
0.295	0.286	0.796	0.426

Table 8. Gamma value (grey relational coefficient)

Tool life	Ra	Tool life	Ra
0.865	0.482	0.756	0.390
0.751	0.476	0.562	0.619
0.859	0.453	0.661	0.604
0.640	0.500	0.732	0.397
1.000	0.490	0.481	0.438
0.499	0.387	0.341	1.000
0.573	0.390	0.333	0.333
0.703	0.477	0.390	0.592
0.629	0.636	0.386	0.540

Table 9. Grey Relational Grade (GRG) and their order

No. test	GRG	Order	No. test	GRG	Order
1	0.674	2	10	0.573	9
2	0.613	7	11	0.591	8
3	0.656	4	12	0.633	6
4	0.570	10	13	0.564	12
5	0.745	1	14	0.459	16
6	0.443	17	15	0.671	3
7	0.482	14	16	0.333	18
8	0.590	11	17	0.491	13
9	0.633	5	18	0.463	15

Table 10 shows the average GRG value table for each factor and level. The greater the level of the grey relational grade, the closer the corresponding cutting parameters are to the optimal. Thus, multiresponse optimization can be converted into a grey relational grade optimization single. Therefore, the level that yielded the largest average response was selected. This is in accordance with Tosun's research, which suggests that a greater degree of relational gray value corresponds to better performance (Tosun, 2006). From the response table for grey relational grade shown in Table 10, the best combination of ST37 lathe machining with a sharpening tool is A1 (cutting depth 1 mm), B1 (cutting speed 17.42 m/min), C3 (feed 0.05 mm/rev), D1 (corner radius 0 mm), E3 (side rake angle (γ) 18^o) and F3 (side rake angle (γ) 75^o). Fig. 2 shows a Grey Relational Grade (GRG) graph, where the dotted line in the image is the total average value of grey relational.

Table 10. Table of average Grey Relational Grade (GRG) values

Parameter	Symbol	Grey Relational Grade (GRG) Level 1	2	3	Max-Min	Rating
Cutting depth	A	0.601	0.531	-	0.070	3
Cutting speed	B	0.623	0.575	0.499	0.125	1
Feeding	C	0.533	0.582	0.583	0.050	5
Nose radius (R)	D	0.523	0.506	0.454	0.069	4
Side rake angles (γ)	E	0.518	0.568	0.610	0.092	2
Side cutting edge angles (Kr)	F	0.566	0.552	0.587	0.035	6

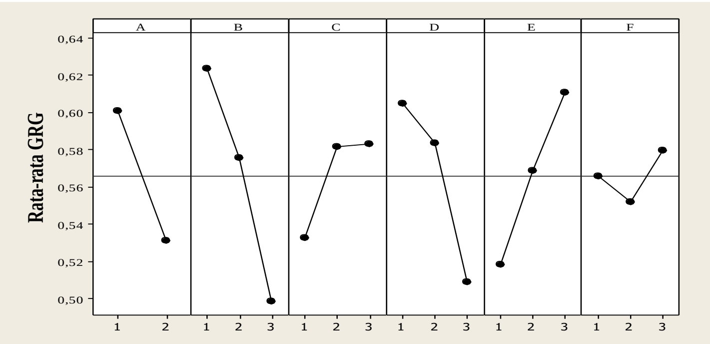

Fig. 2. Grey relational grade graph.

3.3 Determination of Optimal Parameters using ANOVA

The GRG calculated for each trial was used as the response for further analysis. Greater quality characteristics were used for analysis, as they indicate better process performance. The GRG that was obtained was analyzed using ANOVA. ANOVA was used to identify which cutting parameters significantly influenced performance characteristics. The results of the GRG ANOVA (Table 11) show that none of the machining factors simultaneously influences (P ∗0.05) on wear and surface roughness. This is because of the high error, which reduces the accuracy of the experiment. Because none of them had an effect, another indicator was used, namely percent contribution. Percent contribution is obtained by dividing the sum of squares for each factor by the total sum of squares. From the calculation of the percent contribution, there are several factors whose percent contribution is quite large, namely cutting speed, nose radius, rake angle of more than 14%. It can be stated that these three factors have more influence on wear and surface roughness than depth of cut, feed and cutting-edge angle.

Table 11. Results of GRG variety analysis

Factor	Degree of freedom	Sum of squares	Square mean	F test	P (∗0.05)	Cntrb (%)
Depth	1	0.021873	0.021873	3.11	0.128	12.2
Speed	2	0.047424	0.023712	3.37	0.104	26.5
Feeding	2	0.009828	0.004914	0.70	0.533	5.5
Nose	2	0.030253	0.015127	2.15	0.197	16.9
Rake	2	0.025391	0.012696	1.81	0.243	14.2
Side	2	0.002307	0.001154	0.16	0.852	1.3
Error	6	0.042172	0.007029			23.4
Total	17	0.179247				100

4 Conclusion

1. Based on GRG analysis, the parameters that influence the optimization of wear and surface roughness were sequentially as follows: cutting speed > chip angle > cutting depth > tool tip radius > feed speed > cutting angle.
2. The best combination of ST37 lathe machining with a sharpening tool was A1 (cutting depth 1 mm), B1 (cutting speed 17.42 m/min), C3 (feed 0.05 mm/rev), D1 (corner radius 0 mm), E3 (side rake angle (γ) 18^o) and F3 (side rake angle (γ) 75^o).
3. From the Analysis of Variance (ANOVA), three factors must be considered to produce machining with good tool wear and surface roughness: cutting speed, tool tip angle, and chip angle.

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