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Surface Roughness Optimisation in Turning Using Taguchi Approach

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Abstract: *Surface roughness is one of the key machining variables adopted to classify the aesthetics of finished products. This variable is characterised by the combination of cutting parameters and machine tool dynamics. However, different workpiece materials require pre-determined cutting parameters to achieve the desired surface finish. This has to be determined for each of the materials. Hence, this work aimed to determine the optimum cutting parameter combinations for AISI 1018 and AISI 314 steels using the Taguchi Design of Experiment to achieve best surface finish and high material removal rate (MRR). The turning tests were conducted on the Centre Lathe with triangular carbide cutting tool inserts under flood cutting environment. The turning parameters were varied with a cutting speed of 110-160 m/min, feed of 0.05-0.10 mm/rev, and depth of cut of 0.5-1.0 mm for both the selected workpiece materials. After machining, surface roughness of the machined surfaces was measured. Results show that lower surface roughness values of the selected workpiece materials were obtained by combining cutting speed of 160 m/min (higher cutting speed), feed of 0.05 mm/rev (lower feed), and depth of cut of 0.5 mm (lower depth of cut). Also, feed is the dominant cutting parameter that influences surface roughness, followed by depth of cut and cutting speed. In addition, the combination of a higher cutting speed of 110 m/min, higher feed of 0.10 mm/rev, and a higher depth of cut of 1.0 mm yielded a higher material removal rate value when turning AISI 1018 and AISI 314 steels respectively. It is proposed that these cutting parameter combinations should be adopted when turning AISI 1018 and AISI 314 steels respectively. This could also minimise machining time which in turn could reduce the total manufacturing cost. Consequently, these cutting parameter combinations are recommended for machine tool operators for better surface finish and machine utilisation.*

Keywords: *Cutting parameters, MRR, surface roughness, optimisation, Taguchi method*

1. INTRODUCTION

Mechanical machining is one of the commonly used technologies in the manufacturing sector due to its flexibility and precision in the fabrication of consumer products [1, 2]. It is defined as a process in which a wedge-shaped tool removes a thin layer of metal in form of chips or swarfs from a workpiece [3]. The purpose of mechanical machining is to manufacture products with high material removal rates and low surface roughness. However, metal cutting industries are faced with challenges such as the manufacture of products with high quality in terms of workpiece dimensional accuracy, surface finish, aesthetics, increased production rates, lower tool wear, economy of machining in terms of cost, time saving, and with minimum environmental impact [4, 5]. Consequently, these challenges could be overcome by optimising the cutting parameters during machining.

Turning is one of the important types of mechanical machining processes. It is the removal of material from the outer diameter, and sometimes inner diameter (as in the case of boring) of a rotating cylindrical workpiece. It is used to produce cylindrical workpieces [6]. Turning processes could be undertaken manually on the engine lathe or automatically on the computer numerical control (CNC) lathe. The most important parameters in turning processes are referred to as cutting parameters. Thus, the increase in production rate, improved product quality, minimal machining cost, low power demand, and increased tool life are guaranteed through the proper selection of cutting parameters during machining [7, 8]. The material removal rate (MRR) of a turning process is the volume of material removed per unit time. It can be evaluated as shown in equation 1.

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$$MRR = \pi D_{avg} d f N \quad (mm^3/min) \quad (1)$$

where $D_{avg} = \frac{(D_0 - D_f)}{2}$ in mm, D_0 is the initial diameter in mm, D_f is the final diameter in mm, f is the feed in mm/rev, d is the depth of cut in mm, N is spindle rotation speed in rev/min.

The functional efficiency of machined parts could be determined by the integrity of the machined surface such as surface roughness; defects on the surface (such as micro cracks); and the condition of the subsurface (plastic flow orientation of the grains). Surface roughness is a measured specification for machined or ground surfaces. It is referred to as the finely spaced surface irregularities that might be generated by the action of cutting tool on the machined surface. Surface finish describes the geometric features of the machined surfaces, while surface integrity pertains to properties such as fatigue life and corrosion resistance [6]. The type of surface finish and surface integrity obtained after the material removal process significantly influences the aesthetics and quality of machined part surfaces, as well as the production cost [9]. Several factors may affect the surface finish of a machined part in turning. These may include the cutting parameters (cutting speed, feed, depth of cut); workpiece (workpiece design, workpiece quality and structure, workpiece setup); cutting tool (tool wear, tool geometry, stability); and the machinery (machine tool rigidity, fixture design, power, cutting environment) [10]. In addition to surface finish quality, the material removal rate (MRR) is also an important characteristic in turning operation and higher material removal rate (MRR) is always desirable. Hence, there is need to optimize the process parameters in a systematic way to achieve the output characteristic/responses by using Taguchi method. The Taguchi method is an experimental methodology that could be adopted to discover the required minimum number of experiments to be performed within the permissible limit of factors and levels. This method uses a special set of orthogonal arrays, which is based on selecting the level combination of the input design variables for each experiment. Consequently, manufacturing costs could be minimised through the reduction of machining cost and production time when this approach is utilise.

In view of this, few researchers undertook studies to investigate the influence of cutting parameters on surface roughness and material removal rate when turning various workpiece materials. For example, Doddapattar and Batakurki [11] performed the turning of Al-7050 workpiece on a CNC lathe with carbide tool of various nose radii. This was necessary in order to correlate the economics of machining to the technological factors using the Taguchi method. The study showed that lower depth of cut of 0.02 mm resulted in increased surface roughness. Also, higher spindle speed value of 2000 rev/min resulted in increased surface roughness. In addition, medium feed of 1.0 mm/rev led to lower surface roughness values. The material removal rate increased at higher spindle speed of 2000 rev/min, while higher feeds of 2.0 mm/rev resulted in higher MRR, and increased depth of cut of 0.08 mm resulted in higher MRR. As the spindle speed increased, machining time improved by 4.54 times and was also reduced. Also, as the feed increased, the machining time decreased and was improved by 4.34 times. However, the increase in depth of cut had no influence on the machining time. Suresh and Basavarajappa [12] utilised the response surface method to determine the effect of machining parameters on surface roughness and tool wear. Also, mathematical models which showed how these factors relate were also developed. The study showed that increase in feedrate resulted in higher surface roughness values, followed by depth of cut and cutting speed. Bagaber and Yusoff [7] studied the influence of cutting parameters such as cutting speed, feedrate, and depth of cut on surface roughness, and machining time of coated carbide tool in dry turning of stainless steel 316. It was shown that feedrate had dominant influence, followed by depth of cut, while cutting speed had slight influence on surface roughness.

Deshpande and Pant [13] utilised the Taguchi method to optimise machining parameters such as spindle speed, feed and depth of cut when machining EN 8 alloy steel under dry cutting environment with coated (PVD coated TiAlN insert) and uncoated inserts (with a geometry of WNMG 12 04 08) on a CNC lathe. The result shows that spindle speed and depth of cut were the prominent factors affecting surface roughness when machining with coated inserts. Also, the depth of cut, spindle speed and feed were the prominent factors affecting the surface roughness when machining the selected workpiece materials with uncoated inserts. Nur et al. [14] undertook cutting tests to optimise cutting parameters in order to achieve higher material removal rate when turning Al-11% Si base alloy with a PVD coated carbide tool on a two-axis CNC lathe in dry cutting environment. It was reported that increased material removal rate was obtained when the cutting speed and feedrate increased. Mandal et al. [15] studied the effect of spindle speed, feedrate, and depth of cut on the surface roughness and power demand during CNC turning of aluminium with coated carbide in dry cutting using the response surface method. Results show that power demand increases as both the depth of cut and feedrate increase. Singh et al. [16] used the Taguchi method to optimised cutting conditions for achieving lower surface roughness during the CNC turning of AISI 316 austenitic stainless steel with carbide inserts coated with titanium nitride coating (TiN) under dry cutting. Results show that surface roughness was highly influenced by feed, while depth of cut had minimal effect on surface roughness. Additionally, speed had least influence on surface roughness. Salgar et al. [4] achieved minimum surface roughness and higher material removal rate using the Taguchi method to optimise cutting parameters such as cutting speed, depth of cut, and feedrate in the turning of AISI 1018 steel.

Recently, Dhanalakshmi and Rameshbabu [17] utilised the Taguchi method to optimise cutting parameters such as cutting speed, depth of cut, and feedrate in CNC turning of LM 25 aluminium alloy to achieve high material removal rate, low surface roughness values, and reduced machining cost. It was found that feed had more effect on the MRR when compared to cutting speed and depth of cut. It is important to note that increase in feed, depth of cut and cutting speed resulted in high MRR. Additionally, higher cutting speed led to lower surface roughness, while higher feed resulted in high surface roughness. The study also showed that as the cutting speed, depth of cut, and feed increase, the machining cost is reduced with regards to high MRR.

From the reviewed literature, it is clear that few researchers undertook studies to determine the influence of cutting parameters on surface roughness of the machined parts and material removal rate. In addition, cutting parameters were also optimised to obtain improved surface finish of the turned parts and high material removal rates. However, the reviewed authors' works did not investigate the influence of cutting parameters on surface roughness and material removal rate, as well as optimisation of cutting parameters for achieving improved surface finish and high MRR when turning two major applicable steel workpiece materials. Consequently, this gap would be addressed in this study.

1.1 Aim and objectives

This study is aimed at optimising cutting parameters based on the Taguchi method in order to achieve minimum surface roughness values and high material removal rates. This would involve the turning of two different cylindrical workpiece materials of mild steel and stainless steel on a centre lathe with triangular carbide inserts under flood cutting environment. After the turning process has been completed, surface roughness of the selected workpiece materials was measured. Thus, this study will elucidate further on the dominant cutting parameter affecting surface roughness, and also provide recommendations for achieving low manufacturing cost and high productivity with regards to minimum surface roughness values and high material removal rate.

2. EXPERIMENTAL METHODS

2.1 Experimental Setup and Procedures

Turning tests were conducted on the centre lathe D250 × 500G in order to determine the influence of process parameters such as cutting speed, feed, and depth of cut on surface roughness and material removal rate. This machine tool has spindle speeds within the range of 125 to 2000 rev/min, power range of 750W, maximum turning diameter 250 mm and longitudinal feed in the range of 0.07 to 0.2 mm/rev.

Two workpiece materials namely AISI 1018 steel (mild steel) and AISI 314 (stainless steel) were considered for the study. This was necessary in order to assess the effect of cutting parameters on surface roughness of two major applicable steel workpiece materials for adequate comparison and standardisation. Mild steel was considered because they are easy to machine, weld, and are also cheap to produce. They are used to manufacture automobile body components, structural shapes (I-beams), and sheets that are used in pipelines, buildings, bridges, and tin cans. Stainless steel was also considered because they are highly resistant to corrosion due to the presence of chromium (Cr) as the main alloying element. They are used in the manufacturing of bars, sheets, wires, turbine blades, shafts, ball bearings, high temperature steam boilers, heat treating furnaces, aircraft missiles, and nuclear power generating units. The parameters for both workpieces are presented in Table 1.

Table 1: Workpiece parameters

Workpiece material	AISI 1018 (mild steel)	AISI 314 (Stainless steel)
Length of workpiece (mm)	80	80
Machining length (mm)	40	40
Workpiece diameter (mm)	30	30
Chemical composition of the workpiece	0.18%C, 0.27%Si, 0.05%S max, 0.80%Mn, 0.05%P max	0.25%C, 2%Si, 22%Ni, 2%Mn, 26% Cr, 0.045%P, 0.03%S
Workpiece hardness (HV)	233.3	212
Workpiece mass (g)	650	650

The as received round bars of AISI 1018 steel and AISI 314 steel with dimensions of 1000 mm in length and 30 mm diameter were adopted for the turning tests. The selected workpiece materials were cut into twelve equal sizes each at 80 mm in length with machining length of 40 mm, and the workpiece was then clamped on a three jaw chuck with overhang of 40 mm. The experimental setup is shown in Figure 1.

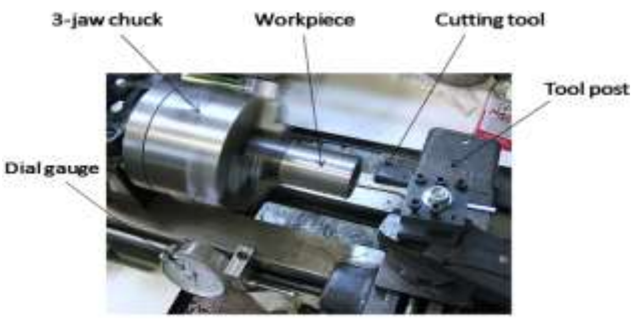

Figure 1: Experimental setup

For each of the workpiece material, a triangular carbide insert with nose radius of 0.60 mm was mounted on an insert holder, which has a short steel bar and a shank for the turning process. Three new inserts were used for each combination of the cutting parameters as obtained from the Taguchi design of experiment, which means that a total of 12 new inserts were used for turning each of the selected workpiece material. Figure 2 shows the triangular inserts and insert holder used in this study.

Figure 2: Triangular carbide inserts and insert holder

The initial and final diameters of the workpieces were measured using the Digital Vernier Calliper. The surface roughness of each of the turned workpiece materials were measured using the Mitutoyo SJ-210 portable surface roughness checker. This was achieved by the direct contact of the stylus' tip (i.e. the measuring probe attached to the device) with the surface of the machined samples. The experiment was undertaken based on a two-level orthogonal array using the Taguchi design of experiment which is embedded in Minitab 16 software.

2.2 Taguchi Design of Experiment

In order to understand the dominant cutting parameter that could result in lower surface roughness and higher material removal rate, three cutting parameters were selected namely cutting speed, feed, and depth of cut. An L4 Taguchi orthogonal array Design of Experiments (DOE) was used.

The cutting parameters were selected based on the recommended cutting speeds, feeds and depth of cuts for each of the considered workpiece material from machining hand books in Kalpakjian and Schmid [6], as well as the speed ranges from machine tool data. Consequently, each cutting parameter was assigned to either high or low level parameter depending on its numerical value, and the chosen levels are presented in Table 2.

Table 2: Cutting parameters and their levels for AISI 1018 steel and AISI 314 steel

Cutting parameters	Level 1	Level 2
Cutting speed (m/min)	110	160
Feed (mm/rev)	0.05	0.10
Depth of cut (mm)	0.5	1.0

After inserting the number of factors together with their corresponding levels, the experimental plan obtained from Minitab 16 software shown in Table 3 is then used for the turning process to enable adequate comparison between the two selected materials. The cutting process was undertaken under flood cutting environment to reduce the excessive heat and friction between the cutting edge and the workpiece.

Table 3: Taguchi L4 orthogonal array of DOE

Experimental number	Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)
1	110	0.05	0.5
2	110	0.10	1.0
3	160	0.05	1.0
4	160	0.10	0.5

3. RESULTS AND DISCUSSIONS

The material removal rate for turning AISI 1018 steel alloy and AISI 314 steel alloy was evaluated using Equation 1 and is presented in Table 4, while the result for surface roughness values when turning the aforementioned workpiece materials are presented in Tables 5 and 6 respectively.

Table 4: Material removal rate for turning AISI 1018 steel and AISI 314 steel alloy

S/N	Cutting parameters			Material removal rate
	Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	(mm^3/min)
1	110	0.05	0.5	2734.13
2	110	0.10	1.0	10844.62
3	160	0.05	1.0	7878.57
4	160	0.10	0.5	7945.33

The material removal rate for each of the selected workpiece material was evaluated based on the combination of the cutting parameters in Tables 4. It is observed that the combination of the cutting speed of 110 m/min, feed of 0.10 mm/rev, depth of cut of 1.0 mm yielded higher material removal rate value of 10844.62 mm^3/min when turning mild steel and stainless steel respectively. Thus, machining at these cutting parameters would result in minimal machining time which in turn reduces the manufacturing cost.

Table 5: Result for surface roughness and material removal rate when turning AISI 1018 steel alloy

S/N	Cutting parameters			Surface roughness			Average surface roughness (μm)
	Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Run 1	Run 2	Run 3	
1	110	0.05	0.5	2.100	1.990	2.060	2.050
2	110	0.10	1.0	1.950	1.750	1.700	1.800
3	160	0.05	1.0	2.050	2.000	1.950	2.000
4	160	0.10	0.5	1.970	1.990	2.010	1.990

Table 6: Result for surface roughness and material removal rate when turning AISI 314 steel alloy

S/N	Cutting parameters			Surface roughness			Average surface roughness (μm)
	Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Run 1	Run 2	Run 3	
1	110	0.05	0.5	1.750	1.720	1.780	1.750
2	110	0.10	1.0	0.750	0.650	0.700	0.700
3	160	0.05	1.0	1.680	1.665	1.672	1.672
4	160	0.10	0.5	1.640	1.670	1.671	1.660

The main effect plots which show the parameters that affect surface roughness when turning mild steel and stainless steel under flood cutting environment are presented in Figures 3 and 4 respectively.

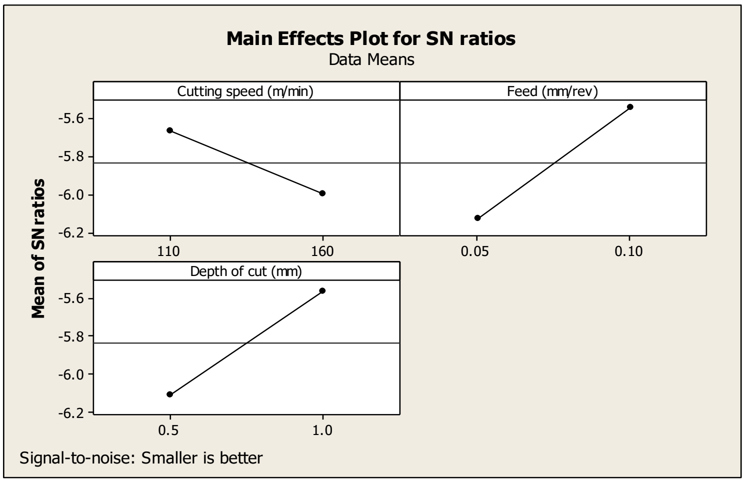

Figure 3: Cutting parameters affecting surface roughness when turning mild steel

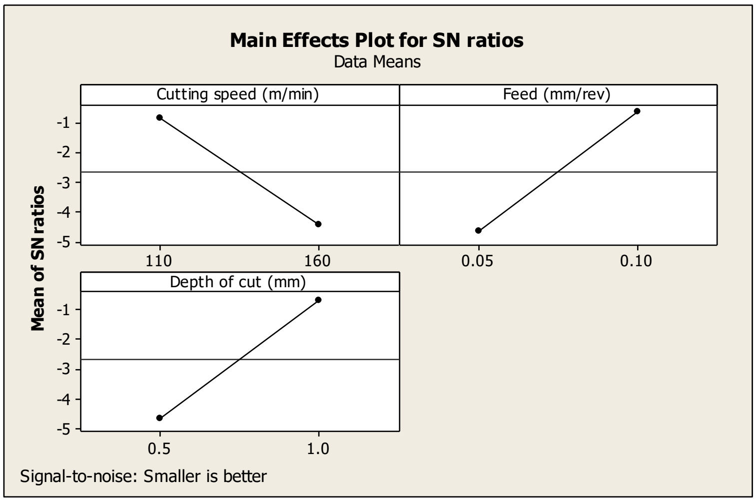

Figure 4: Cutting parameters affecting surface roughness when turning stainless steel

Based on the smaller-is-better objective, the lowest point on the signal to noise ratio curve indicates the set of cutting conditions which lead to lower surface roughness values. As shown in Figures 3 and 4, surface roughness could be reduced by selecting a higher cutting speed of 160 m/min, a lower feed of 0.05 mm/rev, and a lower depth of cut of 0.5 mm. These cutting parameter combinations are recommended for machine tool operators for better surface finish of the machined parts.

It is also indicated in Figures 3 and 4 that the variable with the largest signal-to-noise ratio gradient is the dominant parameter, which in this study is the feed, followed by the depth of cut, and cutting speed. This is evident in Tables 7 and 8 which show the responses of the cutting tests for AISI 1018 and AISI 314 alloy respectively generated automatically from the Minitab 16 software.

Table 7: Response table for signal to noise ratios when turning AISI 1018 steel alloy

Level	Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)
1	-5.670	-6.128	-6.106
2	-5.999	-5.541	-5.563
Delta	0.329	0.587	0.543
Rank	3	1	2

Table 8: Response table for signal to noise ratios when turning AISI 314 steel alloy

Level	Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)
1	-0.8814	-4.6627	-4.6315
2	-4.4334	-0.6521	-0.6833
Delta	3.5521	4.0107	3.9481
Rank	3	1	2

From Tables 7 and 8 for AISI 1018 and AISI 314 alloy respectively, feed was ranked 1 and hence observed to be the dominant parameter affecting surface roughness of the machined workpiece surfaces. This could be due to the fact that when feeds increase, the amount of heat generated and the friction at the tool-chip cutting interface wears the tool rapidly, resulting in poor machined surfaces. The depth of cut is ranked 2 hence its effect on surface roughness of the machined surfaces could be due to the fact that as the depth of cut increases, tool vibrations tend to increase (impact of the rigidity and workpiece holding fixture of the machine tool) thereby resulting in poor surface finish. Also, cutting speed ranked 3 influenced the surface roughness minimally due to less vibration and lower cutting forces generated during machining.

4. CONCLUSION

This study was aimed at optimising cutting parameters using Taguchi method to achieve minimum surface roughness values and high material removal rates when turning AISI 1018 steel and AISI 314 stainless steel alloy. The following conclusions were inferred from this study:

- The dominant parameter affecting surface roughness when turning AISI 1018 steel and AISI 314 stainless steel alloy workpiece surfaces was the feed. As the feed increases, the amount of heat generated and the friction at the tool-chip interface wears the tool rapidly, resulted in poor machined surfaces.
- The depth of cut affects surface roughness of the machined surfaces due to the fact that as the depth of cut increases, tool vibrations increase thereby resulting in poor surface finish. Also, cutting speed influenced the surface roughness minimally due to less vibration and lower cutting forces generated during machining.
- Cutting speed of 110 m/min, feed of 0.10 mm/rev, and depth of cut of 1.0 mm yielded a higher material removal rate value of 10844.62 mm^3/min when turning AISI 1018 steel and AISI 314 stainless steel alloy respectively. Thus, machining at these cutting parameters would result in minimal machining time which in turn could reduce the total manufacturing cost.
- It is proposed that the surface roughness when turning AISI 1018 steel and AISI 314 stainless steel alloy respectively could be reduced by selecting cutting speed of 160 m/min, feed of 0.05 mm/rev, and a depth of cut of 0.5 mm.
- These optimized cutting parameter combinations are therefore recommended for machine tool operators when turning AISI 1018 steel and AISI 314 stainless steel alloy.

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