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Parametric design optimization of hard turning of AISI 4340 steel (69 HRC)

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Abstract:

Continuous research endeavors on hard turning (HT), both on machine tools and cutting tools, have made the previously reported daunting limits easily attainable in the modern scenario. This presents an opportunity for a systematic investigation on finding the current attainable limits of hard turning using a CNC turret lathe. Accordingly, this study aims to contribute to the existing literature by providing the latest experimental results of hard turning of AISI 4340 steel (69 HRC) using a CBN cutting tool. An orthogonal array was developed using a set of judiciously chosen cutting parameters. Subsequently, the longitudinal turning trials were carried out in accordance with a well-designed full factorial-based Taguchi matrix. The speculation indeed proved correct as a mirror finished optical quality machined surface (an average surface roughness value of 45 nm) was achieved by the conventional cutting method. Furthermore, Signal-to-noise (S/N) ratio analysis, Analysis of variance (ANOVA), and Multiple regression analysis were carried out on the experimental datasets to assert the dominance of each machining variable in dictating the machined surface roughness and to optimize the machining parameters. One of the key findings was that when feed rate during hard turning approaches very low (about 0.02mm/rev), it could alone be most significant (99.16%) parameter in influencing the machined surface roughness (Ra). This has, however also been shown that low feed rate results in high tool wear, so the selection of machining parameters for carrying out hard turning must be governed by a trade-off between the cost and quality considerations.

Keywords: Hard turning; Taguchi method; precision finishing; tool wear; CBN tool.

Abbreviations:

<i>AISI</i>	<i>American Iron and Steel Institute</i>
<i>ANOVA</i>	<i>Analysis of variance</i>
<i>HT</i>	<i>Hard turning</i>
<i>HRC</i>	<i>Hardness on Rockwell 'C' Scale</i>
<i>CBN</i>	<i>Cubic boron nitride</i>
<i>CNC</i>	<i>Computer numerically controlled lathe</i>
<i>DOE</i>	<i>Design of experiments</i>

Nomenclatures:

α	Constant (intercept)
ε_i	Normally distributed error
f	Feed rate
a_p	depth of cut
β	Expected increment in the response
N_{rpm}	Spindle speed in revolutions per minute (RPM)
v_c	Linear cutting speed in m/min
r	Tool nose radius
S/N	Signal to noise ratio as defined by Taguchi
R_a	Average value of machined surface roughness
Ra_i	per unit change in surface roughness for i^{th} experiment

1. Introduction

AISI 4340 (medium carbon (0.4%C) having 1.8% nickel - chromium – molybdenum) is a high strength martensitic steel. It is generally supplied hardened and tempered in the tensile range of 0.9 to 1 GPa but a further improvement in the mechanical properties beyond pre-hardening and

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tempering is possible through surface hardening by flame or induction hardening and by nitriding. It is used for manufacturing critical components for aerospace engineering, automotive transmissions (e.g. manufacturing of bearings, gears, heavy duty shafts, axles, spindles, couplings, Pins and cams etc which require tighter geometric tolerances, longer service life and good surface finish) and metal forming moulds where severe dynamic load imposes strict conditions on surface quality. The ever increasing demand for improved surface quality and tighter geometric tolerances on such products has resulted in great deal of manufacturing research in this area. One key outcome is the refinement of a machining method known as hard turning (HT) which employs a single point cutting tool to machine hard ferrous alloys that exhibit hardness values over 45 HRC.

Figure 1: Comparison of conventional processing and hard turning method.

The traditional way of processing hard steel involves an established sequence of operations i.e. forming, annealing, rough cutting, heat treatment and grinding, all of which consumes significant amounts of time and cost [1-2]. This is compared in Figure 1 with HT where the latter eliminates the requirement for annealing and grinding. Grinding operation, as is well known, requires a rough turning cut and heat treatment as a *priori* for its execution, making it somewhat a time-consuming and labor-intensive process. The practice of hard turning (HT) gained significant momentum in the 1970s [3], primarily due to the discovery and commercialization of a newer cutting tool material, now popularly known as Cubic Boron Nitride (CBN), that propelled the hard turning technology onto shop floors as a substitute to grinding [4]. Thus, it has become an alternative way to machine hardened steel into a final finishing stage in just one single machining step, without requiring pre or post machining treatment on the machined component and is now also being explored to produce

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surface textures [5]. Thus, primarily on account of lower equipment cost, setup time, and the reduced number of process steps, hard turning has emerged as a key technology as a substitute to the conventional grinding processes. This is, however, being impeded by a number of challenges that must be resolved to make the hard turning process a complete replacement for the grinding process. Amongst others, surface integrity and the quality of the finished machined surface are some of the pronounced issues in hard turning, because rapid variations in the high deviatoric strains and/or temperature due to the movement of the cutting tool result in the generation of an amorphous layer of material, the details of which are not fully known. Consequently, surface residual stresses, the appearance of a white layer resulting in surface deterioration and attainable surface roughness have given only partial success to the commercialization of HT. Therefore, several attempts were made by the researchers in the past to study the possibilities of solving some of these aspects by different approaches, such as [6-9]:

- 1- optimization of the cutting parameters
- 2- inclusions of the microstructures in the cutting tool
- 3- changing the geometry of the cutting tool, and
- 4- changing the mechanism of cutting

These developments are running in parallel with the technological developments in the cutting tool and machine tool technology and, hence, the attainable machinable limits are being constantly pushed forward. Therefore, in this experimental study, the primary aim was actually to examine the current attainable limit of hard turning on a CNC turret lathe, and enroute to that objective, a number of soft computing methods were applied to the experimental datasets to optimize the cutting parameters for AISI 4340 steel, which was hardened up to 69 HRC. In the first instance, the quality of the machining or the component is normally judged by a tangible examination of surface roughness, but the surface roughness also dictates the functionality and service life of a component under hostile environments and, hence, is important. One of the foremost benchmarks set for hard turning was to attain a machined surface finish of $0.1\mu\text{m Ra}$, which was attainable only from

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2. Literature Review

2.1. Brief Description of Taguchi method

The Design of Experiment (DOE) using Taguchi's approach can be used to evaluate the effect of control parameters for parameter optimization. Taguchi's approach allows the study of the whole parameter space with a limited number of experiments, as long as they are carried out in a planned orthogonal array [10]. In addition, since only a limited number of experiments are needed, the methodology helps reduce the variability of the response variable, and is therefore an important tool for improving the productivity of the experiments. Taguchi's approach to the design of experiments involves the following steps [11]:

1. Select the response variable to be optimized
2. Identify the input variables that affect the response
3. Choose the levels of these factors
4. Select the appropriate orthogonal array
5. Conduct experiments (randomize the experiments so that there is no systematic bias)
6. Analyze the results by signal-to-noise (S/N) ratio or by using analysis of variance (ANOVA)
7. Determine the optimal process parameters

The sequence of experiments with the combination of parameters and levels is determined by an orthogonal array that determines the number of trials to be performed, ensuring that all levels of all factors are tested in an equal measure. The appropriate array is selected according to the number of factors and levels. For example, consider the problem of optimizing the surface roughness for a

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given feed (f), depth of cut (a_p), and spindle speed in RPM (N_{rpm}) to improve the surface roughness (Ra). If it is decided to run experiments at four different levels for these three factors, then a full factorial search would require a total of $4^3 = 64$ runs. In contrast, Taguchi proposed using an orthogonal array to determine the effects of individual process parameters. For example, an appropriate orthogonal array for such a scenario (e.g. the L'16 array) comprises 16 trials, which test 4 levels of up to 5 different experimental factors. Thus, the L'16 orthogonal array only requires 16 runs to complete the optimization of four levels of three factors.

The selection of an appropriate orthogonal array is based on total degree of freedom (DOF), which is computed as,

$$DOF = (L-1) \text{ for each factor} + (L-1) \times (L-1) \text{ for each interaction} + 1 \quad (1)$$

Taguchi proposed that the parameter design must aim to determine the optimal levels of the control factors, such that the response variable is robust to the variability caused by the noise factors. He proposed that there were three specific goals in an experiment:

- (i) Minimize the response (Smaller is better)
- (ii) Maximize the response (Larger is better)
- (iii) Achieve a desired target value.

For achieving each of these goals, Taguchi defined signal-to-noise (S/N) ratios, which measure the variation present in the response data. The maximization of the S/N ratio simultaneously optimizes the quality characteristic and minimizes the effect of noise factors. For each trial in the selected orthogonal array, if the performance measure (y) is repeated n times, then the S/N ratio can be computed as follows:

- Smaller-the-better :

$$Y = -10 \log_{10} + \left[\frac{1}{n} \sum y_i^2 \right] dB, \quad (2)$$

- Larger-the-better- :

$$Y = -10 \log_{10} + \left[\frac{1}{n} \sum y_i^{-2} \right]^{-2} dB, \quad (3)$$

- Achieving a target:

$$Y = -10 \log \left(\frac{s^2}{y^2} \right) \quad (4)$$

where s denotes the sample variance. It may be noted that Y in the above equation denotes the S/N ratio, and not the response parameter.

2.2. Brief review of the machining studies using Taguchi method

There are a number of excellent studies reported in the literature regarding optimization of surface roughness using Taguchi methods and, among others, Yang *et al.* [12] were noticeably the first to present a systematic study of the application of the Taguchi method to the turning operation. They used three factors, namely, feed rate, cutting speed, and depth of cut, with three different values for each factor, called levels. Researchers have used the Taguchi parameter design method for the purpose of optimizing turning parameters for minimizing surface roughness and to obtain dimensional accuracy and long life of the cutting tool [13-17] and some success has been reached [18-22]. Across these studies, it was Tamizharasan *et al.* [23] who presented a rather skeptical finding that the depth of cut and the feed rate have negligible and little respective effect on the surface finish, which presents an opportunity for a reassessment of this finding.

The second step in Taguchi is to determine the number of levels for each factor. Zhang *et al.* [24] selected three levels for three factors, linear cutting speed (0.5 m/sec, 2.5 m/sec, 4.5 m/sec), feed rate (0.05, 0.15, 0.25), and depth of cut (0.025mm, 0.08mm, 0.135mm), for investigating the surface integrity for hardened bearing steel. They indicated that feed rate bears the most important impact on surface finish; cutting speed bears the most important impact on the depth of sub-surface damage and residual stress. The average surface roughness achieved by them was in the range of 0.165-0.475 μm . Ozel *et al.* [25] used four factors and two levels – a total of 16 runs, which were replicated by them 16 times, to end up with 256 tests. They used a high-precision rigid CNC lathe

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(Romi Centur 35E) for longitudinal hard turning of hardened AISI H13 steel bar and 16 inserts were used for each run having similar parameters and they arrived at a minimum average surface roughness of about 0.25 μm . Thiele *et al.* [26] used a three-factor full factorial design to determine the effects of work piece hardness and tool edge geometry on surface residual stresses in finish hard turning using CBN tools. The ANOVA developed by them showed that, although the cutting edge geometry and feed rate impacts surface roughness, the interaction between the hardness and feed rate is also significant. Aslan *et al.* [27] combined the effects of three cutting parameters, namely cutting speed, feed rate, and depth of cut, by employing Taguchi techniques on two performance measures: surface roughness (Ra), and flank wear (VB). Three levels were selected for each factor, thus making a total of 27 runs for turning 63 HRC AISI 4140 steel with an uncoated $\text{Al}_2\text{O}_3+\text{TiCN}$ cutting tool. Their results showed that cutting speed is the most significant factor in influencing the wear of the cutting tool, i.e. an increase in cutting speed causes high tool wear. Davim *et al.* [28] used orthogonal arrays for three factors and three levels for each factor. They conducted a total of 27 runs to investigate the machinability of cold worked tool steel D2 by the hard turning process. Their ANOVA and S/N ratio showed that surface roughness measurements Ra were between 0.26 μm and 1.48 μm and cutting speed is the most influencing parameter for tool wear. Similarly, Chou *et al.* [29] examined the tool performance based on the surface roughness and tool flank wear measurements. They used two factors with three levels, namely linear cutting speed (60,120, and 240 m/min), depth of cut (10, 50, 250 μm), and the feed rate was fixed (12.5 $\mu\text{m}/\text{rev}$). The results of the machining experiment of 62 HRC AISI 52100 shows that low CBN content tools (CBN-L) generate better surface finish and a lower flank wear rate than high CBN (CBN-H). The average surface roughness Ra obtained by the CBN-L was in the range of 0.2-0.4 μm . Xueping *et al.* [30] used L9 orthogonal arrays to optimize hard turning process parameters on inducing subsurface compressive residual stress. Three levels for each cutting condition were selected as reported, linear cutting speed (0.5, 2.5, 4.5 m/s), depth of cut (0.025, 0.080, 0.135mm), and feed rate (0.05, 0.15, 0.25 mm/rev). The optimal combination was found to be 0.5m/s, 0.135 mm, 0.25 mm/rev. Bouacha

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et al. [31] investigated the machinability of the AISI 52100 (64 HRC) by applying L27 Taguchi orthogonal array for three factors and three levels, i.e. linear cutting speed (125,176,246 m/min), feed (0.08, 0.12, 0.16 mm/rev), and depth of cut (0.15, 0.3, 0.45 mm). Their ANOVA results show that surface roughness is influenced significantly by the feed rate and linear cutting speed. The average surface roughness obtained was 0.19-0.77 μm and the optimum cutting parameters they suggested were 246 m/min, 0.08 mm/rev, 0.15 mm. Asiltürk *et al.* [32] applied the Taguchi method to minimize the surface roughness (R_a , R_z) for hard turning. Three factors and three levels were selected to machine AISI 4140 (51 HRC). While implementing a L9 orthogonal array, they used linear cutting speed (90,120,150 m/min), feed rate (0.18, 0.27, 0.36 mm/rev), and depth of cut (0.2, 0.4, 0.6 mm). They showed that the feed rate has the most significant effect on R_a and R_z . On a previous occasion, the authors of this work have carried out regression modeling [33] for this workpiece-tool combination to predict the surface roughness. However, that work does not include the datasets developed in this work for the combination of several parameters and feed rate (as low as 0.02 mm/rev) and hence the necessity of developing this work.

Beside all the above works, Suresh *et al.* [34] have reviewed a great deal of literature concerning hard turning studies carried out between the years 2001 and 2008. They have listed all the cutting parameters and levels of each parameter used in each study. An interesting observation from this review is that much of the research has used 0.05 mm/rev feed rate as the minimum feed used in their experiments and the lowest average surface roughness obtained was 0.2 μm . In another review, Bartarya *et al.* [9] show the cutting condition and the range of each parameter used by various researchers in hard turning and this review shows that the range of feed rate chosen is between 0.05-0.2 mm/rev. In summary, it was realized that most of the researches used almost similar or the same cutting conditions by neglecting the ongoing developments on the machine tool and cutting tool technology and thereby discarding the wisdom of having chosen tighter limits of feed rate. Consequently, the attainable surface roughness achieved did not meet the desired expectations. This motivates the current experimental study.

3. Experimental details

In this experimental study, the first step was to develop an orthogonal array by choosing a set of judiciously chosen cutting parameters. These are listed in Table 1 and, unlike the previously published literature, a much lower feed rate of down to 0.02 mm/rev was chosen in this work for the experimental trials.

Table 1: Cutting parameters and their levels

Cutting parameters	Level 1	Level 2	Level 3	Level 4
Feed rate (mm/rev)	0.02	0.06	0.1	0.15
v_c (m/min)	90	150	200	250
Depth of cut (mm)	0.1	0.2	0.3	0.4

For the purpose of Taguchi analysis, this study neglects the interaction between the cutting parameters. Consequently, an L_{16} array with three columns and 16 rows came as input for the experiments, as shown in Table 2. In Table 2, each cutting parameter is assigned to a column with 16 different combinations of feed rate (f), cutting speed (v_c), and depth of cut (a_p). Thus, these 16 cutting trials enable the study of the entire parameter space using the L_{16} orthogonal array.

Table 2: Cutting parameters and their levels

Experiment Number	Feed rate (mm/rev)	Cutting speed (m/min)	Depth of cut (mm)	CBN cutting tool used
1	0.02	90	0.1	Cutting tool # 1
2	0.02	150	0.2	
3	0.02	200	0.3	
4	0.02	250	0.4	
5	0.06	90	0.2	Cutting tool # 2
6	0.06	150	0.1	
7	0.06	200	0.4	
8	0.06	250	0.3	
9	0.1	90	0.3	Cutting tool # 3
10	0.1	150	0.4	
11	0.1	200	0.1	

12	0.1	250	0.2	Cutting tool # 4
13	0.15	90	0.4	
14	0.15	150	0.3	
15	0.15	200	0.2	
16	0.15	250	0.1	

A conventional mathematical formula was used for converting linear cutting speed (m/min) into the equivalent spindle speed in rev/min (RPM) as below:

$$\text{Rotational cutting speed in RPM} = \frac{1000 \times \text{Linear cutting speed (m/min)}}{\pi \times \text{Diameter of the workpiece}} \quad (5)$$

After designing the experimental array, the next step was to perform the longitudinal turning trials. In Table 2, column 4 is of particular interest. Column 4 was added to this array to add some more value to the experimental results. We were interested to find out economically if the lower or higher feed rate is healthier for tool life. We therefore chose four cutting inserts for the trials instead of sixteen individual cutting inserts. Each cutting insert was used to cut the same cutting length of 80 mm, but at four different feed rates (Table 2). The machining trials were performed on a Mori-Seiki SL-25Y (4-axis) CNC lathe with Fanuc 18TC control. Some of the important specifications of this machine tool are spindle speed (RPM) range of 35-3500, maximum cutting diameter of 260 mm, maximum turning length of 530mm, spindle motor power 15 kW, axial stiffness of about 1000-1500 N/ μ m and radial stiffness of about 10,000-11,000 N/ μ m for spindle and stiffness of slide being about 800 N/ μ m. The work piece specimen used was AISI 4340 steel that was hardened up to 69 HRC through the heat treatment process. The cutting tool used was a CBN cutting insert, which was procured from Warren Tooling Limited, UK (type CNMA 12 04 08 S-B). The cutting tool had a rake angle of 0°, clearance angle of 5°, and a nose radius of 0.8 mm. Further details of the experiments for replication of results are provided in Table 3.

Table 3: Experimental parameters

S.NO.	Details	Values
1	Work piece material	AISI 4340 steel hardened up to 69 HRC by quenching and tempering processes in a local workshop. Hardness was

		measured using a conventional hardness tester.
2	Diameter of work piece before turning	28.8 mm
3	Cutting tool specifications	CNMA 12 04 08 S-B (ISO code)
4	Tool nose radius (r)	0.8 mm
5	Tool rake and clearance angles	0° and 5°
6	Length of cut	20 mm for each test 1 insert was thus used for a total length of $20 \times 4 = 80$ mm length of cut

Thus, the experimental trials revealed two tangible outcomes, i.e. machined surface roughness and the worn CBN tips (which were used to machine at the different feed rate but the same cutting length). The measurement of the machined surface roughness was done through a Form Talysurf while a high magnification scanning electron microscope (SEM FIB-FEI Quanta 3D FEG) was used to measure the flank wear length (V_b) to estimate the tool wear. The intent of this work was only to identify the optimum machining parameters and hence extensive analysis of machined surface has not been presented here. Readers are referred to see this elsewhere [8]. In the subsequent section, the outcome of the machining trials is presented and discussed.

4. Analysis of the experimental results and discussions.

4.1. Signal-to-noise (S/N) ratio analysis

Taguchi recommended the use of the signal-to-noise (S/N) ratio to measure the quality characteristics deviating from the desired values. The term signal (S) in the S/N ratio represents the desirable value (mean) and the term noise (N) represents the undesirable value (S.D.) for the output characteristic. Therefore, the S/N ratio is actually the ratio of the mean to the S.D. Consequently, a greater S/N ratio corresponds to better quality and, hence, a greater S/N ratio signifies better parameters. In general, there are three categories of quality characteristics, which are the-lower-the-better, the-higher-the-better and the-nominal-the-better. Depending on the objective of the task, the characteristic may be chosen accordingly; for example, while evaluating tool life, one may chose

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the-higher-the-better criterion and, contrarily, while evaluating surface roughness, the-lower-the-better criterion is better.

Accordingly, as per the lower-the-better criterion, S/N ratio η is defined as $\eta = -10 \log (M.S.D.)$, where $M.S.D. = S_i^2$ is the mean-square deviation for the output characteristic, as in, S_i is the value of surface roughness for the i th observation.

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

Experiment number	Feed Rate (mm/rev)	Linear cutting speed (m/min)	Depth of Cut (mm)	Measured experimental surface roughness (micron) (S_i)	S_i^2 or M.S.D.	S/N ratio (dB)
Level	A	B	C			
1	0.02	90	0.1	0.0428	0.0018	27.37
2	0.02	150	0.2	0.0478	0.0023	26.41
3	0.02	200	0.3	0.0527	0.0028	25.56
4	0.02	250	0.4	0.0497	0.0025	26.07
5	0.06	90	0.2	0.3281	0.1076	9.68
6	0.06	150	0.1	0.2883	0.0831	10.80
7	0.06	200	0.4	0.2172	0.0472	13.26
8	0.06	250	0.3	0.2065	0.0426	13.70
9	0.1	90	0.3	0.5612	0.3149	5.02
10	0.1	150	0.4	0.6005	0.3606	4.43
11	0.1	200	0.1	0.6351	0.4034	3.94
12	0.1	250	0.2	0.6449	0.4159	3.81
13	0.15	90	0.4	1.0345	1.0702	-0.29
14	0.15	150	0.3	1.0846	1.1764	-0.71
15	0.15	200	0.2	1.1135	1.2399	-0.93
16	0.15	250	0.1	1.1384	1.2960	-1.13
Total mean						10.44

The effect of each cutting parameter at different levels can be calculated by averaging the S/N ratio; for example, the mean S/N ratio for linear cutting speed at levels 1,2,3, and 4 can be computed by averaging the S/N ratio for the experiments (1,5,9,13 for level 1), (2,6,10,14 for level 2), (3,7,11,15 for level 3), and(4,8,12,16 for level 4). For the other cutting parameters, the mean S/N ratio can be calculated in a similar way. Table 5 shows the summary of the mean S/N ratio for each cutting parameter.

Table 5: Response table mean S/N ratio for surface roughness factor and significant interaction

Symbol		Level 1 (Expt. 1, 2, 3 and 4)	Level 2 (Expt. 5, 6, 7 and 8)	Level 3 (Expt. 9,10,11,12)	Level 4 (Expt. 13, 14, 15 and 16)	Max-Min
A	Feed rate (mm/rev)	0.02	0.06	0.1	0.15	
	Mean S/N ratio	26.355	11.862	4.3	-0.765	27.12
		Level 1 (Expt. 1, 5, 9 and 13)	Level 2 (Expt. 2, 6, 10 and 14)	Level 3 (Expt. 3,7,11,15)	Level 4 (Expt. 4, 8, 12 and 16)	
B	Linear cutting speed (m/min)	90	150	200	250	
	Mean S/N ratio	10.444	10.23	10.46	10.61	0.38
		Level 1 (Expt. 1, 6, 11 and 16)	Level 2 (Expt. 2, 5, 12 and 15)	Level 3 (Expt. 3,8,9,14)	Level 4 (Expt. 4, 7, 10 and 13)	
C	Depth of cut (mm)	0.1	0.2	0.3	0.4	
	Mean S/N ratio	10.248	9.742	10.89	10.868	1.152

Figure 2: Mean S/N ratio for various parameters (feed rate, depth of cut and linear cutting speed)

Figure 3: Close comparison of S/N ratio for linear cutting speed and depth of cut

Taguchi noted that the greater S/N ratio corresponds to the smaller variance of surface roughness. It can be seen from Figure 2 that the maximum S/N ratio for the feed rate was clearly at Level 1 (feed rate of 0.02 mm/rev). Furthermore, variation in the S/N ratio for higher feed rates decreases exponentially, which signifies that feed rate has a very strong influence on the surface roughness—the lower the feed rate, the better the machined surface roughness or the higher the feed rate, the worse the machined surface roughness. However, from Figure 2, the influence of linear cutting speed and depth of cut is not very clear, primarily because the variation in the S/N ratio is not much. This suggests that feed rate is by far the most dominant variable in influencing the machined surface roughness, in comparison to the other two machining variables linear cutting speed and depth of cut. To reveal more insights of it, two individual plots were plotted, which are shown in Figure 3. From Figure 3, it can be seen that the maximum S/N ratio for linear cutting speed was observed to be at Level 4 (linear cutting speed of 250 mm/min), while maximum S/N ratio for depth of cut was observed to be at Level 3 (depth of cut of 0.3 mm). It is also quite surprising that, particularly at level 2, the S/N ratio for both linear cutting speed and depth of cut become the lowest and then rise again. It will be interesting to explore why the S/N ratio dropped from Level 1 to Level 2 and then increased again in Level 3 (this will be expanded in future work). However, Figure 2 and Figure 3 in conjunction with each other clearly indicate that the optimal cutting parameters are A1, B4, C3; i.e. the optimal machining parameters are the feed rate of 0.02mm/rev, linear cutting speed of 250

5.2. Analysis of Variance

Analysis of variance (ANOVA) is an established way to assert the dominance of one parameter over the other parameter in influencing the quality characteristic. An important thing to do with ANOVA is to find out the degree of freedom. In this work, sixteen experiments were done and, therefore, the total degree of freedom is equal to the number of experiments minus one, which gives the degree of freedom as 15. Four levels for each parameter counts for three degree of freedom. The total sum of squared deviations SS_T for each parameter can then be calculated as follows:

$$SS_T = \sum_{i=1}^m \eta_i^2 - 1/m \left[\sum_{i=1}^m \eta_i / 16 \right]^2 \quad (6)$$

For example, feed rate can be calculated as follows:

$$SS_{T_{FEED}} = \sum \frac{(1+2+3+4)^2}{4} + \frac{(5+6+7+8)^2}{4} + \frac{(9+10+11+12)^2}{4} + \frac{(13+14+15+16)^2}{4} - \frac{(\sum S/N)^2}{16} \quad (7)$$

$$SS_{T_{Cuttingsped}} = \sum \frac{(1+5+9+13)^2}{4} + \frac{(2+6+10+14)^2}{4} + \frac{(3+7+11+15)^2}{4} + \frac{(4+8+12+16)^2}{4} - \frac{(\sum S/N)^2}{16} \quad (8)$$

$$SS_{T_{DOC}} = \sum \frac{(1+6+11+16)^2}{4} + \frac{(2+5+12+15)^2}{4} + \frac{(3+8+9+14)^2}{4} + \frac{(4+7+10+13)^2}{4} - \frac{(\sum S/N)^2}{16} \quad (9)$$

where numbers from 1 to 16 represent the corresponding S/N ratio obtained for each experiment as shown in Table 4. The total sum of squares can be calculated by:

$$SST_{TOTAL} = (\sum (1^2) + (2^2) + (3^2) \dots + (16^2)) - \frac{(\sum S/N)^2}{16} \quad (10)$$

The error can then be computed as:

$$SST_{ERROR} = SST_{TOTAL} - SST_{FEED} - SST_{SPEED} - SST_{DEPTH} \quad (11)$$

The mean square is equal to half of the sum of squares, which can be used to calculate F, as follows:

$$F_{FEED} = SST_{FEED} / SST_{ERROR} \quad (12)$$

Finally, contribution of the factor can be calculated by % Contribution = $\frac{F}{(\sum F) + 1} \times 100\%$ (13)

Table 6 shows a summary of the ANOVA results for all the experiments. It can be seen from Table 6 that the feed rate makes the maximum contribution of 99.16%, thus signifying that, across all the other cutting parameters, it has the most influence, followed by depth of cut and linear cutting speed, respectively.

Table 6: Results of the ANOVA for surface roughness

Symbol	Cutting parameter	Degree of freedom	Sum of squares	Mean square = (Sum of Squares /2)	F (sum of square /Error)	Contribution (%)
A	Feed rate	3	1674.182	837.1	162.43	99.16%
B	Linear cutting speed	3	0.292	0.146	0.028	0.017 %
C	Depth of cut	3	3.655	1.827	0.355	0.216 %
Error (Total-A-B-C)		6	10.31			0.611%
Total		15	1688.46 (SST _{Total})			100

5.3. Confirmation experiments

In the previous section, the optimal level of the design parameter had been arrived from the sixteen numbers of experimental arrays which were designed based on the Taguchi method. S/N ratio analysis revealed that the optimal cutting parameters are A1, B4, C3; i.e. the optimal machining parameters are the feed rate of 0.02mm/rev, linear cutting speed of 250 mm/min, and depth of cut of 0.3 mm. It will thus be of particular interest to find out from the experiments what level of surface

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roughness can be reached using these machining parameters using the same configuration that was originally used for the other experiments. Accordingly, a confirmatory machining trial was performed to predict the surface roughness on these optimized machining parameters. Accordingly, the outcome of the experiments i.e. measured surface roughness obtained from the experiment is shown in Figure 4. An average value of surface roughness of about 48.3 nm was achieved using the optimal parameters. Least to mention that this precise range of surface roughness of 48 nm was achieved not by using an ultra precision lathe but only by a turret lathe and hence is indicative of the developments in the machine and cutting tool research that have took place over the years in the domain of hard turning.

Figure 4: Measurement of the surface roughness using the optimal cutting parameters

Table 7: Output of the confirmatory trial

	Initial cutting parameters	Optimal cutting parameters	
		Prediction	Experiment
Level	A2B2C2	A1B4C3	A1B4C3

Ra μm	0.360	0.0481	0.0483
S/N ratio (db)	8.874	26.355	26.321

Using table 4, the following equation can be used for predicting the S/N ratio as follows:

$$\eta_p = \eta_m + \sum_{i=1}^p (\eta_m - \eta_{im}) \quad (14)$$

where η_m is the total mean of S/N ratio and it is equal to 10.438. As shown in table 5, η_m is the mean S/N ratio at the optimal level for the significant parameter as in 26.355 corresponds to A1, 10.615 is for B4 and 10.894 for C3. p is the number of significant cutting parameters effecting the performance characteristic and in this study the only parameter of relevant importance is the feed rate. Accordingly, the predicated Ra can be calculated as:

$$Ra_{prediction} = \sqrt{10^{(S/N_{predicted} / -10)}} \quad (15)$$

A comparison of the predicted and experimental values of the surface roughness using the optimal cutting parameters is shown in table 7. A good agreement between the predicted value and the experimental value can be seen. The increase of the S/N ratio from the initial cutting parameters to the optimal cutting parameters is 17.447 dB and therefore the surface roughness value can be seen to improve a bit.

5. Discussion on tool wear

The performance of any mechanical machining process is known to be influenced deeply by the in-process degradation, or the wear of the cutting tool. Wear of the cutting tool changes the contact surface of the cutting tool and the work piece, which causes worsening of the machined surface. Wear of cutting tool is therefore of paramount importance, both to the academic and the industrial community. It is widely known that tool wear can initiate either by mechanical or by chemical activities, but the main purpose of this work was not to unravel the basic mechanism of tool wear but to examine the influence of the machining parameter, in particular the feed rate in influencing

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the tool wear. Table 2, in this aspect, became an advantage to this study, as four feed rates are in common with each other. So, sixteen experiments involve the use of four cutting tips only. These four cutting tips were used to cut 80 mm length of cut, each at a different feed rate. Accordingly, Table 8 presents the SEM examination results of the cutting tool, which identifies the tool flank wear length V_b in each case.

Table 8: Experimental measurement of tool flank wear length V_b

Cutting length (experimental trial number)	Tool used at the feed rate of	Tool flank wear (VB) length	
80 mm (1-4)	0.02 mm/rev	26.12 μm
80 mm (5-8)	0.06 mm/rev	19.17 μm
80 mm (9-12)	0.1 mm/rev	17.11 μm

80 mm (13-16)	0.15 mm/rev	16.71 μm
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It can be seen from Table 8 that maximum wear length V_b was observed to be about 26.12 μm , while cutting was performed at a lower feed rate of 0.02 mm/rev. Similarly, a very low flank wear length of about 16.71 μm was observed while a high feed rate of 0.15 mm/rev was used, and intermittent flank wear lengths were observed for intermittent feed rates. It is thus clear from this examination that feed rate influences the tool wear. Now, an important aspect of this particular examination is that a lower feed rate was earlier shown to provide better machined surface roughness but this comes at an expense of higher wear volume of the cutting tool. This can best be understood from a schematic diagram shown in figure 5. In figure 5, it has been shown that the undeformed chip thickness varies from zero at the centre of the tool tip to a maximum value at the top of the uncut shoulder. Thus, a “zero-cutting zone” exists within which no chips are produced. In this zone, the tool acts more like a roller than a cutter and continuously slides on and burnishes the machined surface [35-36]. Consequently, the cutting edge of the tool continues to recede, and this accelerates the rate of tool wear during hard turning operation.

Figure 5: Schematic of the groove wear [37]

Thus, it's understood that lower feed rates result in a better surface finish however; lower feed rates also result in more tool wear due to the longer track length covered by the tool during machining. On the other hand, at higher feed rates, tool wear is low but this produced poor machined surfaces. Therefore, in a practical case, the option of choosing the feed rate must consider both machined surface roughness and the wear volume of the cutting tool before finalizing the machining parameters.

6. Conclusions

Taguchi method was applied to develop an L_{16} array with individual combinations of feed rate (f), depth of cut (a_p) and linear cutting speed (v_c) to optimize the surface roughness of AISI 4340 steel (69 HRC). S/N ratio, ANOVA analysis and multiple regression analysis were applied to the machining data to gain further insights. Based on the foregoing discussions, following conclusions can be drawn:

1. It is shown that the modern day facilities and use of CBN cutting tool can produce an average machined surface roughness of 45 nm without requiring any additional means on AISI 4340 steel as hard as 69 HRC.
2. Multiple Regression Models applied to the 16 experimental datasets obtained from the machining trials in this work revealed the following generalised mathematical equation for predicting the machined surface roughness for 69 HRC AISI 4340 steel:

$$Ra = -0.11706992 + 8.148467886 f + 97.5658 \times 10^{-6} v_c - 0.20935731 a_p$$

where f is the feed rate (mm/rev), v_c is the linear cutting speed (m/min) and a_p is the depth of cut (mm).

Based on the above results and the confirmation trial obtained from the Taguchi array, the optimal cutting parameters identified for machining of 69 HRC AISI 4340 steel on a CNC turret lathe are feed rate of 0.02mm/rev, linear cutting speed of 250 mm/min and depth of cut of 0.3 mm. Furthermore, ANOVA revealed that feed rate can make a contribution of up to

99.16% whereas other parameters do not carry appreciable contribution in influencing the machined surface roughness.

3. Finally, it is shown that while the lower feed rate provides an improved machined surface roughness, it also influences tool life (because of the increased track length and time of engagement with the workpiece). Therefore, a trade-off criterion for selection of an appropriate feed rate must be determined based on the cost and quality considerations.

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