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Optimization of Cutting Parameters Based on Surface Roughness and Assistance of Workpiece Surface Temperature in Turning Process

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Abstract: Problem statement: In machining operation, the quality of surface finish is an important requirement for many turned workpieces. Thus, the choice of optimized cutting parameters is very important for controlling the required surface quality. **Approach:** The focus of present experimental study is to optimize the cutting parameters using two performance measures, workpiece surface temperature and surface roughness. Optimal cutting parameters for each performance measure were obtained employing Taguchi techniques. The orthogonal array, signal to noise ratio and analysis of variance were employed to study the performance characteristics in turning operation. **Results:** The experimental results showed that the workpiece surface temperature can be sensed and used effectively as an indicator to control the cutting performance and improves the optimization process. **Conclusion:** Thus, it is possible to increase machine utilization and decrease production cost in an automated manufacturing environment.

Key words: Surface roughness, cutting temperature, Taguchi parameter design, turning

INTRODUCTION

Increasing the productivity and the quality of the machined parts are the main challenges of metal-based industry; there has been increased interest in monitoring all aspects of the machining process. Surface finish is an important parameter in manufacturing engineering. It is a characteristic that could influence the performance of mechanical parts and the production costs. The ratio between costs and quality of products in each production stage has to be monitored and immediate corrective actions have to be taken in case of deviation from desired trend.

Surface roughness measurement presents an important task in many engineering applications. Many life attributes can be also determined by how well the surface finish is maintained. Many surface roughness prediction systems were designed using a variety of sensors including dynamometers for force and torque (Lin *et al*., 2001; Azouzi and Guillot, 1996), accelerometers for mechanical vibrations (Abouelatta and Madl, 2001; Choudhury and Sharat, 1993; Jang *et al*., 1995; Kirby *et al*., 2006), acoustic emission for (AE) sensors (Sundaram *et al*., 2007; Sundaram *et al*., 2008; Collacott, 1975) and current probes for current/power measurement of spindle and feed motors (Sundaram *et al*., 2008). The purpose of using these sensors in machining processes is to increase part quality while decreasing cost and time of manufacture. A review and more details about predicting surface roughness in machining presented by (Benardos and Vosniakos, 2003).

The cutting temperature is a key factor which directly affects cutting tool wear, workpiece surface integrity and machining precision according to the relative motion between the tool and work piece (Ming *et al*., 2003). The amount of heat generated varies with the type of material being machined and cutting parameters especially cutting speed which had the most influence on the temperature (Liu *et al*., 2002). Several attempts have been made to predict the temperatures involved in the process as a function of many parameters. Da Silva and Wallbank (1999) presented a review for cutting temperature prediction and measurement methods. Additionally, many experimental methods to measure temperature directly, only a few systems have as yet been used this temperature as an indicator for machine performance monitoring and for industrial application. Therefore, design and develop control system to control the temperature lead to better surface finish as machine performance parameter.

Taguchi and Analysis Of Variance (ANOVA) can conveniently optimize the cutting parameters with

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several experimental runs well designed. Taguchi parameter design can optimize the performance characteristics through the settings of design parameters and reduce the sensitivity of the system performance to source of variation (Berger and Maurer, 2002; Ryan, 2000). On the other hand, Analysis Of Variance ANOVA used to identify the most significant variables and interaction effects (Henderson, 2006; Ryan, 2000).

A lot of researches have been conducted for determining optimal process parameters. Kwak (2005) Presented the Taguchi and response method to determine the robust condition for minimization of out of roundness error of workpieces for the center less grinding process. Yang and Tarng (1998) employed Taguchi method and optimal cutting parameters of S45C steel bars for turning operations were obtained.

Determination of optimal cutting conditions for surface finish obtained in turning using the techniques of Taguchi and a correlation between cutting velocity, feed and depth of cut with the roughness evaluating parameters R_a and R_t was established using multiple linear regression by Davim (2001). John *et al*. (2001) demonstrated a systematic procedure of using Taguchi parameter design in process control in order to identify the optimum surface roughness performance with a particular combination of cutting parameters in an end milling operation. Kopac *et al*. (2002) described the machining parameters influence and levels that provide sufficient robustness of the machining process towards the achievement of the desired surface roughness for cold pre-formed steel workpieces in fine turning.

This study describe how to select the control factors levels (cutting speed, Feed rate and depth of cut) that can minimize the effect of noise factors on the response (surface roughness). An experimental work will be conducted to analyze the influence of cutting parameters (control factors) on surface roughness (response) and workpiece surface temperature (signal factor), then select the optimal cutting parameters which lead to optimal response by assistance of optimal signal factor.

A good trade-off between cost and performance, with a high reliability and a reduced computing time will be proposed from in-process optimization of cutting parameters during machining process using temperature sensing.

Theory: The temperature can be calculated using Steffen-Boltzman law by the following equation Ming *et al*. (2003):

$$E = \varepsilon\sigma T^4 \text{ (W m}^{-2}\text{)} \tag{1}$$

Where:
ε = The emissivity of the material radiation element
σ = The Steffen-Boltzman constant, 5.67×0^{-8} W m^{-2} K^4
T = The surface temperature of radiation element (K)
E = The radiation energy of radiation element unit^{-1} (W)

The radiation energy could be received and measured on the radiation element of the material by an infrared thermometer and then the surface temperature of the radiation element could be calculated according to the Steffen-Boltzman law if the emissivity of the radiation element was known. This was a visual, simple and non-contact method to measure the temperature by an infrared thermometer. The infrared thermometers have been used in more reports than any other method and the advantages in the use of infrared sensor are; non-contact, respond to rapid changes in temperature, enable the easy measurement of high temperatures without disturbing the heat distribution and not affected by cutting process (Longbottom and Lanham, 2005).

MATERIALS AND METHODS

Experimental procedures and conditions: In this study, medium carbon steel AISI 1020 and 250 mm long with 50 mm diameter was used as work material for experimentation using a lathe turning machine. The chemical composition of the selected workpiece is shown as follows: C, 0.20; Si, 0.15; Mn, 0.72; P, 0.011; S, 0.023. CNMG 432 TT5100 insert with Sandvik tool holder PCLNR 2525M/12 universal turning machine tool was used in the experiments. All tests were performed dry.

Cutting speed, feed rate and depth of cut were selected as the machining parameters to analyze their effect on surface roughness and workpiece surface temperature as well. A total of 27 experiments based on Taguchi's L27 (3^{13}) orthogonal array were carried out with different combinations of the levels of the input parameters. Among them, the settings of cutting speed include 950, 1150 and 1400 rpm; those of feed rate include 0.05, 0.1, 0.15 mm rev^{-1}; the depth of cut is set at 0.5, 1.0 and 1.5 mm. Experimental planning was prepared by using cutting parameters and test conditions that were advised for a couple of tool-workpiece by tool manufacturer and the information available in the literature. A schematic diagram of the experimental set-up is shown in Fig. 1.

For workpiece surface temperature measurement, handheld infrared thermometer type (OS534E) with built-in laser circle to dot switchable and RS-232 output was used.

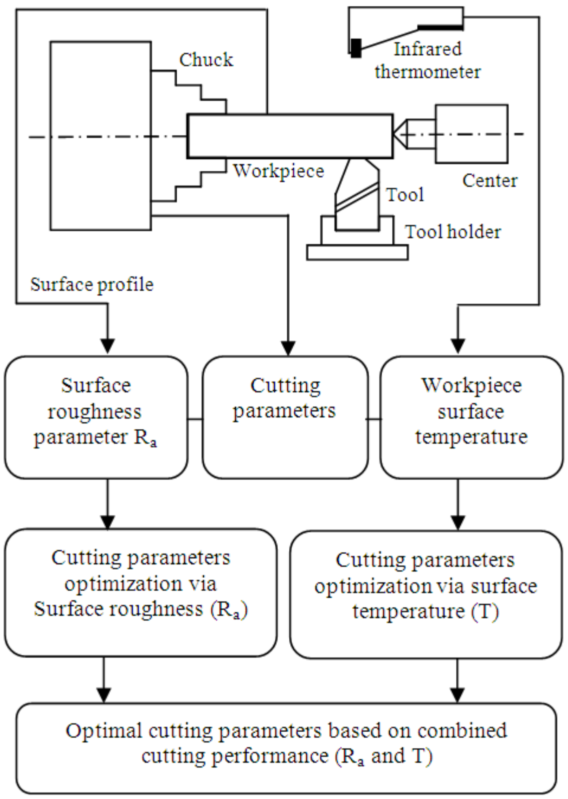

Fig. 1: Schematic diagram of the experimental setup of turning operation

The amount of standard surface roughness parameter (Arithmetic average deviation from the mean line Ra) is carried out using surface roughness tester model Mahr Perthometer (MarSurf PS1, produced by Mahr GMbH, Germany). Three measurements for workpiece surface roughness were made and averaged for each test.

This set-up was connected to computer using necessary hardware and software for data acquisition. The relationship between the workpiece surface temperature and the cutting parameters is examined.

A series of experiments was conducted to obtain the surface temperature of the workpiece by the aid of the infrared thermometer and surface roughness by the aid of stylus type tester. Taguchi method is being applied in to select the control factors levels (Cutting speed, Feed rate and depth of cut) that minimize the effect of noise factors on the response (surface roughness) and get the relationship between the signal factor (workpiece surface temperature) and the response, to come up with the optimal surface roughness value using the rate of change for the response relative to the signal factor.

Table 1: Orthogonal array L27 [15] of Taguchi

	Column no.												
Test no.	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

The goal of this experimental work was to investigate the effects of cutting parameters on workpiece surface temperature and surface roughness and to establish a correlation between them. Experiments were planned according to Taguchi's L27 (3^{13}) orthogonal array, which has 27 rows corresponding to the number of testes (26 degree of freedom) with 13 columns at three levels, as shown in Table 1. The factors and the interactions are assigned to the columns.

The first column of the Table 1 was assigned to the Depth of cut (D), the second to the Feed rate (F), the fifth to the cutting Speed (S) and the remaining were assigned to the interactions. It means a total 27 experimental number must be conducted using the combination of levels for each independent factor (speed, S; feed, F and depth of cut, D) as shown in Table 1. This orthogonal array is chosen due to its capability to check the interactions among factors.

The procedure for these tests were to measure the workpiece surface temperature while machining (in-process) using the infrared thermometer. When the pass is finished, the surface was then cleaned and surface roughness measured with the contact profilometer to obtain the corresponding roughness. The experimental results are then transformed into a Signal to Noise (S/N) ratio.

There are three categories of quality characteristic in the analysis of the S/N ratio, (i) the-lower-the-better, (ii) the-higher-the-better and (iii) the-nominal-the-better. Regardless of the category of the quality characteristic, process parameter settings with the highest S/N ratio always yield the optimum quality with minimum variance. The category the-lower-the-better was used to calculate the S/N ratio for both quality characteristics surface roughness and workpiece surface temperature, according to the equation:

$$\eta = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \quad (2)$$

Where:
η = Signal to noise ratio
n = Number of repetitions of experiment
y_i = Measured value of quality characteristic

In addition, a statistical Analysis Of Variance (ANOVA) is performed to see which process parameters are significantly affecting the responses (surface roughness, R_a and workpiece surface Temperature, T).

RESULTS

The measured values of surface roughness and workpiece surface temperature for the machined surfaces corresponding to all the experimental runs are given in Table 2.

Signal to noise ratio: Analysis of the influence of each control factor (S, F and D) on the surface roughness Ra and workpiece surface temperature T has been performed with a so-called signal to noise ratio response table. Response tables of S/N ratio for surface roughness and workpiece surface temperature are shown in Table 3. and Table 4. respectively. It show the S/N ratio at each level of control factor and how it is changed when settings of each control factor are changed from one level to other.

The influence of each control factor can be more clearly presented with response graphs. Response graphs for all control factors are shown in Fig. 2, the slope of the line which connects between the levels can clearly show the power of the influence of each control factor.

In addition, the analysis of interactions gives more accurate and additional information about optimal cutting parameter. Figure 3 and 4 present interaction plot for S/N ratios for surface roughness Ra and surface temperature T respectively.

Table 2: Experimental results for R_a and T

S	F	D	R_a	T
950	0.05	0.5	1.22000	55.8958
1150	0.05	0.5	1.09900	62.9655
1400	0.05	0.5	1.00200	70.3913
950	0.10	0.5	1.53000	61.9286
1150	0.10	0.5	1.33067	63.8000
1400	0.10	0.5	1.25767	68.5789
950	0.15	0.5	2.28000	55.8667
1150	0.15	0.5	2.17200	60.8500
1400	0.15	0.5	1.87333	63.5000
950	0.05	1.0	2.77700	75.8750
1150	0.05	1.0	1.51000	76.5714
1400	0.05	1.0	0.92633	76.7826
950	0.10	1.0	1.97433	68.1667
1150	0.10	1.0	1.43000	69.1818
1400	0.10	1.0	1.29333	69.8125
950	0.15	1.0	3.09367	60.8000
1150	0.15	1.0	2.72000	64.8889
1400	0.15	1.0	1.79867	71.0556
950	0.05	1.5	1.43000	76.2400
1150	0.05	1.5	1.07733	78.6800
1400	0.05	1.5	0.83133	92.6136
950	0.10	1.5	1.98533	70.1053
1150	0.10	1.5	1.50667	74.2727
1400	0.10	1.5	0.70333	81.6250
950	0.15	1.5	2.72233	61.6875
1150	0.15	1.5	2.25867	67.8947
1400	0.15	1.5	1.40933	72.7619

S: Cutting speed; T: Experimental temperature; F: Feed rate; R_a: Experimental Surface roughness; D: Depth of cut

Table 3: Response table for S/N ratios (smaller is better) for R_a

Level	S	F	D
1	-6.103	-1.833	-3.342
2	-4.078	-2.875	-5.182
3	-1.383	-6.856	-3.041
Delta	4.720	5.023	2.141
Rank	2.000	1.000	3.000

Table 4: Response table for S/N ratios (smaller is better) for T

Level	S	F	D
1	-36.23	-37.31	-35.91
2	-36.72	-36.84	-36.92
3	-37.35	-36.15	-37.46
Delta	1.12	1.16	1.55
Rank	3.00	2.00	1.00

Table 5: ANOVA table for the surface Roughness (R_a)

Source	df	SE	t-stat	p-value
S	2	0.0004041	-4.819961	7.293E-05
F	2	1.8222418	5.155438	3.174E-05
D	2	0.1822241	0.097346	0.923294

R^2 = 68.41529%; R^2(adj) = 64.2955%

Analysis of variance ANOVA: The experimental results were analyzed with Analysis Of Variance (ANOVA), which is used for identifying the factors significantly affecting the performance measures. The results of the ANOVA with surface roughness and workpiece surface temperature are shown in Table 5 and 6, respectively. This analysis was carried out for significance level of $\alpha = 0.05$, i.e. for a confidence level of 95%.

Table 6: ANOVA table for the surface roughness (T)

Source	df	SE	t-stat	p-value
S	2	0.0037041	5.385827	1.800E-05
F	2	16.7028103	-5.768151	7.090E-06
D	2	1.67028103	7.457421	1.400E-07

R^2 = 83.6754%; R^2(adj) = 81.5461%

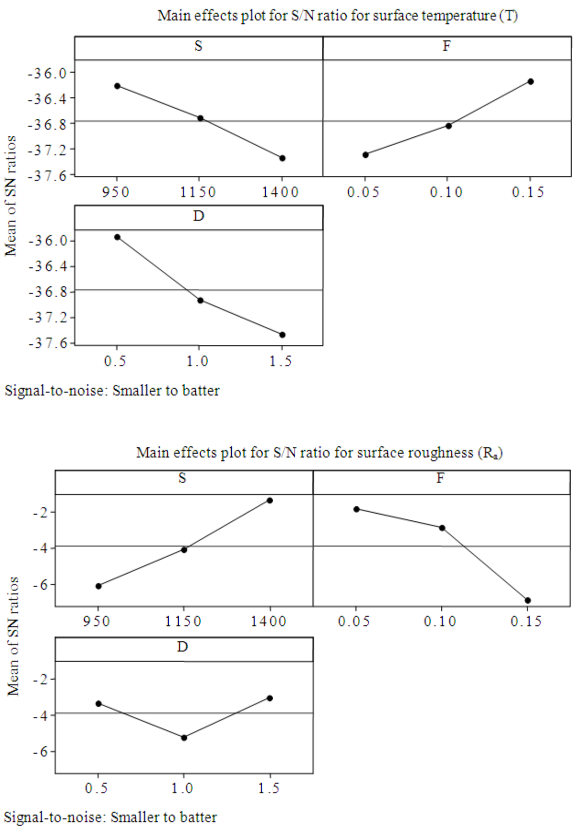

Fig. 2: Main effect plots for S/N ratio for surface Roughness (R_a) and surface Temperature (T)

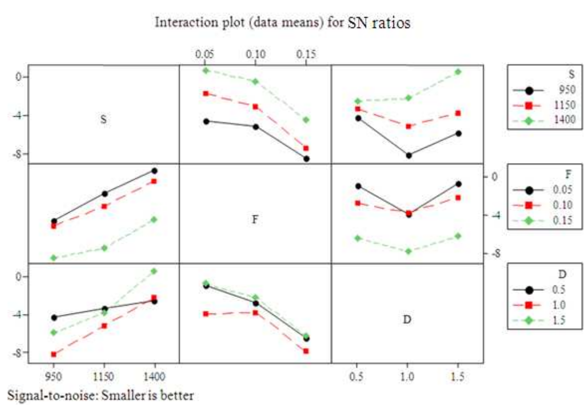

Fig. 3: Interaction plot for S/N ratio for surface Roughness (R_a)

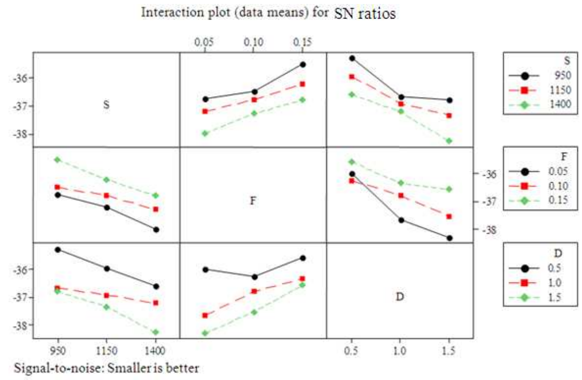

Fig. 4: Interaction plot for S/N ratio for workpiece surface Temperature (T)

DISCUSSION

It can be seen from Table 3 and according to the rank value for each control factor that the feed rate had the strongest influence on surface roughness followed by cutting speed and last by depth of cut. Similarly from Table 4 it can be seen that the depth of cut had the strongest influence on workpiece surface temperature followed by feed rate and then by cutting speed.

From the main effects plot for S/N ratio for surface roughness Fig. 2, the surface roughness appears to be an almost linear increasing function of feed rate (F) and decreasing function of cutting speed (S). Thus, in order to reduce the level of surface roughness, F should be set to its lowest level (0.05 rev mm^{-1}) and S to its highest level (1400 rpm). Also, high level (1.5 mm) or low level (0.5 mm) of depth of cut (D), may be preferred, while the effect of D has not been found statistically significant (p-value = 0.923).

For comparison; the main effects plot for workpiece surface temperature (T) at the same levels shows that the highest cutting speed and lowest feed rate produce higher surface temperature and higher depth of cut as well. Thus, the higher surface temperature gives better surface roughness and high level for depth of cut was better. So, using the-higher-the-better of quality characteristic is more suitable for this case.

From Fig. 3 the significant interaction only can be seen between cutting speed and depth of cut ($S \times D$) and between feed rate and depth of cut ($F \times D$). So, the optimum cutting conditions for surface roughness with high evidence should be set to lowest level of feed rate (F) which was a dominant parameter for the surface roughness, and highest level of both cutting speed (S) and depth of cut (D). Same interactions were found significant from Fig. 4 which means that the signal factor (workpiece surface temperature) follow significantly the response factor (surface roughness).

From Table 5, analysis of variance ANOVA for surface roughness. It can be found that cutting speed and feed rate are the significant cutting parameters for affecting surface roughness. The change of the depth of cut in the range given in Table 2 has an insignificant effect on surface roughness (p-value = 0.923). Therefore, based on S/N and ANOVA analysis, the optimal cutting parameters for surface roughness are the feed rate at level 1, the cutting speed at level 3, and depth of cut at level 3. Table 6 shows the results of ANOVA for surface temperature. Cutting speed, feed rate, and depth of cut are significant parameters for affecting surface temperature. However, the P value order of the cutting parameters for surface temperature is depth of cut, then feed rate, and then cutting speed. The optimal cutting parameters for surface temperature are cutting speed at level 3, the feed rate at level 1, and the depth of cut at level 3.

CONCLUSION

This study discussed an application of the Taguchi method for optimizing the cutting parameters in turning operations using combined of two performance measures, workpiece surface Temperature (T) and surface roughness (R_a). From this research, following conclusions could be reached with a fair amount of confidence:

Regardless of the category of the quality characteristic, the-lower-the better for surface roughness the lowest feed rate (F = 0.05 mm rev^1), the highest cutting speed (S = 1400 RPM) and highest depth of cut (D = 1.5 mm) lead to optimal surface roughness value.

Similarly the-higher-the better quality characteristic for workpiece surface Temperature (T) follow significantly the-lower-the-better quality characteristic for surface roughness.

Control parameters (S, F and D) can be monitored using workpiece surface temperature as signal factor fairly more accurate according to p-values from ANOVA analysis table and high R-value as well.

Finally the experimental results show that workpiece surface temperature can be sensed and used effectively as an in-process signal for cutting parameters optimization.

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