International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:5, No:11, 2011

Investigations Into the Turning Parameters Effect on the Surface Roughness of Flame Hardened Medium Carbon Steel with TiN-Al_2O_3-TiCN Coated Inserts based on Taguchi Techniques

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***Abstract*—**The aim of this research is to evaluate surface roughness and develop a multiple regression model for surface roughness as a function of cutting parameters during the turning of flame hardened medium carbon steel with TiN-Al2O3-TiCN coated inserts. An experimental plan of work and signal-to-noise ratio (S/N) were used to relate the influence of turning parameters to the workpiece surface finish utilizing Taguchi methodology. The effects of turning parameters were studied by using the analysis of variance (ANOVA) method. Evaluated parameters were feed, cutting speed, and depth of cut. It was found that the most significant interaction among the considered turning parameters was between depth of cut and feed. The average surface roughness (R_a) resulted by TiN-Al_2O_3-TiCN coated inserts was about 2.44 μm and minimum value was 0.74 μm. In addition, the regression model was able to predict values for surface roughness in comparison with experimental values within reasonable limit.

***Keywords*—**Medium carbon steel, Prediction, Surface roughness, Taguchi method

I. INTRODUCTION

EXESSIVE manufacturing cost of mechanical components is usually resulted from unnecessary surface specifications and tight tolerances. Machining is one of the major manufacturing processes used to produce mechanical parts. The relationship between cost and quality through production ought to be monitored and corrective actions have to be made to sustain the required trend [1]. Today's dynamic market requires high production response to attain high competitiveness and sustainable reputation. Accordingly, machinability tests ought to be performed as one of the initial steps to optimize machining parameters of machined component before launching full scale production. These tests usually examine selected machining parameters to attain optimal results. The usually tested machining parameters, but not limited to, are wear test, coolant application, power consumption, metal removal rate, and surface finish.

Surface finish (R_a) of produced parts is a very important aspect in mechanical design, and it is also used as an indicator for quality measurement of manufacturing processes, which is, in return, necessary for proper part geometries [2]. It was found that surface finish in turning is influenced by several factors such as feed, work material characteristics, workpiece hardness, coolants, cutting speed, depth of cut, tool nose radius and tool cutting edge angles [3]-[4].

The effect of cutting speed, feed, and depth of cut on attained surface roughness of machined work pieces have been investigated by many researchers [5]-[9]. Recent research works are focusing on hard machining as a valuable choice to expedite production process for machined parts. These studies aim to explore the effect of machining parameters on final product qualities. Unfortunately, limited numbers of these researches are available, which they proposed prediction models for machining hardened steel.

Özel and Karpat [10] had utilized neural network modeling to predict surface roughness and tool flank wear over the machining time for variety of cutting conditions in finish turning of hardened AISI H-13 and AISI 52100 steels. The predictive neural network model developed was able to predict tool wear and surface roughness patterns in finish finish turning of hardened steel processes.

Benardos and Vosniakos [11] presented various methodologies and practices that were employed for the prediction of surface roughness. The approaches listed in their review paper were classified into those based on machining theory, experimental investigation, designed experiments and artificial intelligence (AI).

Choudhury and El-Baradie [12] discussed the development of surface roughness prediction models for turning EN 24T steel (290 BHN) utilizing response surface methodology. A factorial design technique was used to study the effects of the main cutting parameters such as cutting speed, feed, and depth of cut, on surface roughness. The tests were carried out using uncoated carbide inserts without any cutting fluid. The results revealed that the response surface methodology combined with factorial design of experiments was a better alternative to the traditional one-variable-at-a-time approach for studying the

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effects of cutting variables on responses such as surface roughness and tool life.

Vivancos et al. [13] proposed a mathematical modeling of the surface roughness in high speed milling of hardened steels for injection moulds using design of experiments. The main considered variables that affected surface finish were spindle speed, feed per tooth (mm/z), axial depth of cut and radial depth of cut.

The aim of the present study is to present the influence of turning parameters (feed, cutting speed, and depth of cut) on surface finish of hardened AISI 1055 steel by using Taguchi techniques. Theses techniques present a plan of experiments to execute, collect data, in a controlled way, and analyze the data to get information about the manner of the process under study. Orthogonal arrays are used by these techniques to define the plans of experiment. Then, the analysis of average and the analysis of variance (ANOVA) is used to treat the experimental results [14]-[15].

II. EXPERIMENTAL SETUP

A. Materials

Specimens of medium carbon steel (AISI 1055) in the forms of bars were used. All specimens were flame hardened and the hardness was measured after heat treatment. The average hardness was 45 HRC through out the under surface hardness depth of 3.5 mm. The depth of cuts performed on the bars was not allowed to exceed the mentioned hardeness depth.

Table I shows the AISI 1055 chemical composition specified by the manufacturer. Each specimen used in the experimental work has a diameter of 42 mm and a length of 37 mm.

TABLE I
MEDIUM CARBON STEEL COMPOSITION (WT%)

C	Si	Mn	P	S	Cu	Cr	Ni
0.56	0.19	0.82	0.12	0.04	0.06	0.15	0.08

B. Equipments

The equipments used are listed bellow:

- The cutting inserts used were multi layer coated cemented carbide by (TiN-Al_2O_3-TiCN) from SANDVIK with a standard notation off TCMT 11 03 08-PF. Table II lists the cutting tool geometry. The selected cutting tool was based on the cutting tool manufacturer's manual [16].
- Tool holder with STJCR/L 1010K 11-S designation number based on the cutting tool manufacturer's manual [16].
- Heavy duty Colchester Master 2500 turning machine with 40 horse power.
- Digital surtronic 3P instrument for arithmetic average roughness-height (R_a)
- Cutting test was performed under dry cutting condition.
- Tinus-Olsen hardness testing machine.

TABLE II
CUTTING TOOL GEOMETRY

Insert shape	Clearance angle	Tolerance	Insert size (mm)	Insert thickness (mm)	Nose radius (mm)
Triangl.	7^0	±0.13	11	3.18	0.8

III. EXPERIMENTAL DESIGN

The aim of the experiments was to analyze the effect of turning parameters on the surface roughness of hardened AISI 1055 steel. Based on Taguchi principles, an L_{54} orthogonal array was set up. Table III shows the number and levels of control parameters used. The control factors (turning parameters) were within the range specified by manufacturer [16]. The length of cut was kept at 10 mm. The measurement of R_a was repeated twice, and finish turning was performed under dry cutting condition. On the other hand, each experiment was carried out with a fresh cutting tool in order to prevent the negative effect of tool wear on surface roughness.

TABLE III
CONTROL FACTORS LEVELS OF FINISH TURNING PROCESS

Code	Control factors	Levels		
		1	2	3
A	Depth of cut (mm)	0.4	0.8	1.2
B	Cutting speed (m/min)	40	98	177
C	Feed (mm/rev)	0.1	0.2	0.3

A. Taguchi Method:

In order to expedite the optimization process and pin point the optimal values of controlling factors, Taguchi method was implemented. Based on Taguchi methodology, the control factors were arranged in an orthogonal array, where each experimental trial performed was listed in a separate row. A loss function was used to quantify the characterized performance deviation from the required value. Having calculated the loss function it was later transformed into signal-to-noise ratio (S/N). The S/N was calculated based on equation 1 and indicates that the smaller is the better quality criteria. Table IV shows the orthogonal array with arranged control factors, the mean value of surface roughness from two measuring trials and calculated S/N.

The numbers 1, 2, and 3 mean the first level, second level, and third level of each control factor. In presented Taguchi trials, the greater contribution toward the reduction of surface finish was produced by the lower value of the S/N ratio. Surface roughness, in the current study, was the measured characteristic and the larger S/N the better is the surface roughness:

$$\zeta = -10\log_{10}\left(\frac{1}{m}\sum_{j=1}^{m} y_j^2\right) \tag{1}$$

Where :

ζ signal to noise ratio

m: number of repetitions

y_i :quality characteristic measured value

TABLE IV
L_{54} ORTHOGONAL ARRAY AND CALCULATED VALUES

	control factors						
Exp. No.	A	B	C	Ra(μm)	MSD	ζ	MRR(mm^3/min)
1	1	1	1	0.88	0.7744	-1.1	2392.38
2	1	2	1	0.81	0.6561	1.46	5861.33
3	1	3	1	1.03	1.0609	0.78	10586.29
4	1	1	1	1.34	1.7956	-1.1	2392.38
5	1	2	1	0.88	0.7744	1.46	5861.33
6	1	3	1	0.78	0.6084	0.78	10586.29
7	2	1	1	1.38	1.9044	-1.1	4769.52
8	2	2	1	0.58	0.3364	3.55	11685.33
9	2	3	1	0.72	0.5184	1.6	21105.14
10	2	1	1	0.81	0.6561	-1.1	4769.52
11	2	2	1	0.74	0.5476	3.55	11685.33
12	2	3	1	0.93	0.8649	1.6	21105.14
13	3	1	1	1.16	1.3456	-0.9	7131.43
14	3	2	1	0.89	0.7921	-1.8	17472
15	3	3	1	1.02	1.0404	-0.6	31556.57
16	3	1	1	1.05	1.1025	-0.9	7131.43
17	3	2	1	1.5	2.25	-1.8	17472
18	3	3	1	1.11	1.2321	-0.6	31556.57
19	1	1	2	2.19	4.7961	-7.1	4784.76
20	1	2	2	1.53	2.3409	-4.7	11722.67
21	1	3	2	1.66	2.7556	-4.5	21172.57
22	1	1	2	2.32	5.3824	-7.1	4784.76
23	1	2	2	1.89	3.5721	-4.7	11722.67
24	1	3	2	1.68	2.8224	-4.5	21172.57
25	2	1	2	2.35	5.5225	-9.7	9539.05
26	2	2	2	1.48	2.1904	-5.6	23370.67
27	2	3	2	1.67	2.7889	-5.6	42210.29
28	2	1	2	3.65	13.3225	-9.7	9539.05
29	2	2	2	2.25	5.0625	-5.6	23370.67
30	2	3	2	2.12	4.4944	-5.6	42210.29
31	3	1	2	1.88	3.5344	-5.8	14262.86
32	3	2	2	1.83	3.3489	-5.9	34944
33	3	3	2	2.35	5.5225	-6.6	63113.14
34	3	1	2	2.02	4.0804	-5.8	14262.86
35	3	2	2	2.12	4.4944	-5.9	34944
36	3	3	2	1.91	3.6481	-6.6	63113.14
37	1	1	3	4.94	24.4036	-14	7177.14
38	1	2	3	4.57	20.8849	-13	17584
39	1	3	3	2.84	8.0656	-12	31758.86
40	1	1	3	4.59	21.0681	-14	7177.14
41	1	2	3	4.25	18.0625	-13	17584
42	1	3	3	4.51	20.3401	-12	31758.86
43	2	1	3	4.83	23.3289	-13	14308.57
44	2	2	3	3.95	15.6025	-13	35056
45	2	3	3	4.1	16.81	-12	63315.43
46	2	1	3	4.52	20.4304	-13	14308.57
47	2	2	3	5.27	27.7729	-13	35056
48	2	3	3	4.24	17.9776	-12	63315.43
49	3	1	3	5.02	25.2004	-13	21394.29
50	3	2	3	4.61	21.2521	-12	52416
51	3	3	3	3.64	13.2496	-12	94669.71
52	3	1	3	4.23	17.8929	-13	21394.29
53	3	2	3	3.1	9.61	-12	52416
54	3	3	3	4.02	16.1604	-12	94669.71

IV. DATA ANALYSIS RESULTS AND DISCUSSION

A. Analysis of Variation (ANOVA)

Tables V and VI present the results of ANOVA analysis and indicate that feed was the most significant factor influence the surface finish followed by cutting speed ($P<0.01$). In addition, the most significant interaction between machining parameters on average S/N response for surface finish was between depth of cut and feed.

TABLE V
THE ANOVA ANALYSIS OF VARIANCE FOR S/N RATIOS

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	0.2507	0.2507	0.1254	0.57	0.573
B	2	2.3964	2.3964	1.1982	5.43	0.010
C	2	102.8362	102.836	51.4181	233.01	0.000
A*B	4	0.3878	0.3878	0.0969	0.44	0.779
A*C	4	0.8287	0.8287	0.2072	0.94	0.457
B*C	4	0.7714	0.7714	0.1928	0.87	0.492
A*B*C	8	1.2263	1.2263	0.1533	0.69	0.693
Error	27	5.9580	5.9580	0.2207		
Total	53	114.6554				

Table VI presents the S/N ratio factor response data of surface roughness for each of the three controlling factors at the three identified levels. Fig. 1 presents a plot of the resulted data tabulated in Table VI, where the optimal value of each controlling factor appeared to have the largest S/N ratio. For instance the optimal value of feed that provide best surface finish is at 0.1 m/rev with S/N equal to 0.219 (dB).

TABLE VI
RESPONSE TABLE FOR S/N RATIOS

Level	DOC(mm)	Speed(m/min)	feed(mm/rev)
1	-5.8959	-7.3284	0.2190
2	-6.2269	-5.6887	-6.1703
3	-6.5001	-5.6058	-12.6716
Delta	0.6043	1.7226	12.8906
Rank	3	2	1

The main effects plot shows that depth of cut is insignificant as the slope gradient is very small Fig. 1. From the same figure it is shown that feed is significant with the high gradient of the slope, while cutting speed is less significant than feed. However, based on the larger is the better characteristic; the analysis of variance for S/N ratio and Fig.1 propose that in order to achieve the best surface finish, the highest cutting speed (177 m/min) and lowest value of depth of cut (0.4mm) and lowest value of feed 0.1 (mm/rev) should be selected (A1B3C1). The results are supported by Davima et al. [17] similar findings.

Fig 2 shows significance and interaction between control factors. It is another way to represent ANOVA results appeared in Table V. The most significant combination influence on surface finish is depth of cut and feed (AC). Similar conclusions could be drawn by observing the surface plots of surface roughness with controlling parameters Fig. 3.

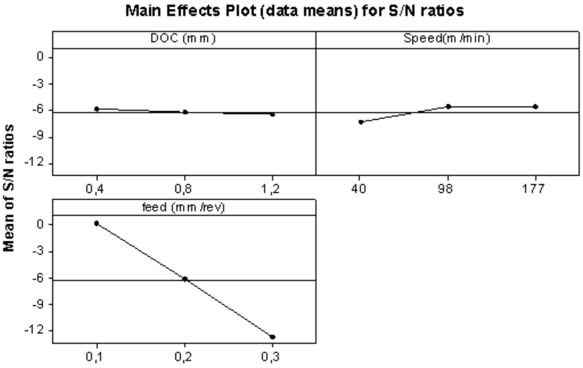

Fig. 1 Main Effect Plot for S/N Ratio

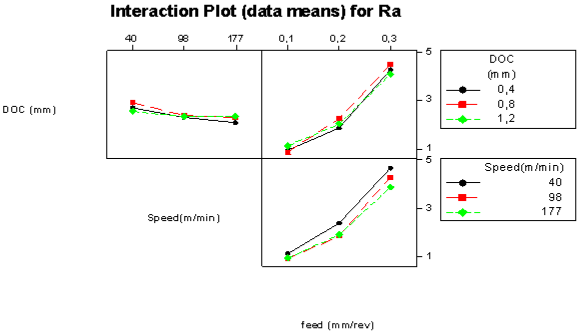

Fig. 2 Interaction Plot

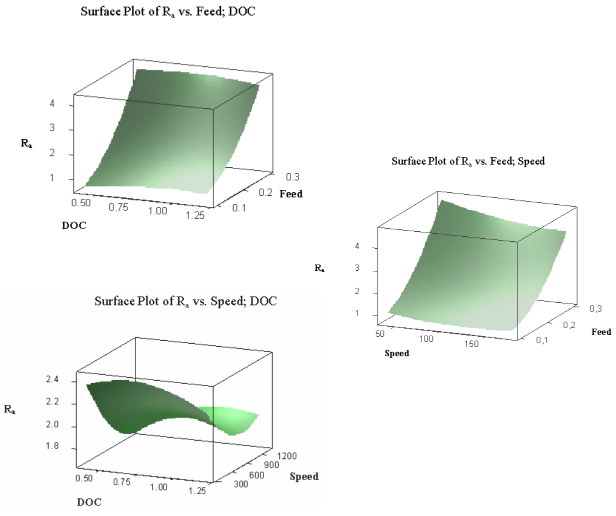

Fig. 3 Surface Plot of Surface Roughness vs. Controlling Parameters

B. Material Removal Rate (MRR)

Surface was measured using a Digital surtronic 3P instrument with a cut-off length of 2.0 mm and sampling length of 10 mm. The calculated metal removal rate (MRR) values are listed in Table IV. Table IV expresses the impact of different turning parameters on MRR and the best MRR conditions occur at experiment number 51, 54, 48, 45, 36 and 33. It is widely known that increasing depth of cut leads to increase metal removal rate. However, increasing depth of cut requires high cutting speed and slow feed.

C. Correlation

Multiple linear regression was implemented to obtain the correlation between the controlling factors (depth of cut, cutting speed, and feed) and the measured surface roughness.

The obtained equation was as follows:

$$R_a = 5.3\times10^{-2}D - 3.45\times10^{-3}V + 16.6F - 0.553, R = 87.9 \qquad (2)$$

where R_a denotes the arithmetic average roughness-height (μm), D the depth of cut (mm), V the cutting speed (m/min), F the feed (mm/rev), R the coefficient of regression.

D. Confirmation Experiment

Table VII shows the turning conditions, the results obtained from the confirmation test, the foreseen values calculated from the developed model [Eq. (2)], and the calculated error between both results. The mediated results presented in Table VII shows the calculated error (maximum 11.1% and minimum 8.5%). Therefore, Eq. (2) correlates the arithmetic mean surface roughness with the turning conditions (depth of cut, cutting speed, and feed) with a realistic degree of approximation.

TABLE VII
CONFIRMATION TURNING TESTS AND FORSEEN RESULTS

				Surface Roughness, R_a (μm)		
Test	D(mm)	V(m/min)	F(mm/rev)	Experiment	Model (Eq. 2)	Error (%)
1	0.6	60	0.25	3.79	3.42	9.7
2	0.8	80	0.18	1.98	2.20	11.1
3	1.0	140	0.1	0.74	0.68	8.5

V. CONCLUSION

The analyzed results from turning flame hardened medium carbon steel AISI 1055 with CVD ($TiN\text{-}Al_2O_3\text{-}TiCN$) coated cemented carbide inserts revealed the following conclusions:

- Taguchi is an efficient and systematic methodology for optimizing turning parameters and can be utilized rather than engineering judgment.
- Feed is the most influential controlling factor on surface finish variation followed by turning speed.
- The depth of cut was found to be insignificant on surface roughness.
- The most significant interaction among the analyzed interactions of controlling parameters was depth of cut/feed.
- The average surface roughness values R_a resulted from machining hardened medium carbon steel with ($TiN\text{-}Al_2O_3\text{-}TiCN$) coated cutting tools is about 2.44 μm and minimum value was 0.74 μm. The fluctuation of R_a values is explained by the fact that R_a depends on the turning parameters.
- Multiple regression produced a satisfactory correlation (87.9).
- The regression model [Eq. (2)] was able to predict values for surface roughness with reasonable degree of approximation.

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