SURFACE ROUGHNESS EVALUATION WHEN MACHINING CARBON STEEL WITH CERAMIC CUTTING TOOLS

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Abstract: The response surface methodology was adopted to investigate the effects of main cutting parameters such as cutting speed, feed rate, and depth of cut on the surface roughness when turning AISI 1050 carbon steel. Machining tests were carried out with uncoated ceramic (KY1615) and coated ceramic cutting tools (KY4400). Optimal machining conditions for the desired surface finish were determined. The adequacy of the second order developed model was analyzed by using analysis of variance. The experimental results indicated that the feed rate was the dominant factor, followed by the depth of cut. The cutting speed showed the minimal effect on the surface roughness. It could be seen that the KY1615 tool produced a better surface roughness than the KY4400 tool. It was shown that average surface roughness' of Ra values were about 2.515 µm, 2.984 µm for the KY1615, KY4400 cutting tools, respectively. Furthermore, the analysis of variance for the second-order model indicated that squares terms were significant on the roughness, but interaction terms of cutting parameters were insignificant for both cutting tools.

Key Words: Turning, ceramic cutting tool, carbon steel, surface roughness, response surface methodology.

Karbon Çeliğinin Seramik Kesici Takımlarla İşlenmesinde Yüzey Pürüzlülüğünün Değerlendirilmesi

Özet: AISI 1050 karbon çeliğinin tornalanmasında yüzey pürüzlülüğü üzerinde ana kesme parametreleri kesme, ilerleme miktarı ve talaş derinliğinin etkilerini araştırmak amacıyla yanıt yüzey tekniği benimsenmiştir. İşlenebilirlik deneyleri kaplamasız seramik (KY1615) ve kaplamalı seramik (KY4400) takımlarla yapılmıştır. İstenilen yüzey pürüzlülüğü için optimum kesme şartları tanımlanmıştır. Deneysel sonuçlarda ilerleme miktarı en etkin faktör iken bunu talaş derinliği izlemiştir. KY1615 takımların KY4400 takımlardan daha iyi yüzey pürüzlülüğü sağladığı görülmüştür. Ra yüzey pürüzlülük değerlerinin ortalaması KY1615 takım için 2.525 µm iken KY4400 takımlar için 2.984 µm'dir. Ayrıca, ikinci dereceden modellerin varyans analizleri terimlerin karelerinin yüzey pürüzlülüğü üzerinde etkili olduğunu göstermiş fakat kesme parametrelerinin etkileşim terimleri her iki kesici takım içinde anlamsız etki yaratmıştır.

Anahtar Kelimeler: Tornalama, seramik kesici takım, karbon çeliği, yüzey pürüzlülüğü, yanıt yüzey tekniği

1. INTRODUCTION

Ceramic cutting tools are widely used in metal cutting industry for cutting of various hard materials such as, alloy steel, bearing steel, white cast iron and graphite cast iron. The past few decades have witnessed great advancements in the development of these cutting tools. During machining, coated carbide/ceramic tools ensure higher wear resistance, lower heat generation and lower cutting forces, thus enabling them to perform better at higher cutting conditions than their uncoated counterparts (Sahin and Motorcu, 2005). Surface roughness and dimensional accuracy have been important factors to predict machining performance of any machining operation (Arbizu and Perez, 2003). In material removal processes, however, an improper selection of cutting conditions will cause to obtain surfaces with high roughness and dimensional errors. Therefore, a proper estimation of surface roughness has been the focus study of number of researchers in the past three decades. In order to determine the optimal cutting conditions reliable mathematical models have to be formulated to associate the cutting parameters with cutting performance. In literature, Response Surface Method (RSM) has been used by some researchers on the analysis of surface roughness due to its practical, and relatively easy

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for use (Feng and Wang, 2002; Hasegawa et al., 1976; Lambert, 1983; Mital and, Mehta, 1998;; Sata et al.,1985; Sundaram and Lambert, 1981; Petropoulos, 1974; Sahin and Motorcu., 2004a; Sahin and Motorcu, 2004b; Taraman, 1974). However, there were numbers of surface roughness prediction models produced by ceramic cutting tools on steels and other hard materials in literature (Darwish, 2001; Davim, 2001; Davim 2007; Escalona and Cassier, 1998; Kopac et al., 2002; Lee and Tarng, 2001; Lin et al., 2001; Sahin and Motorcu 2008; Suresh et al., 2002; Ozel and Karpat 2005; Yang et al., 1998). The most of the surface roughness prediction models given above are the Taguchi method or empirical while some of them are generally based on experiments in the laboratory (Choudhury and El-Baradie, 1997; Beauchamp, 1996; Chou and Song 2004; Grzesik and Wan 2006; Lima et al., 2005; Noordin et al., 2004; Motorcu, 2006).

The aim of the present study was, thus, to develop a mathematical model for the surface roughness prediction using the response surface methodology based on the main cutting parameters such as cutting speed, feed rate, depth of cut. The machining tests were carried out on AISI 1050 carbon steel with uncoated ceramic and coated ceramic cutting tools. Second-order predicting equation for the surface roughness was developed within ±5 % standard error. Furthermore, analysis of variance (ANOVA) was employed to investigate the cutting characteristics of steel bars.

2. EXPERIMENTAL WORK

2.1. Materials

The machine used for turning tests was a Johnford TC35 Industrial type of CNC lathe machine. The lathe equipped with variable spindle speed from 50 rpm to 3500 rpm, and a 10 KW motor drive was used for the tests. Cutting tools tested were mixed ceramic and coated ceramic tools. One of tools was a mixed ceramic with an Al_2O_3 (70%) +TiC (30%) matrix, which was designated by KY1615. The other inserts were coated using a Physical Vapour Deposition (PVD) method. Coating substance took place on the mixed ceramic substrate and TiN coated mixed ceramic with a matrix of Al_2O_3 (70%) +TiC (30%) +TiN, which was called as KY4400 grade. The insert type was TNGA 160408-KY1615 and TNGA 160408-KY4400. All tools were commercially available inserts according to ISO code. The cutting tools were supplied by Kennametal Inc. for the machining tests. The material used throughout this work was an AISI 1050 steel. The chemical analysis of AISI 1050 steel used in this study is presented in Table I. The steel bar stock was 40 mm diameter, 250 mm in length and these bars are machined under dry condition. The work material bars were trued, centered and cleaned by removing a 1 mm depth of cut from the outside surface, prior to the actual machining tests. The surface roughness of the carbon steel was measured by aid of a stylus instrument. The equipment used for measuring the surface roughness was a surface roughness tester, MAHR Perthometer-M1 type of portable. The surface roughness measured in the paper is the arithmetic mean deviation of the surface roughness of profile Ra. In collecting the surface roughness data of the shaft with the surface profilometer, three measurements are taken along the shaft axis for each sample.

Table I.
Chemical analysis of AISI 1050 steel

Elements	Wt.%	Elements	Wt.%	Elements	Wt.%
C	0,47	Si	0,176	Mn	0,658
P	0,0144	S	0,0053	Cr	0,0540
Mo	0,0250	Ni	0,133	Al	0,0201
Co	0,0193	Cu	0,169	Nb	<0,002
Ti	<0,001	V	<0,001	W	<0,005
Pb	<0,002	Sn	<0,0048	Mg	-
Sb	<0,002	Fe	98,24		

2.2. Experimental design

To develop a second-order model, a design consisting of 18 experiments was conducted. Details of the model and design are given elsewhere (Sahin and Motorcu, 2004; Motorcu, 2006). 18 experiments constitute 2^3 factorial designs with an added center point repeated four times, the added center point being used to estimate pure error. An augment length of 2 was chosen depending on the capacity of the center lathe. The augments point consists of three levels for each of the independent variables denoted by -2, -1, 0, +1, +2. Table II shows levels of independent variables.

Table II.
Levels of independent variables

Levels	Lowest	Low	Center	High	Highest
Coding number	-2	-1	0	+1	+2
Cutting speed, V (m/min)	306	408	510	612	714
Feed rate, f (mm/rev)	0.145	0.20	0.255	0.310	0.365
Dept of cut, d (mm)	0.43	0.57	0.71	0.85	0.99

3. RESULTS AND DISCUSSION

3.1. Analysis of experiments

The KY1615 and KY4400 cutting tools were used for these experimental results. Analysis of the influence of each independent variable on the surface roughness was performed with a Minitab computer package. Factorial design of experiments, cutting conditions and experimental results are given in Table III. Each coefficient was calculated and then formed the final linear regression Eq.(1) and (2), respectively. The positive value of the Ra from Eq.(1) shows an increase in roughness value while its negative value indicates a decrease in roughness value.

The second-order model was postulated in obtaining the relationship between the surface roughness and the machining independent variables.

Table III.
Experimental results produced by the KY1615, KY4400 cutting tools and their theoretical values with errors for the model

Trial Number	Experimental cutting conditions			Results					
				KY1615 cutting tool			KY 4400 cutting tool		
	V	f	d	Experimental Ra	Theoretical Ra-theo	Average error,%	Experimental Ra	Theoretical Ra-theo	Average error,%
1	408	0.200	0.57	1.449	1.459	0.69	1.893	1.902	0.84
2	612	0.200	0.57	1.478	1.498	1.35	1.93	1.945	0.48
3	408	0.310	0.57	3.409	3.561	4.46	4.053	4.095	1.07
4	612	0.310	0.57	3.416	3.570	4.51	3.835	3.944	2.83
5	408	0.200	0.85	1.490	1.473	1.14	1.952	1.916	1.78
6	612	0.200	0.85	1.502	1.488	0.93	1.94	1.970	1.55
7	408	0.310	0.85	3.527	3.645	3.35	4.16	4.229	1.55
8	612	0.310	0.85	3.503	3.630	3.63	4.036	4.088	1.43
9	306	0.255	0.71	2.297	2.234	2.74	2.909	2.896	0.26
10	714	0.255	0.71	2.333	2.258	3.21	2.867	2.795	2.30
11	510	0.145	0.71	1.089	1.158	6.34	1.445	1.472	1.84
12	510	0.365	0.71	5.609	5.402	3.69	5.883	5.783	1.70
13	510	0.255	0.43	2.384	2.285	4.15	2.78	2.729	1.86
14	510	0.255	0.99	2.396	2.358	1.59	2.909	2.887	0.75
15	510	0.255	0.71	2.354	2.314	1.70	2.776	2.764	0.55
16	510	0.255	0.71	2.339	2.314	1.07	2.76	2.764	0.02
17	510	0.255	0.71	2.343	2.314	1.24	2.794	2.764	1.20
18	510	0.255	0.71	2.356	2.314	1.78	2.786	2.764	0.91
				Absolute average error, %		2.64	Absolute average error, %		1.18

The model equation for the surface roughness of the Ra prediction value for the KY1615 tool is derived from the data shown in Table III and given by;

$$R_a = 2.185 + 0.002349 * V - 22.407 * f - 0.3729 * d - 0.0000001.V^2 + 79.8898 * f^2 + 0.0978 * d^2 - 0.0013 * V * f - 0.0004 * V.d + 2.2727 * f * d \quad (1)$$

Eq.(1) indicates that the feed rate has the most significant effect on the surface roughness of sample when using ceramic tools. The correlation coefficient R^2 is very close to unity (99.2%), which shows the high correlation that existing between the experimental and predicted values. This shows that the second order model can be explained the variation to the extent of 99.2%.

The model equation for the surface roughness of the Ra prediction for the KY4400 tool is given by;

$$R_a = 2.9953 - 0.0007 * V - 15.5138 * f - 1.7599 * d + 0.00000001 * V^2 + 71.6198 * f^2 + 0.6008 * d^2 - 0.0082 * V * f + 0.0004 * V * d + 3.8799 * f * d \quad (2)$$

The model has an adjusted R^2 value of 99.5 %, standard error for the surface roughness is about 0.157. Interactions of V*d and V*f in the range given in Eq. (2) had no significant effect on the surface roughness while the interaction of f*d had a slight effect on it.

3.2. Effect of too type

The effect of cutting tool's type on the surface roughness in machining the AISI 1050 steel was investigated, as shown in Fig.1. The surface roughness was produced by the KY1615, KY4400 cutting tools under different conditions. A comparison was made between these two types of cutting tools. It can be seen in Fig.1 that the KY1615 tool produced a better surface roughness value than that of the KY4400 tool for all experimental conditions. KY1615 tool is uncoated and it has sharper edge.

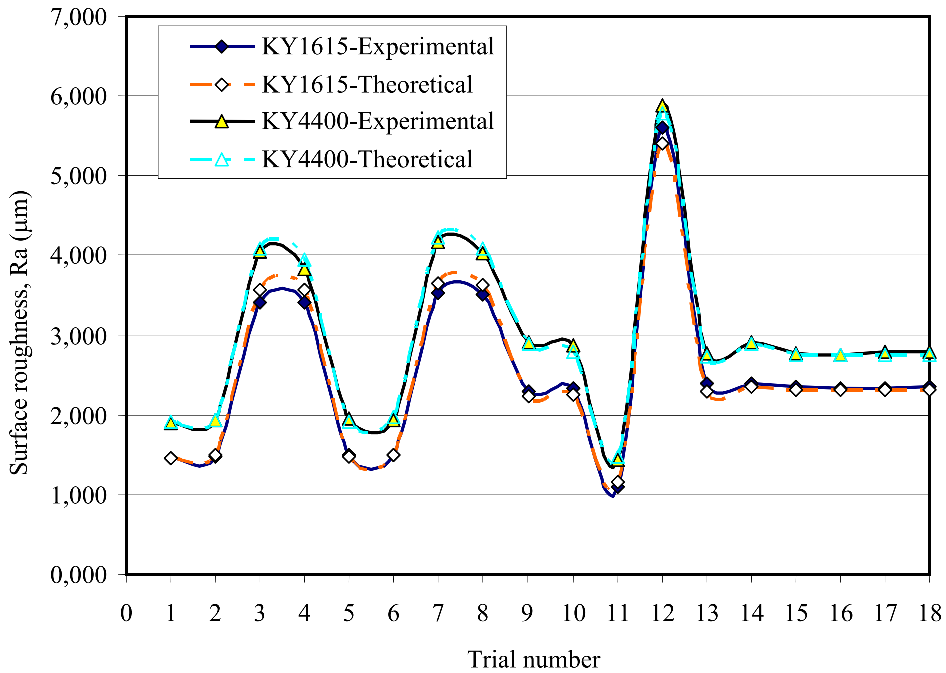

Figure 1:
Effect of cutting conditions on the average surface roughness of Ra produced by two ceramic cutting tools

On the other hand, coating layer was removed from the substrate material when the KY4400 coated cutting tool was used. It is confirmed that the KY1615 tool was more appropriate than that of the KY4400 tool when machining the steel. For example, the average surface roughness' of Ra values were about 2.515 μm, 2.984 μm for the KY1615, KY4400 cutting tools, respectively. This study showed that it was appropriate when machining the carbon steel with ceramic based cutting tools under high speed conditions. But, these values are a little bit high.

The experimental results and their theoretical values are shown in Fig.1 and Table III. As shown in this figure, some differences between the calculated and actual values of the surface roughness' can be seen, but both values for the KY1615, KY4400 cutting tools are within a reasonable limit. For example, absolute average error was about 2.64% for the KY1615 cutting tool, but the average error was about 1.18% for the KY4400 cutting tool. Thus, the results indicate that the model constructed using the multiple regression analysis can be used to provide accurate prediction of the surface roughness in machining the steels within ±5%.

3.3. Analysis of Variance (ANOVA)

The ANOVA was used to investigate which design parameters significantly affected the cutting characteristics of the steels. Examination of the calculated values of variance ratio (F) which is the variance of the factor is divided by the error variance for all independent variables. The result of the analysis of variance for the second-order model is shown in Table IV. This analysis is carried out for a level of significance of 5% i.e., for a level of 95%. From the analysis of Table IV, it was apparent that the F calculated value was greater than the F table value (F 0.05, 9, 8=3.39) except for interaction effects. Thus, the second order developed model was quite adequate. Furthermore, this table showed that quadratic terms were significant for this model, but the interaction terms of cutting parameters were not significant on the surface roughness of the Ra value produced by KY1615 cutting tool. Table IV shows the result of the analysis of variance for the second order model of the Ra equation in machining the steel with the KY4400 cutting tool.

The same table indicated that the quadratic effects were significant on the surface roughness for both equations, but the interaction terms were not significant on the surface roughness of the tested steels. Previous work carried out by Sahin and Motorcu (2005) showed that first order effect of feed rate and cutting speed was significant while depth of cut was insignificant. The ANOVA for the second order model exhibited that interaction terms and square terms were statistically significant while cutting speed and depth of cut was insignificant for turning AISI 1040 steel with PVD-coated ceramic tool (Sahin and Motorcu, 2004a, 2004b). However, interaction of feed rate and tool's nose radius produced statistically significant impact on the surface roughness when machining AISI 4140 alloy steel with CVD-coated cutting tools (Sahin and Motorcu, 2004b). In their work, a better surface finish was obtained with these CVD-tools than those of the ceramic cutting tools used for the present work. This might be due to selecting lower cutting conditions and more appropriate for machining the steel with coated carbide tool in previous study. Although the higher cutting condition was used for machining the carbon steel by ceramic based cutting tool, higher surface roughness was obtained for current work due to related to chip curvature of the tested material. Higher cutting speed resulted in softening the steel. Therefore, plastic deformation ability of the steel increased and the chip curvature decreased due to high speed for machining the steel by ceramic tool. For the carbide tool, however, the steel did not very softened as much as ceramic tool since the cutting speed was lower. However, Kopac et al., (2002) found that the surface roughness decreased with an increase in cutting speed.

4. CONCLUSIONS

The RSM was adopted to investigate the effects of machining factors such as cutting speed, feed rate, and depth of cut on the surface roughness when turning the AISI 1050 carbon steel. The feed rate was the dominant factor, followed by the depth of cut. The cutting speed showed the minimum effect on the surface roughness. Furthermore, it could be seen that the KY1615 cutting tool produced a better surface roughness than that of the KY4400 tool. The average surface roughnesses of Ra values were about 2.515 μm, 2.984 μm for the KY1615, KY4400 cutting tools, respectively. It was found that it was appropriate when machining the mild steel with ceramic based cutting tools under high speed conditions. Moreover, the ANOVA showed that the quadratic effects were significant on the roughness while the interactions terms of cutting parameters were statistically insignificant for both cutting tools.

Table IV.
Analysis of variance for machining the AISI 1050 steels by the KY1615 and KY4400 cutting tools

Source	Degree of free-dom (DF)	Sum of squares (SS)	Mean squares (MS)	F statistic	Contribution, % (P)
K1615 cutting tool					
Regression	9	19.578	2.175	115.19	0.000
Linear	3	18.015	6.005	317.98	0.000
Squares	3	1.559	0.519	27.53	0.000
Interaction	3	0.003	0.001	0.06	0.981
Residual	8	0.151	0.018		
Lack of fit	5	0.150	0.030	430.96	0.000
Pure error	3	0.0002	0.00007		
Total	17	19.729			
K4400 cutting tool					
Regression	9	19.777	2.1974	400.83	0.000
Linear	3	18.6221	6.20738	1000	0.000
Squares	3	1.1306	0.37687	68.74	0.000
Interaction	3	0.0242	0.00808	1.47	0.293
Residual	8	0.0439	0.00548		
Lack of fit	5	0.0432	0.00864	40.26	0.006
Pure error	3	0.0006	0.00021		
Total	17	19.820			

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