

Feed rate affecting surface roughness and tool wear in dry hard turning of AISI 4140 steel automotive parts using TiN+AlCrN coated inserts

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Abstract. This work aims to investigate the effects of feed rate on surface roughness (Ra) and tool wear (VB) and to obtain the optimal operating condition of the feed rate in dry hard turning of AISI 4140 chromium molybdenum steel for automotive industry applications using TiN+AlCrN coated inserts. AISI 4140 steel bars were employed in order to carry out the dry hard turning experiments by varying the feed rates of 0.06, 0.08 and 0.1 mm/rev based on experimental design technique that can be analyzed by analysis of variance (ANOVA). In addition, the cutting tool inserts were examined after machining experiments by SEM to evaluate the effect of turning operations on tool wear. The results showed that averages Ra and VB were significantly affected by the feed rate at the level of significance of 0.05. Averages Ra and VB values at the feed rate of 0.06 mm/rev were lowest compared to average values at the feed rates of 0.08 and 0.1 mm/rev, based on the main effect plot.

1. Introduction

Conventionally, hard turning is one of the most widely used machining processes in various industries such as electronics, automotive, and aerospace. In the automotive industry, surface quality and accuracy characteristics of machined parts using computer numerical control has increased production costs. This is uneconomical for manufacturing industries that utilize extensive machining operations [1]. Hard turning provides relatively high accuracy for a variety of parts, but sometimes problems arise with the quality of the surface finish under different cutting operating conditions and different cutting tools [2]. The turning processes with hardness values higher than 45 HRC use various cutting tools such as cemented carbide inserts, polycrystalline cubic boron nitride (PCBN), cubic boron nitride (CBN), and ceramic tools [3,4]. Sahoo and Sahoo [5] investigated the machinability performance of AISI 4340 grade steel of different hardness using uncoated, multilayer TiN, and ZrCN coated inserts at high cutting speeds. They also studied hard turning of AISI H13 steel using CBN insert tools and predicted surface roughness and tool wear [6]. Chincharikar and Choudhury [7] explored the effect of workpiece hardness and types of coated carbide tools on different machinability, tool life, and surface roughness during the turning of hardened AISI 4340 steel. Krolczyk et al. [8] studied the effect of cutting speed on the geometrical parameters of surface integrity after turning operation of duplex stainless steel with coated sintered carbide wedges. Lin et al. ([9] investigated the performance of TiN, TiAlN and AlCrN coated inserts on tool life and wear resistance under dry and wet turning operations at very high cutting speeds. They found that AlCrN can achieve higher performances of tool life and wear resistance than TiN and TiAlN coated inserts. Chandiran et al. [10] also performed a comparative study on tool life and wear resistance of TiN and AlCrN coated inserts under high cutting speed and



feed rate in various turning conditions using design of experiments (DOE) and response surface methodology (RSM). They stated that AlCrN has better performance than TiN. The aim of this study was to investigate the effects of feed rate on average Ra and VB values in turning operation of AISI 4140 with TiN+AlCrN coated insert using DOE and main effect plot in order to obtain the appropriate feed rate with low Ra and VB.

2. Experimental methodology

In this work, workpiece materials were AISI 4140 chromium molybdenum steel bars with an average hardness of 58 HRC used for producing automotive parts. Chemical composition of workpiece material consisted of 0.47% C, 1.05% Cr, 0.2% Mo, 0.0042% V, 0.012% Al, 0.01% P, 0.01% S, 0.26% Si, 0.67% Mn and 0.19% Cu. An automotive part as a workpiece material was machined with turning operations of four different diameters. Fanuc CNC lathe machine (Takisawa: model NEX-106) was used to carry out the turning experiments with TiN+AlCrN coated inserts for the surface finish. The physical and mechanical properties of the coated insert included hardness of 94 HRA, transverse rupture strength of 0.9 GPa, modulus of elasticity of 400 GPa, and surface roughness of 0.101 μm . Turning experiments were conducted at three different feed rates of 0.06, 0.08 and 0.1 mm/rev while the cutting speed and depth of cut were kept constant at 220 m/min and 0.1 mm, respectively. Figure 1 shows the experimental setup for turning operation dealing with customer desired value of Ra less than 0.8 μm . The Ra values of workpieces produced during these experiments were assessed with a commercial surface roughness tester machine (Germany, Mahr model: MarSurfPSI) with a cut-off length of 0.8 mm and sampling length of 5 mm. A completely randomized experiment with three levels of feed rate and three replicates was run in order to investigate the effect of feed rate on Ra and VB. The statistical model for one-way ANOVA was used to investigate the effect of feed rate on average Ra and VB at the level of significance of 0.05.

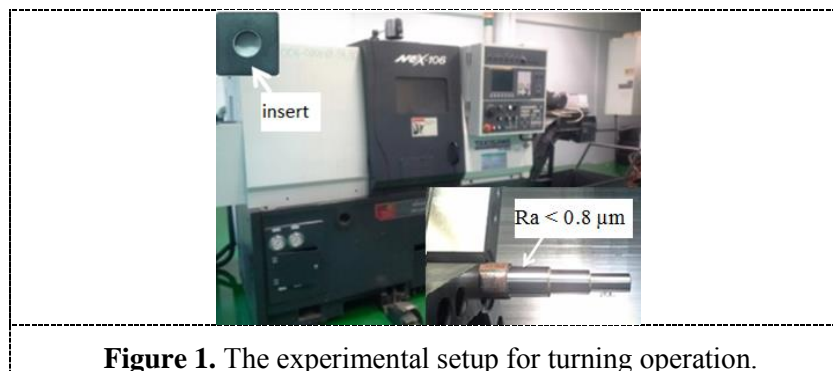


Figure 1. The experimental setup for turning operation.

3. Results and discussion

Experimental matrix and results of Ra and VB values when turning AISI 4140 steel bar with TiN+AlCrN coated inserts after machining time of 32 min are shown in Table 1.

Table 1. Experimental matrix and results for feed rate affecting Ra and VB.

Run order	Feed rate (mm/rev)	Ra (μm)	VB (μm)
8	0.06	0.768	48
2	0.06	0.788	53
6	0.06	0.747	36
9	0.08	1.025	158
1	0.08	1.079	192
3	0.08	0.886	133
7	0.10	0.896	139
4	0.10	0.909	148
5	0.01	0.946	180

According to the results of Ra and VB values from Table 1, Figures 2(a) and (b) show the scatter plots of Ra versus VB and VB versus Ra, respectively. These revealed that there was a correlation between the two responses. This indicated that Ra and VB depended on tool performance. This also implied that Ra of the machined part increased with increasing VB of the coated insert. Hence the TiN+AlCrN coated inserts should be investigated for machined part surface and tool life improvements. Before performing ANOVA, the data set of Ra and VB values should be tested whether they distribute as normality. The probability plot was used to display the data points, fitted line of the data points and associated confidence intervals (C.I.) based on parameters estimated from the data sets along with an Anderson-Darling (AD) goodness-of-fit statistic and associated p -value [11]. Figures 3 (a) and 4 (a) show probability plots of Ra and VB, respectively. The probability plots reveal that the plotted points of the complete data set of Ra roughly form a straight line and fall within the 95 % confidence interval. In addition, AD statistics of both data sets were small with high p -values compared to the level of significance of 0.05. This confirmed that normal probability distribution fitted the data sets of the Ra and VB values well.

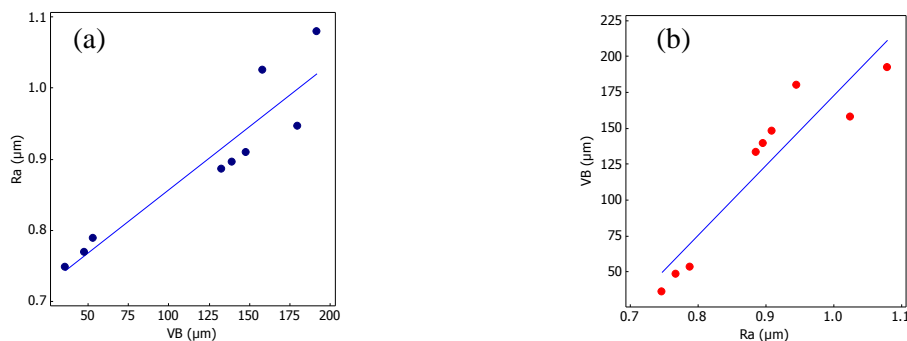


Figure 2. (a) Scatter plot of Ra versus VB values and (b) Scatter plot of VB versus Ra values.

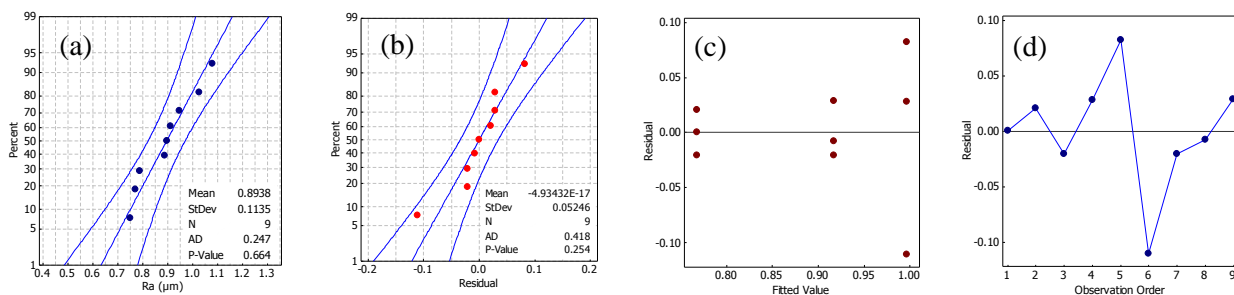


Figure 3. (a) Probability plot of Ra value and model adequacy checking for Ra (b) normal probability residual plot (c) residual versus fitted value and (d) residual versus run order.

Additionally, the adequacy of the underlying model should be checked. The primary diagnostic tool is residual analysis. Figures 3 (b) and 4 (b) illustrates normal probability plots of residuals. If the underlying error distribution is normal, this plot will resemble a straight line [11]. Clearly, the normal probability plot of residuals for Ra did not indicate anything particularly troublesome, although some residuals upward slightly on the left side. The normal probability plot of residuals for VB did not indicate problem of normality. If the model is adequate and the assumption is satisfied, the residuals should be structureless. The residuals should be unrelated to any other factors including the fitted values. A plot of residuals versus fitted values is used to check nonconstant variance. Nonconstant variance arises if the plot look like an outward-opening funnel or megaphone. Figures 3(c) and 4(c) b. do not show violation of the assumption of homogeneity of variances. Figures 3 (d) and 4(d) exhibit the validity of the independence assumption of model. The model adequacy checking indicated that the one-way ANOVA model was effective for investigating the effects of feed rate on Ra and VB.

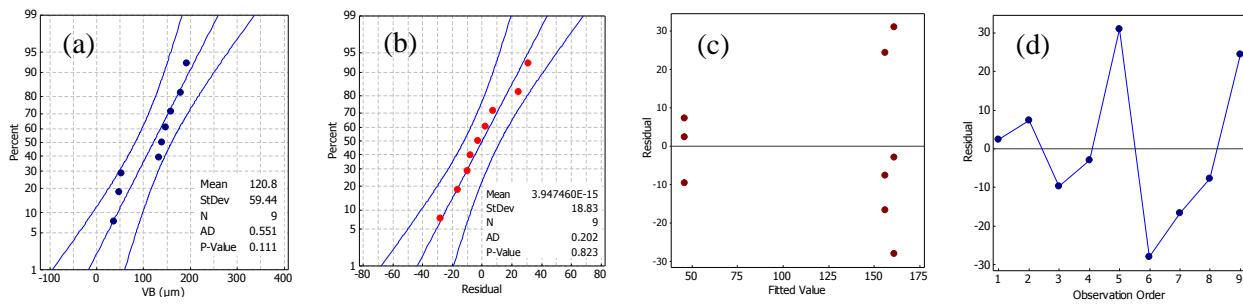


Figure 4. (a) Probability plot of VB value and model adequacy checking for VB (b) normal probability residual plot (c) residual versus fitted value and (d) residual versus run order

The results in Tables 2 and 3 were analyzed with ANOVA, which is employed for investigating the effect of factor feed rate on responses Ra and VB, respectively. Table 2 shows that the model F -value of 11.05 with a small p -value is adequate with a coefficients of determination (R^2) of 0.7865 which define as the ratio of the explained variation to the total variation and is a measure of the degree of fit. The adjusted R^2 of 0.7153 and predicted R^2 of 0.5196 are in reasonable agreement in which the difference between the two values is less than 0.2. This concluded that the feed rate significantly affected the mean Ra at the level of significance of 0.05. This result agrees with the previous research works [12,13]. Wang et al. [13] reported that the effects of feed rate and interaction between feed rate and cutting speed were statistically significant to mean Ra based on ANOVA results. Table 3 also shows that the model F -value of 26.91 with very small p -value is adequate with high R^2 of 0.8997, adjusted R^2 of 0.8663 and predicted R^2 of 0.7743. This also concluded that the feed rate significantly affected the mean VB at the level of significance of 0.05. This result also agrees with [12].

Table 2. ANOVA table for Ra during turning operation with coated insert TiN+AlCrN

Source	Df	SS	MS	F -value	p -value
Model	2	0.08129	0.04054	11.05	0.009
Feed rate	2	0.08129	0.04054	11.05	0.009
Error	6	0.02202	0.00367		
Total	8	0.10310			
PRESS = 0.05 $R^2 = 0.7865$ Adj. $R^2 = 0.7153$ Pred. $R^2 = 0.5196$					

Table 3. ANOVA table for VB during turning operation with coated insert TiN+AlCrN

Source	Df	SS	MS	F -value	p -value
Model	2	25430.22	12715.11	26.91	0.001
Feed rate	2	25430.22	12715.11	26.91	0.001
Error	6	2835.33	472.56		
Total	8	28265.56			
PRESS = $R^2 = 0.8997$ Adj. $R^2 = 0.8663$ Pred. $R^2 = 0.7743$					

The main effect plot is a plot of the averages at each level of a factor. A main effect occurs when the average response changes across the levels of a factor. The main effect plot is used to compare the relative strength of the effect of the factor. Although this plot is useful to compare main effect, the ANOVA table is a primary tool used to significantly evaluate the effect of the factor. The main effect plot illustrated in Figure. 5(a) proves that the Ra value was the lowest at the feed rate of 0.06 mm/rev whereas the VB value was also the lowest at the feed rate of 0.06 mm/rev as illustrated in Fig. 5(b). Hence the appropriate feed rate of 0.06 mm/rev has the lowest Ra and VB.

Figure 6 show SEM micrographs of wear on the TiN+AlCrN coated insert during machining of AISI 4140 chromium molybdenum steel bar at the feed rate of 0.06 mm/rev after a cutting time of 32 min. Micro-wear behaviors observed during the experiments through SEM micrographs included edge chipping, micro abrasion on the TiN+AlCrN coated insert. Heat energy and workpiece temperature

highly increased resulting the cutting edge lost shapes leading to plowing of chips from workpiece on shear plane and flank wear land heat sources.

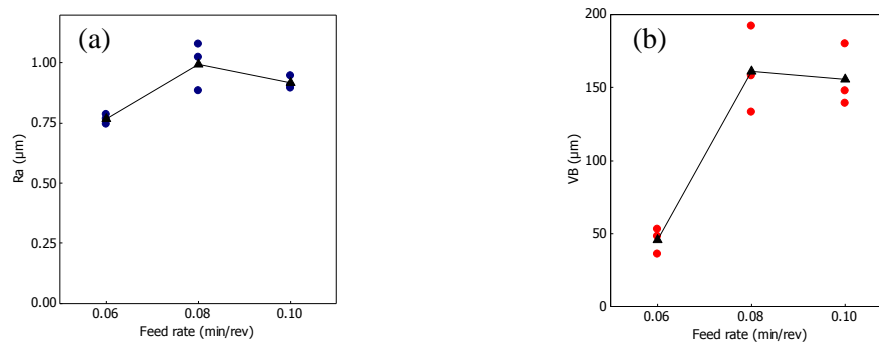


Figure 5. Ra and VB as the function of feed rate for the coated insert TiN+AlCrN.



Figure 6. SEM images of the wear of TiN+AlCrN (a) before and (b) after machining.

4. Conclusion

Feed rate significantly affected the averages Ra and VB values at the level of significance of 0.05 based on the results of analysis of variance. Ra and VB values increased when feed rate increased. The appropriate feed rate of 0.06 mm/rev has the lowest Ra and VB. SEM micrographs indicated edge chipping, micro abrasion on the TiN+AlCrN coated insert.

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