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Effect of Machining Parameters on Surface Finish and Noise Patterns for Machining EN-19 Steel with PVD-TiN Coated Mixed Ceramic Inserts in CNC Turning Operation

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This paper presents a relationship between the surface finish, machining conditions and the noise level generated by the turning operation for machining of EN-19 alloy steel using PVD-TiN coated mixed ceramic (Al_2O_3+TiCN) inserts on a CNC turning centre under wet lubrication conditions. The machining parameters considered in this study include cutting velocity, feed rate and depth of cut. The levels of machining parameters for the experimental investigation are determined using full factorial experiment model and ANOVA is applied to find the effect of machining parameters on surface roughness. Additionally, noise generated during the cutting operation for all set of experiment trials is recorded to determines the relationship between machining conditions and the surface finish.

Keywords: CNC turning, Surface finish optimization, Frequency spectrum analysis

Introduction

Surface finish of a machined part is an important parameter[1,2,3] which affects its wear rate, corrosion resistance, and tribological properties. CNC machining centers have the ability to machine parts with utmost presicion, accuracy and reliability in terms of the surface finish. To perform high speed machining operations on hard to cut materials, one must establish the optimum machining conditions[4] in terms of machining speed, feed and depth of cut[5,6,7] to ensure achievement of desired surface finish with minimum machining time. At the same time the machining noise[8] is also an important parameter which can be used as an indicator of the machining output in terms of surface finish. In the present work, high speed turning[9] of hardened EN-19 alloy steel has been studied for machining with PVD-TiN coated Al_2O_3+TiCN mixed ceramic inserts under wet machining conditions. The paper is organized as follows: Section 2 presents the materials and methods, results and discussions are presented in Section 3 and finally, the conclusions drawn from the presented work are given in Section 4.

Materials and Methods

Sample Preparation

The work pieces used in this study were round bars of 40 mm diameter and length 110 mm of EN-19 alloy steel. The chemical composition of the workpiece samples (measured with the spectrometer Foundry Master) by weight percentage is Fe (97.3), C (0.4), Si (0.26), Mn (0.57), P(0.03), S(0.19), Cr (0.90), Mo (0.19), Ni (0.16), Co (0.01), Cu (0.05), Pb (0.02), Sn (0.03), B (0.02) and V (0.04). The measured physical and mechanical properties of the workpiece samples are: Density (7.85 g/cm^3), Melting point (1416°C), Yield Stress (700 N/mm^2 (min.)), Max Stress (850-1000 N/mm^2), 0.2% Proof Stress (680 N/mm^2 (min)), Impact KCV(55 Joules (min)), Elongation (9% (min)), Hardness (248-302 HB). The sample work pieces were heat treated at 900°C followed by oil quenched to achieve hardness of 50 HRC. Thereafter, tempering of the work piece samples were carried out at 400ºC to eliminate the residual stresses and to achieve homogeneous grain structure before conducting the machining operations. The workpiece hardness was verified after heat treatment operations and it was ensured that the hardness level of 50 HRC is achieved in all test specimens. As a next step, all specimen pieces were pre-machined to remove the oxide layers before

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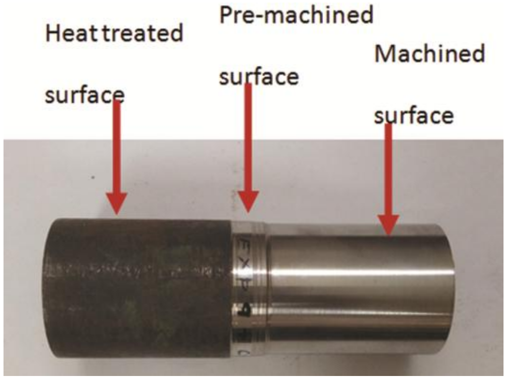

Fig. 1(a) — Sample workpiece specimen

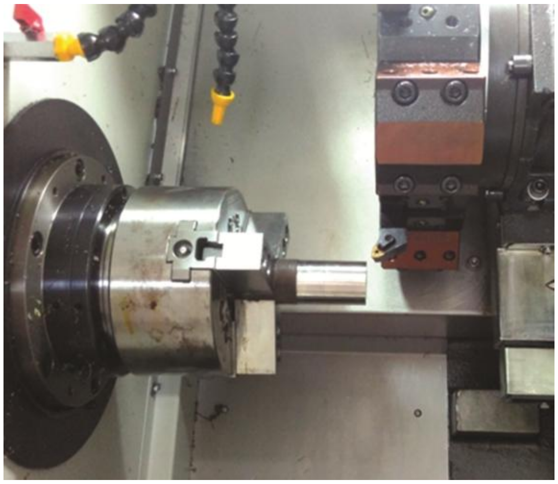

Fig. 1 (b) — Machining zones

starting the actual machining experiments, as seen in figure. 1(a).

Tool material and machining setup used

The Al_2O_3-TiCN mixed ceramic inserts (Model: TNGA 160408S01525; Grade 6050) with TiN coating formed by PVD having the nose radius of 0.8 mm are used in the machining experiments.The ISO designation of the selected inserts is TN1604. The selected inserts are chemically inert, stable and heat resistant which make these suitable for elevated temperatures encountered during machining of hard materials. These inserts were mounted on a -93° cutting angle tool holder (Model: MT JNL 2525-M16) to load them on ATC to ensure the safety and achieve the desired machining performance during CNC turning operation. The turning operations were performed on an 8-station ATC CNC turning centre with self centring three jaw hydraulic chuck and spindle speed range of 150–6000 RPM (Model: MAXTURN PLUS+). All the turning operations were performed under wet lubricant condition using a water soluble cutting fluid (Product code: HocutB50S general purpose semi-synthetic metal working coolant). The machining zone is shown in figure. 1(b).

Table 1 — The levels of machining parameters used

Variable parameters	Levels 1	2	3
$\boldsymbol{v}$ (m/min)	160	170	180
$\boldsymbol{f}$ (mm/rev)	0.025	0.050	0.075
$\boldsymbol{d}$ (mm)	0.15	0.20	0.25

Measurement of surface roughness

The average surface roughness R_a is used in this work as an indicator of quality of surface of the turned part. The surface roughness values were monitored for all machined samples using Mitutoyo SJ-400 surface roughness tester having minimum resolution of 0.000125μm (8μm range). The surface roughness R_a measurements were determined at three different locations on each of the turned workpiece sample and the mean of these average surface roughness values has been used as the value of the response parameter.

Measurement of sound level and frequency spectrum

The sound levels and frequency spectra were monitored for each machining pass in the turning operations using a Type-1 sound level meter (SLM) (Model: SC310, Make: CESVA). Background correction was applied to the measured values of sound level to eliminate the influence of background noise on the observed machining results. For monitoring the sound level and the frequency spectrum, the sound level meter was placed at a distance of 1.0 m from the cutting zone.

Design of Experiments

The 'design of experiments'[7] chosen for the study is a full factorial design with 3 factors at 3 levels each. The variables used in the present study are cutting velocity (v), feed (f) and depth of cut (d). The range of these parameters used in the present work is given in table 1. The surface roughness (R_a) and sound pressure levels are the measured responses. Table 2 shows the complete scheme of design of experiments used in the study along with the recorded values of response parameters. In this work a total of 27 sets of turning experiments were performed on the CNC turning center. A few pilot experiments were conducted prior to actual experiments to ensure the consistency of the measured parameters and to mitigate the effect of errors in measuring instruments. It was ensured during all experiments that there were

Table2 — Values of average surface roughness ($\boldsymbol{R_a}$) and equivalent sound level in A-weighting as well as Z-weighting scale used for the full factorial design of experiment

S.No.	Speed (m/min)	Feed (mm/rev)	DOC (mm)	R_a (μm)	L_A (db)	L_Z (db)
1	160	0.025	0.15	0.39	77.6	82.9
2	160	0.05	0.15	0.62	80.4	83.8
3	160	0.075	0.15	0.89	77.2	82.2
4	170	0.025	0.15	0.25	75.2	81.9
5	170	0.05	0.15	0.51	77.2	81.9
6	170	0.075	0.15	0.7	77.7	82.5
7	180	0.025	0.15	0.31	76.2	80.9
8	180	0.05	0.15	0.47	77.4	83.1
9	180	0.075	0.15	0.36	77.9	81.7
10	160	0.025	0.2	0.25	76.8	80.1
11	160	0.05	0.2	0.69	77.8	83.4
12	160	0.075	0.2	0.81	76.7	81.9
13	170	0.025	0.2	0.3	77.0	82.4
14	170	0.05	0.2	0.53	78.1	84.7
15	170	0.075	0.2	0.63	79.0	88.9
16	180	0.025	0.2	0.27	78.2	82.9
17	180	0.05	0.2	0.39	83.6	84.7
18	180	0.075	0.2	0.27	78.9	84.4
19	160	0.025	0.25	0.4	77.2	80.6
20	160	0.05	0.25	0.61	77.6	83.0
21	160	0.075	0.25	0.8	75.9	83.1
22	170	0.025	0.25	0.2	77.6	82.6
23	170	0.05	0.25	0.42	78.9	84.2
24	170	0.075	0.25	0.59	79.8	86.8
25	180	0.025	0.25	0.28	78.1	82.7
26	180	0.05	0.25	0.37	78.7	84.4
27	180	0.075	0.25	0.16	78.7	87.3

no other major sources contributing to the ambient noise levels around the machining area before and during actual machining operations to ensure the consistency of the recorded sound levels. Moreover, each machining operation was performed for 30 seconds duration to ensure the elimination of any errors in the measured noise levels. Thus the length of cut for different sets of turning operation varied by virtue of the change in feed rate and the spindle rpm used in the respective experimental trial. The coolant flow rate during turning operation was maintained at 0.025 m^3/min for all set of experiments while the temperature of the cutting oil was maintained at room temperature around 24^{o}C.

Results and Discussion

After the turning operation, the surface finish R_a values for each of the machined sample was monitored using Mitutoyo SJ-400 surface roughness tester. After the measurements of surface finish and noise levels for all 27 set of turning operations, the effect of the different operating parameters on the sound level obtained along with the surface finish achieved was studied. The following section presents a detailed discussion about the major observations noted from the analysis of the measured data.

Surface roughness analysis

The measured surface roughness values were analysed using the MINITAB software. Analysis of variance (ANOVA)[10] for mean of surface roughness R_a and F-test were used to analyse the measured data. The analysis of variance was done at significance level of α = 0.05. The p-values and F-values for each factor as observed from the full factorial design of experiments are given in Table 3.

The regression equation developed for average surface roughness R_a as the response, is given as:

$$R_a = -3.15 + 0.0192v + 96.8f + 7.16d \\ - (0.510v \times f) - (22.0f \times d) \\ - (0.04v \times d)$$

The value of $R^2 = 90.8\%$ and $R^2(adj) = 88.0\%$

Table 3 — Analysis of Variance for surface roughness ($\boldsymbol{R_a}$)

Source	Degree of freedom	Sequential Sum of Squares	Adjusted Mean Square	F value	p-value
v	2	0.369919	0.184959	87.92	< 0.0001
f	2	0.398341	0.199170	94.68	< 0.0001
d	2	0.024985	0.012493	5.94	0.0262
$v \times f$	4	0.230815	0.057704	27.43	0.0001
$f \times d$	4	0.011304	0.002826	1.34	0.3339
$v \times d$	4	0.014215	0.003554	1.69	0.2446
Error	8	0.016830	0.002104		
Total	26	1.066407			

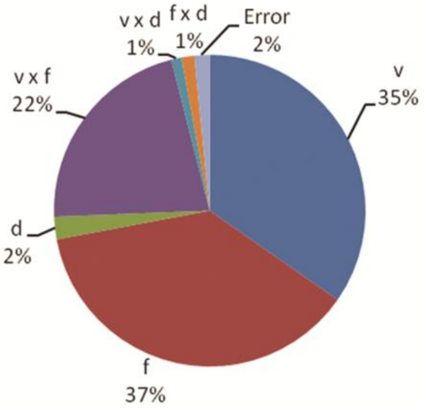

Fig. 2(a) — Percentage contribution of input variables on average surface finish $\boldsymbol{R_a}$

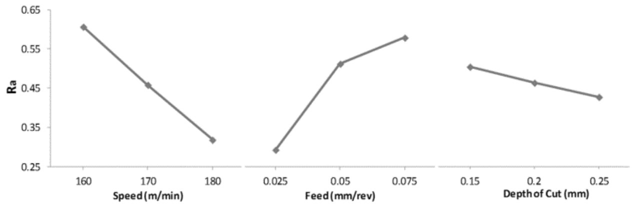

Fig. 2(b) — Main Effect Plots for surface roughness $\boldsymbol{R_a}$

The values of R^2 and $R^2(adj)$ (called adjusted R^2) are 90.8% and 88.0% respectively. The percentage contribution of each factor affecting surface roughness is shown in figure 2(a).

It is clear from the p-values in table 3, that fede rate f is the most significant variable affecting surface roughness R_a with a contribution of 37% as shown in figure 2(a), closely followed by machining speed v with a contribution of 35%. The interaction effects between velocity and feed ($v \times f$) are also significant with a 22% contribution. Depth of cut d, interaction of depth of cut and feed ($d \times f$), and interaction of depth of cut and velocity ($d \times v$) are observed to be less significant with minor contributions as shown in figure 2(a). Finally, the error contribution for surface roughness is 2% only. The main effect of the input parameters can be represented graphically as shown in figure 2(b). It is clear from the graph of surface roughness plotted against speed (shown in figure 2(b)) that the surface roughness R_a value decreases with an increase in cutting speed from 160 m/min to 180 m/min. This can be attributed to a reduction in the formation of build-up edge with an increase in speed. From the graph of surface roughness plotted against feed, in figure 2(b), it is apparent that the surface roughness R_a increases with an increase in feed rate from 0.025 mm/rev to 0.075 mm/rev. Such a trend is observed because of an increase in the vibrations and thrust force with an increment in feed, thus contributing to a rise in the surface roughness.It is observed from the graph of surface roughness $R_a$vs. depth of cut d, shown in figure 2(b), that there is a slight decrease in the surface roughness R_a with an increase in the value of depth of cut from 0.025 mm to 0.075 mm, albeit not considerable compared to the contributions observed with respect to the speed and feed rate as shown in figure 2.

Sound level and surface roughness

The sound level observed was the lowest (corrected L_A of 70.3 dBA) at speed, feed and depth of cut values of 170m/min, 0.025 mm/rev and 0.15 mm respectively. The surface roughness achieved with these parameters was within 0.25µm. The lowest surface roughness value of 0.16µm was obtained at speed, feed, and depth of cut of 180 m/min, 0.075 mm/rev and 0.25 mm respectively, with a corresponding sound level of 76.9 dBA (corrected L_A).

Analysis of frequency spectra

The frequency spectrums of 1/1 octave band were analyzed for each run. The first nine experiments which have the same depth of cut (0.15 mm) were divided into three groups, each having the same cutting speed but varying feed within the group. In these graphs, a high peak in sound level is observed in almost every case at 63 Hz frequency, except when the speed is 170m/min with feed 0.025 mm/rev, where sound level values are extremely low for low frequencies. Peaks were also seen in the mid frequency range. Thereafter, a dip in sound level is observed in the high frequency range which is greatest in the case of speed 180m/min and feed 0.025 mm/ rev. Thus, it is seen that overall, lower sound levels are obtained in case of lowest values of feed rate and depth of cut.

Similarly, the next nine experiments having the same depth of cut (0.20 mm) were divided in three groups having the same cutting speed, but varying feed within the group. It is observed from this set of results that in this case also the high peaks in sound level are obtained specifically at 63Hz and in the mid frequency range. A dip is observed in sound level after 63Hz frequency and with a slight rise in sound level is again observed specifically at 16 kHz. Though this increase in sound level is minimal when the speed is 180m/min for feed rate of 0.025 mm/rev. This shows that with an increase in the level of depth of cut, higher values of sound level are obtained even at high frequency ranges. The last set of nine experiments were also grouped in the similar manner that is based on depth of cut value of 0.25 mm. High peaks for sound level were observed at 63Hz and in the mid frequency range, followed by a dip and an increase in the sound level at 16kHz except in cases where feed rate is 0.025 mm/rev with machining speed of 180m/min. It can be concluded from the results shown that at lowest feed rate of 0.025 mm/rev and highest machining speed of 180m/min the value of noise level observed in high frequency range gets minimised. Thus the appropriate machining parameters selection can definitely help reduce the sound level produced during turning operations without significant compromise on the surface finish achieveable on the machine surface.

Conclusions

The work presented in this paper focuses on finding the optimum values of the machining parameters for high speed turning of hardened EN-19 steel with PVD-TiN coated Al_2O_3-TiCN mixed ceramic inserts in wet machining conditions with an aim to maximize the surface finish while reducing the machining noise level. The full factorial design of experiment model having 27 sets of turning experiments was used to examine the effect of the machining parameters on the measured response. It is observed that feed rate is the most influencing parameter on suface roughness in high speed turning followed by cutting speed. Also, the increase in cutting speed resulted in lower surface roughness while increase in feed rate led to an increase in surface roughness. It was observed that the set of machining parameters which gave the lowest sound level (corrected L_A) of 70.3 dBA were also able to contain the surface roughness within 0.25 µm (at speed, feed and depth of cut values of 170 m/min, 0.025 mm/rev and 0.15 mm respectively). This surface roughness level is very close to the lowest surface roughness value of 0.16µm which is associated with the sound level (corrected L_A) of 76.9dBA (at speed, feed, and depth of cut of 180 m/min, 0.075 mm/rev and 0.25 mm respectively). Thus with a marginal compromise in surface finish, a significant reduction in the sound level can be achieved on the shop floor. This study can be further extended for achieving better surface finish as well as mitigating the sound levels further by using tool materials composed of sound absorbing materials.

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