Turkish J. Eng. Env. Sci.
30 (2006) , 307 – 316.

The Effects of Cutting Tool Coating on the Surface Roughness of AISI 1015 Steel Depending on Cutting Parameters

Hasan GÖKKAYA
Zonguldak Karaelmas University, Safranbolu Vocational High School, Karabük-TURKEY
e-mail: hgokkaya@hotmail.com
Muammer NALBANT
Gazi University, Technical Education Faculty, Beşevler, Ankara-TURKEY

Received 07.11.2005

Abstract

The effects of a number of cutting tool coating materials on the surface quality of workpieces, depending on various cutting parameters, were investigated. AISI 1015 steel was processed without cooling on a lathe using 4 different cemented carbide cutting tools, i.e. uncoated, coated with AlTiN and coated with TiAlN using the PVD technique, and one with 3-layer coatings (outermost being TiN) applied by the CVD technique. Among the cutting parameters, the depth of cut was kept constant (2.5 mm) while the cutting speed and feed rate were changed. Five cutting speeds (50, 73, 102, 145, 205 m/min) and 2 feed rates (0.24 and 0.32 mm/rev) were used during the machining process. Coating type, feed rate and cutting speed have different effects on surface roughness. In the experiments, less average surface roughness was obtained by using a 3-layer coated tool coated outermost with TiN. The lessening of cutting speed by about 33% improves the surface roughness by about 26%, and increasing the cutting speed by about 310% resulted in an improvement of about 69%.

Key words: Machining, Surface roughness, Cutting tool coating, Cutting parameters.

Introduction

In all manufacturing methods, besides the dimensions and geometrical tolerances of products, a satisfactory surface roughness quality is of great importance. Besides other parameters, the desired productivity, tool life and resistance against the outer effects of operating machine tool types are dependent on the surface quality as well. Surface operations realized in various manufacturing systems are affected by the process parameters directly or indirectly. Process parameters chosen with non-accordance cause losses such as rapid tool wear and tool fracture besides the economic losses including spoiled workpieces or reduced surface quality (Thomas, 1982).

In machining, surface quality is one of the most commonly specified customer requirements in which the major indication of surface quality on machined parts is surface roughness. Surface roughness is mainly a result of process parameters such as tool geometry (nose radius, edge geometry, rake angle, etc.) and cutting conditions (feed rate, cutting speed, depth of cut, etc.) (Özel and Karpat, 2005).

The first study on surface roughness was performed in Germany in 1931 (Bayrak, 2002). As a result of this study, the surface qualities were arranged as the standard DIN 140. Surfaces are expressed as "machined or not machined surfaces". In all machined pieces, the examinations performed by hand and eye are taken into consideration. The surfaces are classified according to tactile feeling and the naked eye. Surface qualities are designated in 4 different forms: coarse, rough, medium and fine.

Kopac and Bahor (1999), who studied the changes in surface roughness depending on the process conditions in tempered AISI 1060 and 4140 steels, found speed to be the most dominant factor if the operating parameters were chosen randomly. They also reported that, for both steel types, the cutting tools with greater radius cause smaller surface roughness values. Similar studies were published by Yuan et al. (1996) and Eriksin and Özses (2002).

Gökkaya et al. (2004) investigated the effect of cutting tool coating material, cutting speed and feed rate speed on the surface roughness of AISI 1040 steel. In their study, the lowest average surface roughness was obtained using cutting tool with coated TiN. A 176% improvement in surface roughness was provided by reducing feed rate by 80% and a 13% improvement in surface roughness was provided by increasing the cutting speed by 200%.

Lin and Lee (2001) formulized the experimental results of surface roughness and cutting forces by regression analysis, and modeled the effects of them using S55C steel. Similar investigations were conducted by Risbood and Dixit (2003), Ghani and Choudhury (2002), Petropoulos et al. (2003), Feng and Wang (2002), Sekulic (2002) and Gadelmavla and Koura (2002).

This study was conducted because sufficiently in-depth studies have not been carried out about the effects of coated materials, coating method and cutting parameters on the surface roughness while processing AISI 1015 steel according to the results of previous research. This investigation is concerned with the process parameters, cutting speed and feed rate of cemented carbide cutting tools during the machining of AISI 1015 steel. The materials coated on the cutters were AlTiN and TiAlN, deposited by the PVD tehnique, and TiN, which possesses the smallest friction coefficient, and coated outermost by the CVD technique in 3 layers. While machining, the effect of coating materials and process parameters on the surface roughness of the workpiece was investigated using cutting tools containing the same underlayer. To determine the effect of the built up edge (BUE) on surface roughness, after the cutting process the BUE was investigated using a scanning electron microscope (SEM).

Surface Roughness

The surface parameter used to evaluate surface roughness, in this study, is the roughness average, Ra. This parameter is also known as the arithmetic mean roughness value, arithmetic average (AA) or centerline average (CLA). Ra is recognized universally as the most common international parameter of roughness (ISO 4287, 1997 standard). The average roughness (Ra) is the area between the roughness profile and its center line, or the integral of the absolute value of the roughness profile height over the evaluation length (Figure 1). Therefore, the Ra is specified by the following equation:

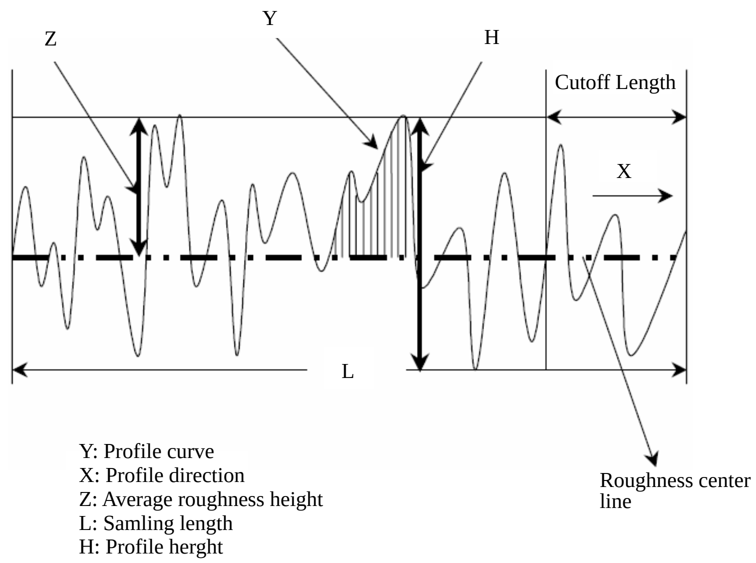


Figure 1. Surface roughness profile.

$$R_a = \frac{1}{L}\int_0^L |Y(x)|\, dx, \quad (1)$$

When evaluated from digital data, the integral is normally approximated by the trapezoidal rule:

$$R_a = \frac{1}{n}\sum_{i=1}^{n} |Y_i| \quad (2)$$

where

R_a is the arithmetic average deviation from the mean line, L is sampling length and Y represents the ordinate of the profile curve

Materials and Methods

Test specimens

During the experimental investigations, AISI 1015 steel test samples of dimensions ø65 × 650 mm were prepared and used. Chemical composition obtained by spectral analysis and other mechanical properties of the test samples are given in Tables 1 and 2, respectively.

Table 1. Chemical composition of the AISI 1015 test specimens (weight%).

C	Mn	Si	P	S	Fe
0.135	0.674	0.321	0.00957	0.0314	Rem.

Cutting tools, machine tool and surface roughness measuring instrument

In attempts to evaluate the effect of cutting tool coating types and cutting parameters on surface roughness, as equivalent to ISO P10-P20 grade for common steel, UTi20T grade uncoated cemented carbide produced by Mitsubishi, UE6005 grade cemented carbide coated with AlTiN and coated with TiAlN by the PVD technique, and 3-layer (the outermost TiN by CVD, Al_2O_3, TiC) coated cemented carbide cutting tools were used. The technical features of the cutting tools are given in Table 3. During the tests, SNMA 120408 indexable inserts and appropriate PSBNR 2525 M12 tool holders were used. For the turning operations a Tezsan type SN50 universal lathe was used under approximately orthogonal machining conditions.

As recommended in the standard ISO 3685, the cutting speed intervals of tool quality given by the tool manufacturers were taken into consideration and 5 different cutting speeds, i.e. 50, 73, 102, 145 and 205 m/min, were selected. Depending on the tool radius of 0.8 mm, at the interval recommended in ISO 3685, 0.24 and 0.32 mm/rev feed rates and 2.5 mm depth of cut were selected.

Surface roughness was measured by a MAHR-Perthometer M1 and measurements were repeated 3 times. To measure the surface roughness formed by machining the workpieces, the cut-off length was taken as 0.8 mm and the sampling length as 5.6 mm. The surface roughness diagram obtained by using the uncoated cemented carbide cutting tools while machining at 205 m/min cutting speed and 0.24 mm/rev feed rate is given in Figure 2.

Table 2. Mechanical properties of the AISI 1015 test specimens.

Hardness BSD 30	Yield Strength N/mm^2	Tensile Strength N/mm^2	Max. Elongation % (5 do)
111	325	385	18

Table 3. The technical features of interconvertible cemented carbide cutting tools.

Coated material	Coating Method	Material quality ISO (Grade)	Hardness (HV)	Coefficient of friction	Thermal Conductivity W/m*K
TiN (TiN, Al_2O_3, TiC)	CVD	P10	2500	0.35	27
TiAlN	PVD	P20	3100	0.4	28
AlTiN	PVD	P20	3200	0.47	29
Wc-Co	Uncoated	P20	1800	0.6	38

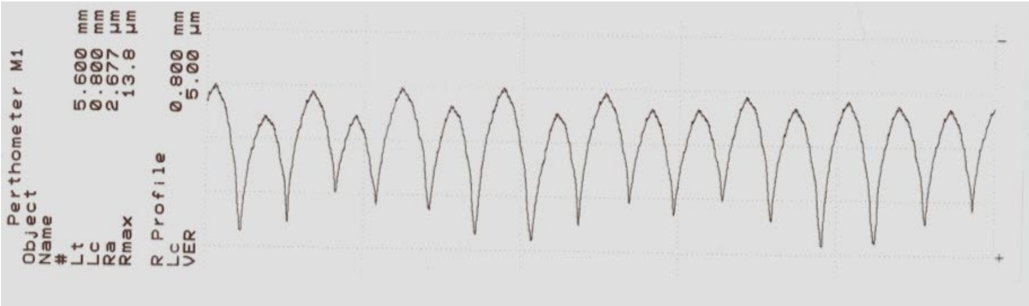


Figure 2. The diagram of average surface roughness value (R_a) obtained by processing AISI steel with an uncoated cemented carbide cutting tool at 205 mm/min cutting speed and 0.24 mm/rev feed rate.

Results and Discussion

In this investigation, the average surface roughness values (R_a) obtained by a machining process with a full factorial design of 5 cutting speeds and 2 feed rates using 4 different cutting tools are shown in Table 4. The results of the variance analysis of cutting parameters and coating type are presented in Table 5.

In the analysis of variance, the main effects of coating type, cutting speed and feed rate on surface roughness were significant. According to the coating type, the lowest average surface roughness was obtained by machining using the TiN coated cutting tools, followed by TiAlN and AlTiN coated tools. The highest average surface roughness was obtained using the uncoated cemented carbide tool set. The box plot of average surface roughness values obtained due to coating type is depicted in Figure 3.

Table 4. Average surface roughness values depending on coating type, cutting speed and feed rate.

Coating Type	Cutting Speed (m/min)	Feed Rate (mm/rev)	Average Surface Roughness	Coating Type	Cutting Speed (m/min)	Feed Rate (mm/rev)	Average Surface Roughness
	V	f	Ra (μm)		V	f	Ra (μm)
Uncoated Cemented Carbide	205	0.24	2.6	TiAlN, PVD	205	0.24	2.2
		0.32	3.3			0.32	2.9
	145	0.24	3.2		145	0.24	2.5
		0.32	4.1			0.32	3.8
	102	0.24	4.2		102	0.24	2.8
		0.32	4.6			0.32	4.1
	73	0.24	4.9		73	0.24	3.2
		0.32	5.1			0.32	4.5
	50	0.24	5.1		50	0.24	3.8
		0.32	5.4			0.32	4.8
AlTiN, PVD	205	0.24	2.3	TiN, CVD	205	0.24	1.9
		0.32	3.1			0.32	2.4
	145	0.24	2.9		145	0.24	2.2
		0.32	3.9			0.32	2.9
	102	0.24	3.2		102	0.24	2.4
		0.32	4.4			0.32	3.1
	73	0.24	3.6		73	0.24	2.8
		0.32	4.8			0.32	3.3
	50	0.24	4.1		50	0.24	3.1
		0.32	5.1			0.32	3.6

Table 5. Analysis of variance for surface roughness in turning of AISI 1015 using various coated tools.

Source	DF	Sum of squares	Mean squares	F values	P values
Coating type	3	11.16	3.72	46.10	0.001
Cutting speed	4	14.87	3.71	46.05	0.001
Feed rate	1	6.90	6.90	85.57	0.001
Error	31	1.22	0.04		
Total	39	35.95			

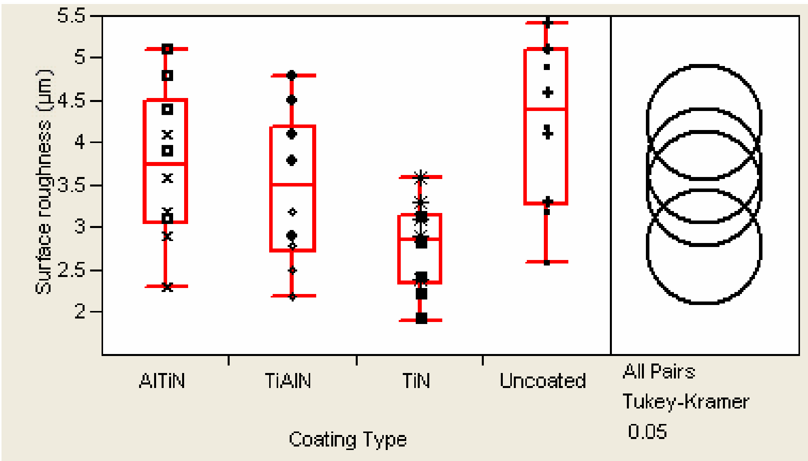


Figure 3. The average surface roughnesses (R_a) obtained by processing the AISI steel using 4 different coating types.

The average surface roughness (4.25 μm) of the workpiece obtained by the machining process with uncoated cemented carbide was greater than the values obtained by using coated cutting tools. The lowest average surface roughness obtained with coated cutting tools was realized with TiN coated cutting tool (2.77 μm). Then the values 3.46 μm with TiAlN coated and 3.74 μm with AlTiN coated cutting tools were obtained. The average surface roughness obtained by machining with uncoated cemented carbide was 4.25 μm, whereas it was improved to 2.77 μm by processing with a TiN coated cutting tool. The reason for the lower average surface roughness obtained from the tools coated with TiN could be that the ones coated with TiN have a higher coefficient of friction and thermal conductivity compared with the other 3 tools.

The average surface roughness values obtained at the selected cutting speeds are, in increasing order, as follows: 2.587 μm at the highest cutting speed of 205 mm/min, 3.187 μm at 145 mm/min, 3.60 μm at 102 mm/min, 4.025 μm at 73 mm/min, and 4.375 μm at 50 mm/min. The roughness values obtained are high, possibly due to the ductility of the 1015 steel. When the average surface roughness values at cutting speeds of 50, 73, 102, 145 and 205 m/min examined, it is seen that the surface roughness decreases as the cutting speed increases (Figure 4). A decreasing correlation exists between the cutting speed and surface roughness ($P < 0.01$). The improvement in surface roughness depending on the augmentation of cutting speed is an expected feature and improving the surface roughness by increasing the cutting speed is a widespread method according to the literature (Boothroyd, 1981; Shaw, 1984; Trent, 1984; Sandvik, 1994; DeGarmo et al., 1997; Şeker, 1997; Altın et al., 2006).

The improvement in surface roughness by increasing the cutting speed can be explained by being an easy deformation process because of the increasing temperature at high speeds, i.e. the easy deformation of workpiece type at the cutting side and around the tip radius, and flow zone (Fz) occurring at these high temperatures. The easily deformed materials can be formed without being torn. By working at low speeds, the considerable improvement (69%) in surface roughness by increasing the cutting speed by about 310% reveals the effect of cutting speed on the surface roughness clearly.

The increase in feed rate from 0.24 to 0.32 mm/rev increases the average surface roughness by 26%. Consequently, there is an increasing relation between the surface roughness and the feed rate values ($P < 0.01$). Another well-known application to improve the surface roughness is decreasing the feed rate values (Shaw, 1984; Trent, 1984; Boothroyd, 1981; Sandvik, 1994; DeGarmo et al., 1997; Şeker, 1997; Gokkaya and Nalbant, 2005). The improvement in average surface roughness of 26% is seen by decreasing the feed rate by about 33% (Figure 5). Average surface roughness was 3.96 μm at 0.32 mm/rev, and 3.15 μm at 0.24 mm/rev feed rates. To compare the averages of surface roughnesses, the Tukey-Kramer test was performed. It is seen that the averages of surface roughness values obtained at 0.24 and 0.32 mm/rev feed rates are considerably different.

To see the influence of cutting speed and feed rate on surface roughness, the effect-test was performed and it was seen that the effect of feed rate is greater than the effect of cutting speed. As a result, to improve the surface roughness, a good combination of cutting speed and feed rate needs to be selected.

A multiple regression analysis was conducted on the tested data. Average coefficients of friction (due to coating type) were used instead of the coating type. The analysis of variance results of the regression model also supported linear relationships in the model (Table 6). The F value of regression was 112.06. This value indicated a great significance ($\alpha <$ 0.0001) for the model in rejecting the null hypothesis (H_0) that every coefficient of the predictor variables in the model was zero. Instead, the alternative hypothesis, that at least one of these coefficients did not equal to zero, was accepted. Therefore, a significant linear relationship between the predicted variable

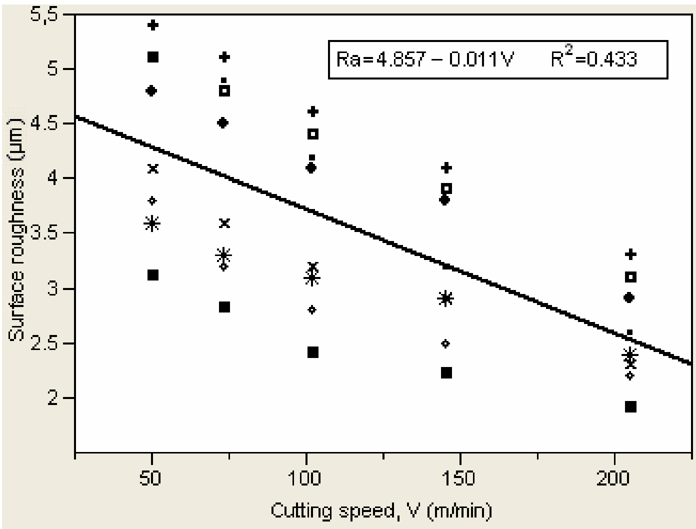


Figure 4. The average surface roughness (R_a) obtained by processing the AISI steel with different cutters at different cutting speeds and at chosen 0.32 and 0.24 mm/rev feed rates.

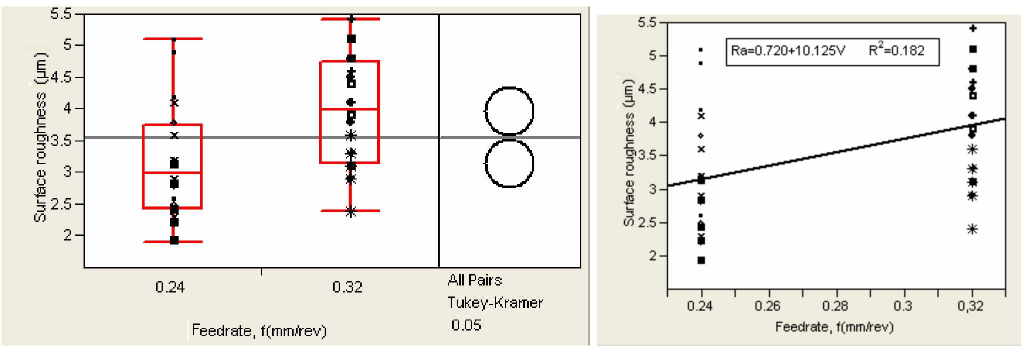


Figure 5. The average surface roughnesses (R_a) obtained by processing the AISI steel using 4 different cutting tools and 2 different feed rates at cutting speeds of 50, 73, 102, 145 and 205 mm/min.

(Ra) and predictor variables existed. From the analysis of variance, coefficients of friction of coating type, cutting speed and feed rate had a significant effect on the surface roughness.

According to calculated coefficients of the main factors, the multiple regression model of surface roughness was built as shown in Eq. (3).

$$Ra = 2.393 + 5.416C - 0.0111V + 0.405f R^2 = 0.903 \quad (3)$$

The scatter plot of surface roughness actual versus surface roughness predicted by regression equation is illustrated in Figure 7. Most of the points lie close to the line of prediction. A line inclined at 45° and passing through the origin is also drawn in the figure. For perfect prediction, all points should lie on this line. Here, it is seen that most of the points are close to this line. Hence, this model provides a reliable prediction. Surface roughness residual versus surface roughness predicted is illustrated in Figure 6. The distribution of values in Figure 7 shows that the tests were reliable.

Figures 3-5 show that the surface roughness is affected by the cutting tool coating material, cutting speed and feed rate. The surface roughness values obtained by using TiN coated tools are lower than those obtained by using AlTiN and TiAlN coated, and uncoated cutting tools. Again, this difference is more considerable at lower cutting speeds. The better surface features of TiN coated tools may be due to the smaller friction coefficient of this type than the others, and the developing temperature. At lower cutting speeds (50 m/min), depending on the developing low temperatures at the tool-chip interface, the occurrence of a BUE was observed on uncoated cemented carbide and AlTiN coated cutting tools (Figure 8). However, at the same speed, the BUE was not formed when TiAlN and TiN coated cutting tools were used.

Table 6. Analysis of variance for the surface roughness linear model in turning of AISI 1015 using various coated carbide tools.

Source	DF	Sum of squares	Mean squares	F values	P value
Model	3	32.48	10.82	112.06	0.001
Coefficient of friction of coating type, C	1	10.35	10.35	107.19	0.001
Cutting speed, V	1	15.56	15.56	161.09	0.001
Feed rate, f	1	6.56	6.56	67.91	0.001
Error	36	3.47	0.09		
Total	39	35.95			

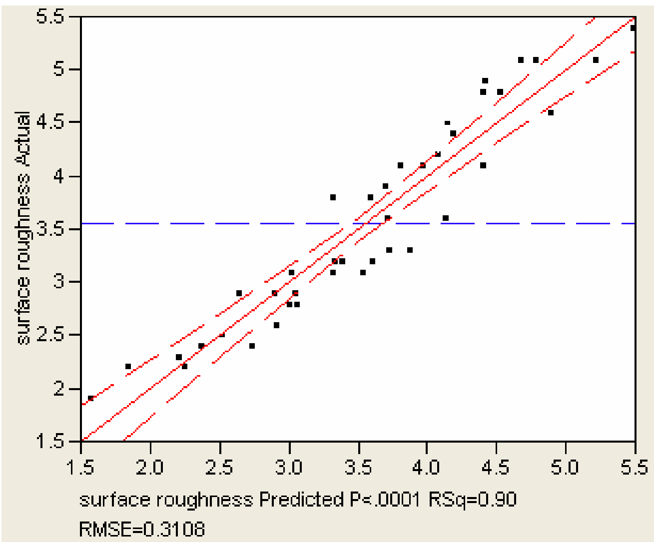


Figure 6. Surface roughness actual versus surface roughness predicted.

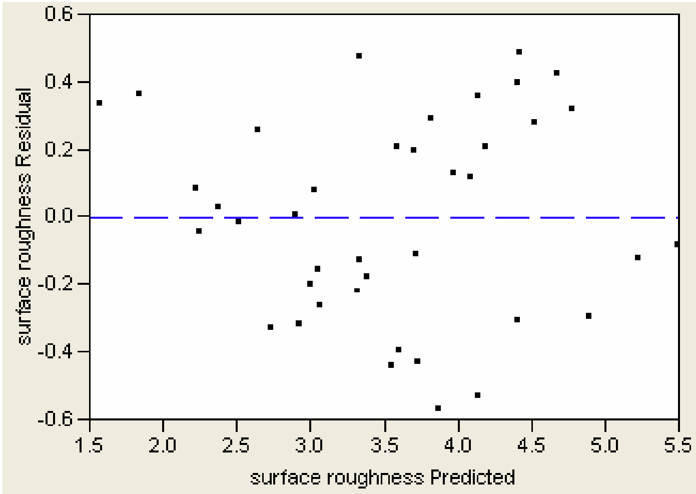
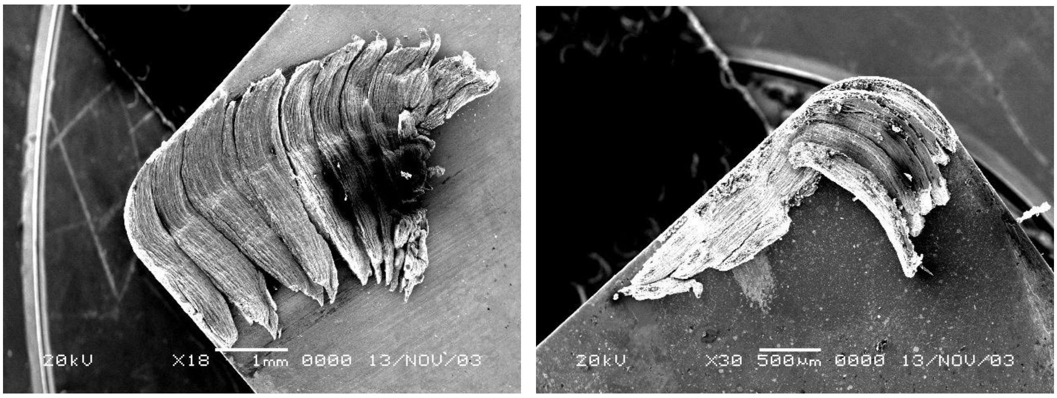


Figure 7. Surface roughness residual versus surface roughness predicted.



(a) (b)

Figure 8. A BUE occurred on the cutting tool during the machining process at the cutting speed of 50 m/min. a) Uncoated cemented carbide, b) AlTiN coated cemented carbide.

If the cutting speeds are 73 m/min or greater, BUE occurrence is not seen on uncoated and coated cutting tools. This effect can be related, depending on the high cutting speed, to the developing high temperature. Increasing the cutting speed is a widespread application to prevent a BUE on the cutting tool (Sandvik, 1994; Şeker, 1997). In addition to the parameters stated above, the BUE formed at low cutting speeds can affect the surface roughness negatively.

This case is seen at 50 m/min cutting speed and the surface roughness obtained by using the TiN coated tool set exhibits an improvement of 33% according to the surface obtained by using the TiAlN coated tool set, of 42% according to the surface obtained by using the AlTiN coated tool set, and about 50% according to the surface obtained by using the uncoated sementite carbide cutting tool set. For each of the 4 tool sets, the developing high temperatures at high speeds facilitate the occurrence of flow zone, and make the flow of the BUE easy. Consequently, the differences between the surface roughness values obtained by using each of the 4 sets are decreasing.

Conclusions

The effects of the coating method, coated materials and cutting parameters on the AISI 1015 steel workpiece were investigated under orthogonal cutting conditions approximated in cylindrical turning. The experiment was established in full factorial design. The conclusions of the investigation can be summarized as follows:

- According to the coating types, the best surface roughness is obtained by means of cutting tools coated with TiN using the CVD technique. The next best cutting tools were ones that were TiAlN and AlTiN coated with the PVD technique and uncoated cemented carbide, respectively.
- The relationship between cutting speed and surface roughness is inversely proportional. Increasing the cutting speed decreases the surface roughness.
- The relationship between feed rate and surface roughness is proportional. Increasing the feed rate increases the surface roughness.
- On surface roughness, the effect of feed rate is more considerable than cutting speed.
- Decreasing the feed rate by 33% improves the surface roughness by about 26%, while increasing the cutting speed by about 310% improves the surface roughness by 69%.
- A good combination of cutting speed and feed rate can provide better surface qualities.
- The average friction coefficient of coating material affects the surface roughness.
- Low cutting speeds of uncoated and AlTiN coated tools cause a BUE.
- Formation of a BUE affects the surface roughness negatively.

This study was carried on a Tezsan type SN50 universal lathe. It should also be carried on a CNC lathe, which can accelerate to higher cutting speeds.

References

Altın, A., Gökkaya, H. and Nalbant, M., "The Effect of Cutting Speed in Machine Parameters on the Machinability of Inconel 718 Superalloys" J. Fac. Eng. Arch. Gazi Univ., 3, 581-586, 2006.

Bayrak, M., "The Effect of Machining Parameters on Surface Roughness and Their Comparison With Expert System", MSc Gazi University Institute of Science and Technology, Ankara, Turkey,2002.

Boothroyd, G., "Fundamentals of Metal Machining and Machine Tools", International Student ed., McGraw-Hill, New York, 1981.

DeGarmo, P.E., Black, J.T. and Ronaldo A.K., Materials and Processes in Manufacturing, Prentice Hall International Inc., Upper Saddle River, NJ, USA, 1997.

Eriksen, E., "Influence from Production Parameters on the Surface Roughness of a Machined Short Fibre Reinforced Thermoplastic", International Journal of Machine Tools & Manufacture, 39, 1611-1618, 1998.

Feng, C. and Wang, X., "Development of Empirical Models for Surface Roughness Prediction in Finish Turning", International Journal of Advanced Manufacturing Technology, 20, 1-8, 2002.

Gadelmavla, E.S. and Koura, M.M., "Roughness Parameter", Journal of Material Processing Technology, 123, 133-145 2002.

Ghani, A.K. and Choudhury, I.A., "Study of Tool Life Surface Roughness and Vibration in Machining Nodular Cast Iron With Ceramic Tool", Journal of Material Processing Technology, 127, 17-22, 2002.

Gokkaya, H., Sur, G. and Dilipak, H., "Experimental Investigating of the Effect of Cemented Carbide Cutting Tools Coated by PVD and CVD on Surface Roughness According to Machining Parameters", Journal of Zonguldak Karaelmas University, Technical Education Faculty, 3-4, 473-478, 2004.

ISO 4287, Geometrical Product Specifications (GPS) - Surface texture: Profile method - Terms, definitions and surface texture parameters, 1997.

Kopac, J. and Bahor, M., "Interaction of the Technological History of a Workpiece Material and the Machining Parameters on the Desired Quality of the Surface Roughness of a Product," Journal of Materials Processing Technology, 92-93, 381-387, 1999.

Lin, W.S. and Lee, B.Y., "Modeling the Surface Roughness and Cutting Forces During Turning", Journal of Material Processing Technology, 108, 286-293, 2001.

Ozses, B., "The Effect of the Different Machining Conditions on the Surface Roughness on CNC Machine Tools", MSc Gazi University Institute of Science and Technology, 2002.

Özel, T. and Karpat, Y., "Predictive modeling of surface roughness and tool wear in hard turning using regression and neural networks". International Journal of Machine Tools and Manufacture, 45, 467-479, 2005.

Petropoulos, G.A., Torrance, A. and Pandazaras, C.N., "Abbott Curves Characteristics of Turned Surfaces", International Journal of Machine Tool & Manufacture, 43, 237-243, 2003.

Risbood, K.A. and Dixit, U.S., "Prediction of Surface Roughness and Dimensional Deviation by Measuring Cutting Forces and Vibration in Turning Process", Journal of Material Processing Technology, 132, 203-214, 2003.

Sandvik Coromant, Modern Metal Cutting, Practical Handbook, Tofters Tryckeri AB, 1994.

Sekulic, S., "Correlation between the Maximal Roughness Height and Mean Arithmetic Deviation of the Profile from the Mean Line of Machined Surface in Finish Turning", International Conference on Tribology, pp 29-34, Kayseri, 2002.

Şeker, U., Textbook Notes on Tool Design, Gazi University, Technical Education Faculty, 1997.

Shaw, M.C., Metal Cutting Principles, Oxford University Press, London, pp. 594, 1984.

Thomas, T.R., Rough Surface, Longman, New York, 1982.

Trent, E.M., Metal Cutting, 2nd ed., Butterworths, London, 1984.

Yuan, Z.J., Zhou, M. and Dong, S., "Effect of Diamond Tool Sharpness on Minimum Cutting Thickness and Cutting Surface Integrity in Ultraprecision Machining", Journal of Material Processing Technology 62, 327-330, 1996.