Structural Engineering and Mechanics, *Vol. 61, No. 4 (2017) 519-526*
DOI: https://doi.org/10.12989/sem.2017.61.4.519

Effects of coating material and cutting parameters on the surface roughness and cutting forces in dry turning of AISI 52100 steel

Ouahid Keblouti*[1], Lakhdar Boulanouar[1], Mohamed Walid Azizi[1] and Mohamed Athmane Yallese[2]

[1]*Advanced Technologies in Mechanical Production Research Laboratory (LRTAPM), Badji Mokhtar-Annaba University, BP 12 Annaba 23000, Algeria*
[2]*Mechanics and Structures Research Laboratory (LMS), May 8th 1945 University, PO Box 401, Guelma 24000, Algeria*

(Received May 30, 2016, Revised December 9, 2016, Accepted December 29, 2016)

Abstract. In the present paper, the effects of cutting parameters and coating material on the performances of cutting tools in turning of AISI 52100 steel are discussed experimentally. A comparative study was carried out between uncoated and coated (with TiCN-TiN coating layer) cermet tools. The substrate composition and the geometry of the inserts compared were the same. A mathematical model was developed based on the Response Surface Methodology (RSM). ANOVA method was used to quantify the effect of cutting parameters on the machining surface quality and the cutting forces. The results show that feed rate has the most effect on surface quality. However, cutting depth has the significant effect on the cutting force components. The effect of coating layers on the surface quality was also studied. A lower surface roughness was observed when using PVD (TiCN-TiN) coated insert. A second order regression model was developed and a good accuracy was obtained with correlation coefficients in the range of 95% to 97%.

Keywords: coating material; cutting tool; mathematical model; RSM; ANOVA; machining surface; cutting forces

1. Introduction

Material cutting is an important process in the field of material removal. It is defined as the chip removal from a workpiece in order to obtain the desired surface finish. These properties are required especially in aerospace and automotive industry. High quality of mechanical parts can be achieved by the control of several parameters like cutting conditions, workpiece hardness, and coating materials of cutting tools, leading to an improvement in mechanical properties like fatigue strength, corrosion resistance, friction and wearing (Hayajneh *et al*. 2007).

Several research works investigated the effect of cutting parameters and workpiece hardness on the surface roughness and cutting forces (Chinchanikar and Choudhury 2013, Azizi *et al*. 2012, Yallese *et al*. 2004). The tool wear, surface roughness, cutting forces and metal volume removed were investigated by Bouacha *et al*. (2014) in hard turning of AISI 52100 steel using CBN tools. A mathematical model was developed for surface roughness and cutting force components based on the Response Surface Methodology (RSM). They found that the surface roughness is mainly influenced by the feed rate and the cutting speed, while the cutting depth has the most significant effect on cutting forces. Also, the cutting time has a considerable effect on cutting performances. The same approach was performed by Aouici *et al*. (2014) in hard turning of cold work tool steel AISI D3 hardened at 60HRC, using ceramic cutting tools under the effect of cutting speed, feed rate and depth of cut. The results concluded that the cutting force components were influenced mainly by feed rate followed by depth of cut. A comparative assessment of wiper and conventional ceramic tools on surface roughness criteria (Ra, Rz and Rt) in hard turning AISI 4140 steel was carried out by Elbaha *et al*. (2013). They found that the surface quality was improved by 2.5 times when using the wiper ceramic insert compared to the conventional tool. In addition to the aforementioned effects, tool geometry and vibration have also an important effect on the machining performance of diverse tool materials (Makadia *et al*. 2013, Hessainia *et al*. 2013). The tool geometry influence on the surface finish, in turning of AISI 1040 steel was investigated experimentally by Neseli *et al*. (2011), which concluded that the tool nose radius was the dominant factor on surface roughness.

The flank wear, surface roughness and material removal rate (MRR) were investigated by Senthilkumar and Tamizharasan (2014) under the effects of geometrical parameters of cutting tool such as cutting insert shape (including angle of cutting edge), relief angle and nose radius. They revealed that insert shape was the most significant parameter contributing on surface roughness with 45.27% followed by nose radius with 36.37% and relief angle with 5.28%.

The surface roughness and cutting forces were investigated by Meddour *et al*. (2015) during hard turning of AISI 52100 steel. They revealed that the force components were influenced by depth of cut, followed by feed rate. Also, smaller feed rate and larger nose radius gave better surface finish. The effects of cutting parameters and vibrations were studied by Upadhyay *et al*. (2013) using

∗Corresponding author, Ph.D.
E-mail: kebloutiusthb@gmail.com

http://www.techno-press.org/?journal=sem&subpage=8 ISSN: 1225-4568 (Print), 1598-6217 (Online)

Table 1 Chemical composition of AISI 52100 steel.

C	Si	Mn	Cr	Ni	Mo	V	Cu
1.09	0.256	0.35	1.382	0.077	0.017	0.005	0.150

acceleration amplitude of vibration in axial, radial and tangential directions. They found that the feed rate has the highest effect, followed by acceleration amplitude of vibration in radial direction, depth of cut, and acceleration amplitude of vibration in tangential direction.

The coating material of cutting tools contributes efficiently in improving the cutting conditions: it protects the substrate, improves the crack resistance and creates a thermal barrier (Grzesik and Nieslony 2004, Das*et al*. 2015). Among coating layers used, Titanium Carbide (TiC), Titanium Nitride (TiN), Titanium Carbonitride (TiCN), Titanium Aluminum Nitride (TiAlN), and Aluminum Oxide (Al_2O_3) are the most preferred materials. These layers are mostly deposited with Chemical Vapor Deposition (CVD) or by Physical Vapor Deposition (PVD) technique (Sahoo and Sahoo 2012, Aurich *et al*. 2012).

The investigations conducted by Grzesik (1998) highlights the crucial effect of different types of coating at dry machining of carbon-based steel AISI 1045 and AISI 304 stainless steel. He used three types of coating layers: TiC, TiC/TiN, and TiC/Al_2O_3/TiN. He found that, considering the tool-chip interface, TiC/Al_2O_3/TiN-AISI 1045 tool-workpiece material couple gave lower values of friction factor and contact pressure, compared to the couples of TiC/TiN-AISI 1045 and TiC-AISI 1045.

The tribological phenomenon at tool-chip interface was investigated by Zhang *et al*. (2015) in dry cutting of hardened steel AISI 1045 using two types of coated cemented carbide. The first one had a nano-scale surface textured rake face which was then coated with a hard-coating of Ti55Al45N hard-coatings. In the second insert, the order of coating layers was inverted. A significant decrease in cutting forces, cutting temperature and friction coefficient at the tool-chip interface were found. The textured tool reduces the contact area, thus the friction at the tool-chip interface.

Sahoo and Sahoo (2013) conducted an experimental investigation on the flank wear behavior in hard turning using multi-layer coated carbide (TiN/TiCN/Al_2O_3/TiN) insert. They found that the flank wear value increases with increasing cutting speed, feed rate and depth of cut. They also observed that both abrasion and diffusion wear mechanisms are predominantly at extreme cutting conditions. A comparative study was performed by Cakir *et al*. (2009) using PVD coated (TiAlN) inserts and CVD coated (TiCN/Al_2O_3/TiN) inserts. They observed that a lower surface roughness value is obtained when employing PVD TiAlN coated inserts.

In this work, an experimental investigation was carried in order to evaluate the effects of cutting parameters (namely, the cutting speed (V), feed (f) and the depth of cut (d)) and coating of turning tool on the surface roughness (Ra) of AISI 52100 steel and cutting forces in dry turning operation. A comparison was performed between uncoated and coated (with TiCN-TiN) cermet tools. The inserts had identical substrate composition and geometry. The effect of tool wear was neglected by using a fresh cutting edge for each experiment. In addition, a mathematical model was developed based on the Response Surface Methodology (RSM). ANOVA method was conducted to analyze the effect of cutting parameters on the machining surface quality and the tool-workpiece mechanical behavior.

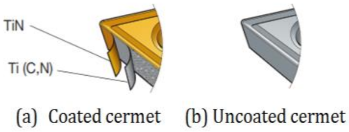

Fig. 1 Illustration of used cutting inserts

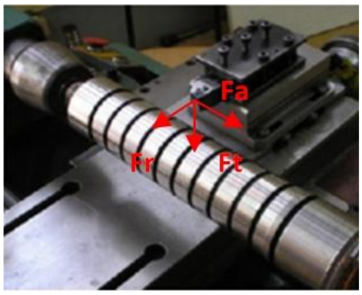

Fig. 2 Experimental setup to measure cutting forces

2. Experimental setup and procedures

2.1 Workpiece material and cutting inserts

Turning runs were carried out in dry conditions using a universal lathe SN 40C type with 6.6 kW spindle power. The workpiece material was AISI 52100 steel in the form of round bars with 66 mm of diameter and 380 mm cutting length. This material is widely used in manufacturing of automotive components regarding to their properties like high tensile strength, shock resistance and Brinell hardness about 230 HB. The chemical composition of AISI 52100 steel is given in Table 1. Coating effect on the cutting performances was investigated using two types of cutting inserts. The first type was GC 1525 coated insert (PVD with TiCN/TiN layer sequence), which is an ISO class P15 grade, with a total thickness of 3 μm. The main coating layer includes titanium carbonitride (TiCN) and a thin layer of titanium nitride (TiN) as shown in Fig. 1. The second insert was CT5015 uncoated cermet. The two inserts (GC 1525 and CT5015) have an identical substrate with the same geometry designation as CNMG 120408. For each experiment, a fresh cutting edge was used. A right hand style tool holder designated by ISO as CSBNR2525M12 was used for mounting the inserts. It is characterized by the following angles: χr=75°, λ=-6°, γ=-6°, α=+6°.

2.2 Measuring instruments

The average values of the cutting force components were measured using a three-component piezo-electric dynamometer (KISTLER Type 9257A) mounted on the

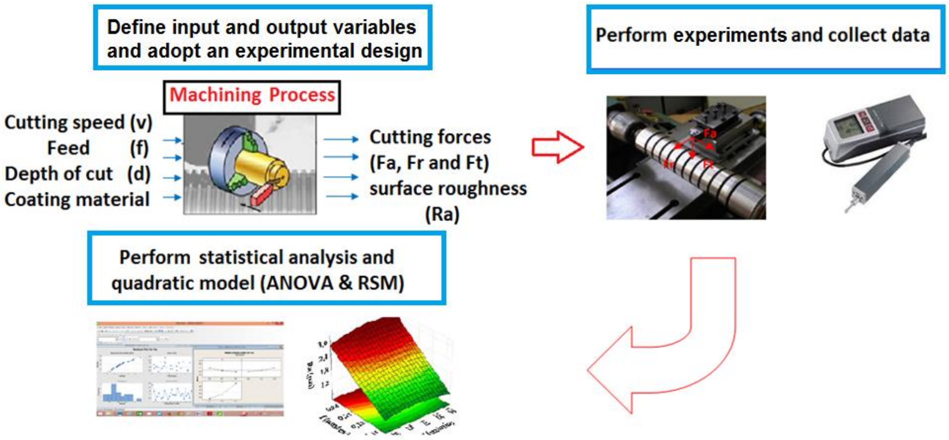

Fig. 3 Experimental design flowchart

Table 2 Operating conditions of cutting parameters.

Level	*V* (m/min)	*f* (mm/rev)	*d* (mm)
Low	150	0.08	0.15
Medium	200	0.12	0.30
High	250	0.16	0.45

lathe cross slide as shown in Fig. 2. The static calibration of the dynamometer was made in each force direction. The force signals acquired were analyzed for a cutting time of 2 sec. The measurement of the arithmetic surface roughness (Ra) was obtained from a Surftest 201 Mitutoyo roughness-meter. The machined length was 24 mm with a basic span of 3 mm. The measurements were repeated at three equally spaced locations around the circumference of the workpiece at 120° and the result was the average of these values. The surface roughness was directly measured on the workpiece, without dismounting from the lathe, in order to reduce measurement errors.

2.3 Experimental design

In this study, (L27) full factorial design was adopted as the experimental design, which involves variation of three factors at three levels (low, medium and high), including cutting speed (*v*), feed (*f*) and depth of cut (*d*) as indicated in Table 2. The experimental design flowchart is shown in Fig. 3. The selected experimental design requires 27 runs with 26 degrees of freedom (DF). For each run, one test was performed (no replications). Also a random order was determined for running the tests.

3. Results and discussion

Using the full factorial experimental design (L27), created by all possible combinations of cutting parameters (namely, the cutting speed (*V*), feed (*f*) and the depth of cut (*d*)), the corresponding experimental results of the surface roughness and cutting force components with coated and uncoated cermet inserts are given in Table 3. In this study, the analysis of variance (ANOVA) method was used to quantify the impact of the cutting speed (*V*), feed (*f*) and

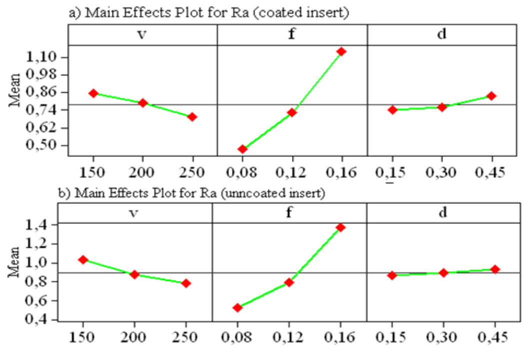

Fig. 4 Surface roughness variation with coated and uncoated inserts

depth of cut (*d*) and their interactions on the surface roughness and cutting force components. The analyses were applied with 95% confidence interval (CI) to determine the significance level of tested variables. The obtained results were analyzed using Minitab-16, a statistical analysis software, which is widely used in engineering optimizations.

3.1 Effects of machining parameters

3.1.1 Surface roughness

The results of variance analysis for surface roughness criteria (Ra) of coated and uncoated cermet inserts are given in Table 4. These analyses were performed for a confidence interval (CI) of 95 %. The characterization of the machined surface quality was limited to the criteria of arithmetic mean roughness (Ra). It can be concluded that feed is the most important parameter affecting surface finish compared to the other factors and their interactions. Its contributions were 85.17% and 85.67% for coated and uncoated inserts, respectively. The second most effective factor on the surface quality was the cutting speed which contributed by 4.91% and 7.55% for coated and uncoated inserts, respectively. The cutting depth gave lower influences on the surface roughness where its contribution was less than 2%. These results can be explained by the phenomenon of the grooving helicoidally furrows on the finish machining surface caused by the rising of feed combined with tool-

Table 3 Experimental results of surface roughness and cutting forces

V (m/min)	*f* (mm/rev)	*d* (mm)	Coated inserts GC1525 Fa (N)	Fr (N)	Ft (N)	Ra (μm)	Uncoated inserts CT5015 Fa (N)	Fr (N)	Ft (N)	Ra (μm)
150	0.08	0.15	48.78	106.65	92.37	0.47	26.74	98.50	60.33	0.96
		0.3	52.12	104.90	89.16	0.45	69.49	128.57	95.03	0.8
		0.45	76.83	131.45	129.35	0.51	113.01	165.04	148.22	0.6
	0.12	0.15	53.14	108.53	117.65	0.78	46.60	119.56	78.65	0.77
		0.3	65.34	114.25	136.24	0.89	76.57	160.59	138.04	0.9
		0.45	102.24	162.04	187.13	0.84	129.13	195.12	190.15	0.96
	0.16	0.15	70.34	127.91	137.54	1.15	43.52	132.53	88.89	1.39
		0.3	83.28	158.70	148.13	1.18	81.32	175.13	174.19	1.45
		0.45	127.96	187.70	211.59	1.42	146.82	244.63	241.24	1.46
200	0.08	0.15	43.05	88.41	78.30	0.52	37.12	88.44	53.55	0.4
		0.3	53.82	110.37	104.31	0.4	70.28	126.06	98.54	0.42
		0.45	69.13	143.15	103.67	0.51	111.24	142.98	149.41	0.47
	0.12	0.15	46.11	88.02	120.49	0.7	46.66	108.76	88.73	0.72
		0.3	54.67	107.77	118.49	0.82	65.15	144.21	145.84	0.74
		0.45	89.91	127.84	161.24	0.7	94.91	155.90	181.57	0.93
	0.16	0.15	48.27	108.91	140.93	1.06	41.06	102.04	89.19	1.37
		0.3	62.89	127.37	149.46	1.06	76.10	150.93	178.32	1.37
		0.45	110.81	169.54	212.82	1.3	108.12	176.50	225.57	1.44
250	0.08	0.15	47.52	107.29	69.76	0.49	37.59	95.14	69.75	0.32
		0.3	74.66	115.53	122.98	0.39	54.41	107.01	99.29	0.37
		0.45	89.87	141.56	138.00	0.5	95.51	124.58	144.59	0.37
	0.12	0.15	43.88	85.18	112.92	0.46	25.47	77.47	74.98	0.57
		0.3	46.50	102.21	124.55	0.75	57.64	117.12	125.01	0.72
		0.45	72.53	144.55	164.30	0.58	108.06	162.28	198.91	0.83
	0.16	0.15	50.35	108.29	127.92	1.02	39.22	92.78	97.91	1.26
		0.3	71.33	128.96	147.20	0.9	84.21	79.65	88.96	1.27
		0.45	123.36	155.66	220.28	1.15	111.50	186.04	233.37	1.3

Table 4 Surface roughness ANOVA results of coated and uncoated inserts

ANOVA of (Ra) (CI= 95%)		Coated insert (R^2= 99.16%, R^2_{adj}= 97.27%)			Uncoated insert (R^2= 98.98%, R^2_{adj}= 96.69%)		
Source	DF	SS	*p*-values	PC (%)	SS	*p*-values	PC (%)
V	2	0.11762	0.000	4.91	0.29503	0.000	7.55
f	2	2.03840	0.000	85.17	3.34792	0.000	85.67
d	2	0.04536	0.009	1.90	0.02003	0.196	0.51
V.f	4	0.04751	0.030	1.99	0.10899	0.020	2.79
V.d	4	0.00222	0.919	0.09	0.02821	0.312	0.72
f.d	4	0.12204	0.002	5.10	0.06806	0.065	1.74
Error	8	0.02011	-	0.84	0.03983	-	1.02
Total	26	2.39327	-	100	3.90807	-	100

workpiece movement as shown in another study (Bouzid *et al*. 2014, Bouchelaghem *et al*. 2007), on the other hand, this phenomenon is explained by the reduce of feed caused low cutting forces, which results less vibration, providing better surface finish. Similar investigations have been made in the same context. For example, Yallese *et al*. (2009) found that

Table 5 Cutting force components ANOVA results of coated inserts

ANOVA (CI= 95%)		Fa (R^2=98.07%)			Fr (R^2=96.86%)			Ft (R^2=97.85%)		
Source	DF	SS	P	PC (%)	SS	P	PC (%)	SS	P	PC (%)
V	2	577.35	0.014	3.73	1117.06	0.012	6.27	201.7	0.422	0.52
f	2	2514.42	0.000	16.25	3861.51	0.000	21.68	17993.4	0.000	46.20
d	2	10026.47	0.000	64.81	10909.70	0.000	61.24	16748.6	0.000	43.01
V.f	4	964.02	0.013	6.23	1000.20	0.059	5.61	496.5	0.387	1.27
V.d	4	47.79	0.857	0.31	59.72	0.924	0.34	665.8	0.267	1.71
f.d	4	1041.00	0.010	6.73	305.50	0.423	1.71	2000.2	0.029	5.14
Error	8	299.23	-	1.93	560.09	-	3.14	838.5	-	2.15
Total	26	15470.29	-	100	17813.78	-	100	38944.8	-	100

Table 6 Cutting force components' ANOVA results of uncoated inserts

ANOVA (CI= 95%)		Fa (R^2= 98.01%)			Fr (R^2= 96.63%)			Ft (R^2= 96.96%)		
Source	DF	SS	P	PC(%)	SS	P	PC(%)	SS	P	PC(%)
V	2	832.9	0.028	2.89	8012.2	0.000	19.40	474.5	0.488	0.60
f	2	794.5	0.031	2.76	3948.7	0.005	9.56	14043.2	0.000	17.64
d	2	25418.1	0.000	88.23	22752.1	0.000	55.09	57096.2	0.000	71.73
V.f	4	409.2	0.310	1.42	1459.2	0.173	3.53	992.2	0.547	1.25
V.d	4	642.3	0.155	2.23	1609.7	0.145	3.90	2009.9	0.250	2.52
f.d	4	138.8	0.748	0.48	2130.6	0.083	5.16	2571.9	0.169	3.23
Error	8	574.5	-	1.99	1390.2	-	3.37	2416.0	-	3.04
Total	26	28810.3	-	100	41302.7	-	100	79603.9	-	100

the improvement of surface roughness (Ra) is caused by decreasing in the cutting forces at high cutting speeds, which also influences the machining system stability. Fig. 4 shows the main effect of the studied factors on the surface roughness. It is clear that the surface roughness is directly proportional to the increase of the feed and cutting depth and inversely proportional to the cutting speed.

3.1.2 Cutting force components

The ANOVA results of cutting force components using coated insert are illustrated in Table 5. This analysis was performed for a confidence interval (CI) of 95 %. It can be seen that cutting depth is the most significant parameter influencing the cutting force components with contributions of 64.81%, 61.24% and 43.01% for Fa, Fr and Ft, respectively. The other factor that has effect on cutting force components is feed with the following percents of contribution: 16.25%, 21.68% and 46.20% for Fa, Fr and Ft, respectively. However, the cutting speed has the smallest impact on the cutting force components. In same context, the ANOVA results of cutting force components for the uncoated insert are presented in Table 6. This analysis was performed for a confidence level of 95 %. It can be seen that cutting depth has the most significant effect, with the contribution percents 88.23%, 55.09% and 71.73%, for the cutting force components namely Fa, Fr and Ft, respectively.

The feed effect on the tangential force component was 17.64% and the cutting speed effect on the thrust

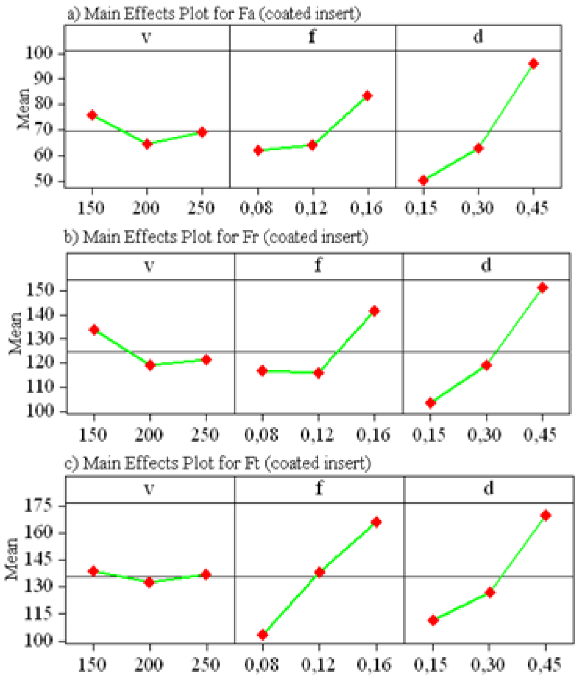

Fig. 5 Force components variation with coated inserts

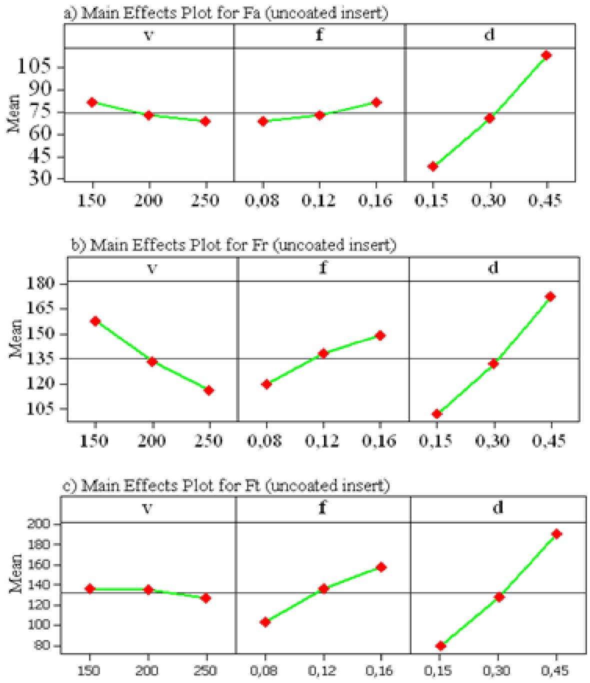

Fig. 6 Force components variation with uncoated inserts

component was 19.4%. However, a small effect of feed, cutting speed and their interaction on the feed component was found. The plots of the main effects of cutting parameters for coated and uncoated inserts are shown in Fig. 5 and Fig. 6, respectively. The analysis shows that the increase of the cutting speeds decrease the cutting forces. Furthermore, an increase in feed or cutting depth increases the cutting forces. This is due to the cut cross-section, which increases with the depth of cut and feed. However, the cutting speed effect on the cutting forces is relatively low. This is interpreted by the increase of temperature in the cutting zone under the effect of the increasing cutting speed and plastic deformation in two shear zones (primary and secondary). This high heat modifies the mechanical properties of the machined material and therefore the creation energy of the chip decreases and so do the cutting forces, as shown by Yallese *et al*. (2009).

3.1.3 Mathematical modeling

The Response Surface Methodology (RSM) is a mathematical and statistical technique widely used in modeling and analyzing many problems, when a response of interest is influenced by several variables and the goal is to optimize this response (Khuri and Mukhopadhyay 2010). In RSM problems, the relationship between the response of interest and independent variables is expressed by the second-degree model called the full quadratic model; this model can be explained as follows

$$Y = a_0 + \sum_{i=1}^{n} a_{ii}\, X_i + \sum_{i=1}^{n} a_{ii}\, X_i^2 + \sum_{i\neq j}^{n} a_{ij}\, X_i X_j \qquad (1)$$

Where, (Y) is the estimated response (surface roughness or cutting forces). a_0, a_i, a_{ij} and a_{ii} are the adopted mathematical model coefficients. They are not identified and must be calculated from the experimental results. (X_i) Is a variable or a factor influencing the response (Y), corresponding to the studied cutting condition parameters such as cutting speed (V), feed (f) and depth of cut (d) and their interactions.

The quadratic models for surface roughness (Ra) and cutting force components (Fa, Ft and Fr) were obtained from the experimental data. The values of the coefficients involved in Eq. (1) were calculated by (RSM) using Minitab v.16 software. Mathematical equations of the fitted models for surface roughness and cutting force components are given below.

The arithmetic mean roughness (Ra) models of inserts with and without coating are given below in Eq. (2) and Eq. (3), respectively.

$$\begin{aligned} Ra_{coated} &= 0.178 + 0.004\, v - 0.917 f - 1.148\, d \\ &-4.667e^{-006}\, v^2 - 0.026\, v.f - 0.002\, v.d \\ &+50\, f^2 8.333 f.d + 1.185\, d^2 \end{aligned} \qquad (2)$$

$$\begin{aligned} Ra_{uncoated} &= 3.178 - 0.013v - 20.94f - 1.537d \\ &+1.289\, e^{-005}\, v^2 + 0.0346\, v.f + 0.005\, v.d \\ &+95.139\, f^2 + 5.833 f.d + 0.098\, d^2 \end{aligned} \qquad (3)$$

Models of the three components of cutting force (Fa, Fr and Ft) of coated insert are given as

$$\begin{aligned} F_a = &\ 216.64 - 1.012v - 842.33f - 303.2\, d \\ &+0.0032\, v^2 - 2.955\, v.f + 0.103v.d + 5407.2f^2 \\ &+1342.92f.d + 456.444\, d^2 \end{aligned} \qquad (4)$$

$$\begin{aligned} F_r = &\ 256.91 - 0.942v - 1070.76\, f - 161.59d \\ &+0.003\, v^2 - 4.28v.f + 0.03v.d + 8387.85f^2 \\ &+749.7\, f.d + 376.69\, d^2 \end{aligned} \qquad (5)$$

$$F_t = 139.81 - 0.888v + 1039.81f - 416.257d + 0.0022v^2 - 0.91\, v.f + 0.35\, v.d - 2161.5f^2 + 1495.9\, f.d + 605.4d^2 \tag{6}$$

Models of the three components of cutting force (Fa, Fr and Ft) of uncoated insert are given below in Eq. (7)-(9) respectively.

$$F_a = 41.35 - 0.265v - 205.26f + 204.79d + 0.001v^2 - 0.625v.f - 0.659v.d + 1627.8\, f^2 + 337.92\, f.d + 227.01d^2 \tag{7}$$

$$F_r = 55.62 - 0.245v + 1443.71f - 8.47d + 0.0016v^2 - 5.352v.f - 0.519v.d - 2273.26f^2 + 1795.8\, f.d + 221.605d^2 \tag{8}$$

$$F_t = -157.39 + 1.11\, v + 1682.46f - 53.1\, d - 0.002\, v^2 - 3.922\, v.f - 0.194\, v.d - 3729.5\, f^2 + 2300\, f.d + 317.5\, d^2 \tag{9}$$

3.1.4 Adequacy test

The adequacy of the obtained models was tested using ANOVA method, according to its results in Table 7. The quadratic models of surface roughness and cutting forces for coated and uncoated inserts, indicates that the relationship between the response variable and the predictor factors was significant within the confidence limit, which is illustrated by the *p*-value=0.000 which is less than alpha value (0.05). The coefficient of determination (R^2) was estimated to check the accuracy of the fit. For the surface roughness of coated and uncoated inserts, the (R^2) values were 94.66% and 96.01, respectively. The predicted coefficient of determination (R^2_{pred}) for surface roughness using quadratic model with coated and uncoated insert were 87.25% and 88.11%, respectively. The coefficients of determination (R^2) for cutting force components (Fa. Fr and Ft), using coated and uncoated inserts, were in excellent agreement, which indicates the fitness of the developed regression models. In addition, the accuracy in prediction may be found by calculating the correlation coefficient (*r*) and root mean square of percentage deviation (*e*) between the theoretical and experimental values (Table 7). The correlation coefficient (*r*) for "*N*" number of observations is evaluated as

$$r = \frac{N\sum X_i Y_i - (\sum X_i)(\sum Y_i)}{\sqrt{N\sum X_i^2 - (\sum X_i)^2}\sqrt{N\sum Y_i^2 - (\sum Y_i)^2}} \tag{10}$$

The percentage deviation (e_i) is expressed as

$$e_i = \frac{X_i - Y_i}{X_i} \times 100 \tag{11}$$

And, the root mean square of percentage deviation (*e*) is expressed as

$$e = \sqrt{\frac{\sum (e_i)^2}{N}} \tag{12}$$

The coefficient of correlation values (*r*) for all models were ranged between 0.95 and 0.97, showing a good agreement between the experimental and theoretical results.

Table 7 Summary of surface roughness and cutting force models with coated and uncoated insert

Model of Studied parameters		*p*-value	R^2 (%)	R^2_{pred} (%)	*r*	*e*
Coated insert	Ra	0.000	94.66	87.25	0.97	2.06
	Fa	0.000	92.58	81.01	0.96	1.88
	Fr	0.000	95.50	87.28	0.97	0.85
	Ft	0.000	92.52	81.28	0.96	1.76
Uncoated insert	Ra	0.000	96.01	88.11	0.97	2
	Fa	0.000	95.13	87.96	0.97	2.65
	Fr	0.000	91.19	75.87	0.95	2.12
	Ft	0.000	93.79	84.04	0.96	2.58

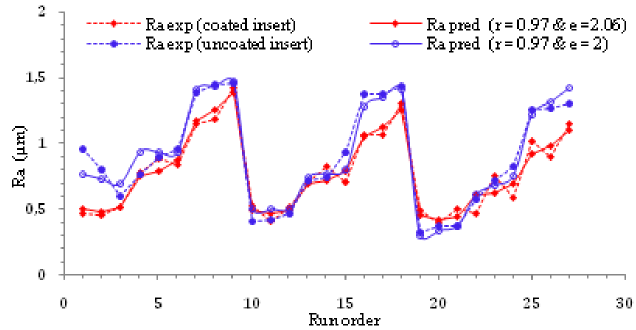

Fig. 7 Comparison between measured and predicted values of Ra with and without coating

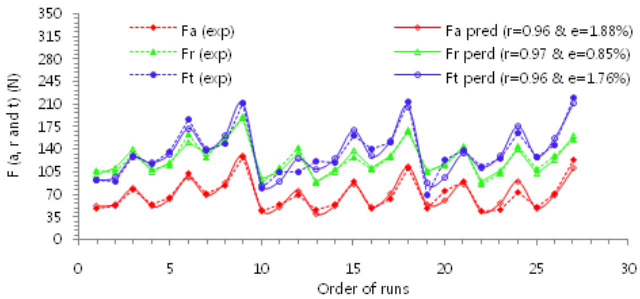

Fig. 8 Comparison between measured and predicted values of Fa, Fr and Ft for coated insert

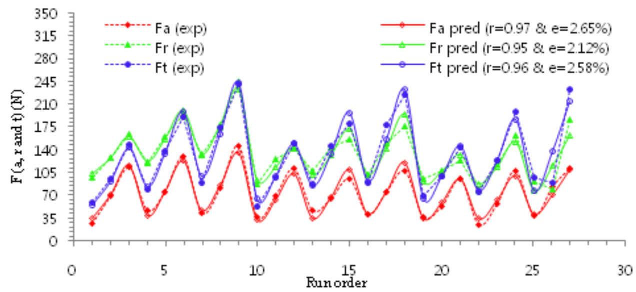

Fig. 9 Comparison between measured and predicted values of Fa, Fr and Ft for uncoated insert

The root mean square deviation of thrust force (Fr) regression model if using coated insert provided a smaller value of 0.85. For the surface roughness of coated and uncoated inserts, the root mean squares were 2.06% and 2.65%, respectively. Figs. 7-9 show a graphical comparison

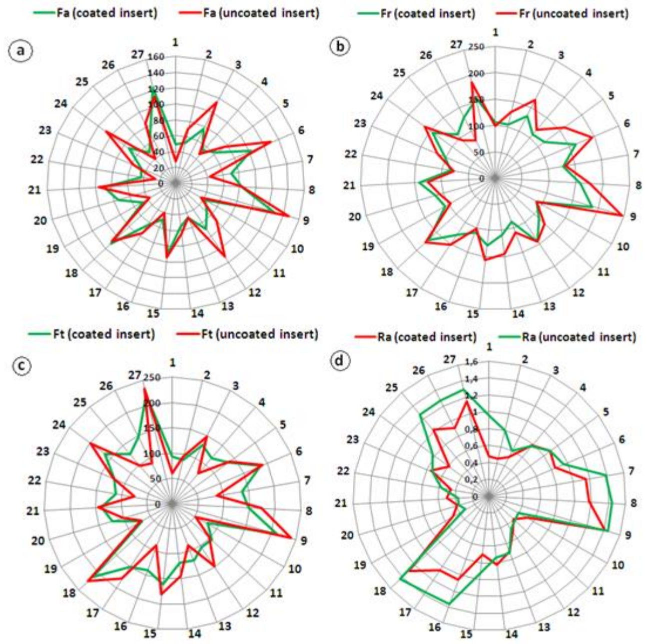

Fig. 10 Effect of coating layers on surface roughness and cutting force components

between the predicted and experimental values of surface roughness (Ra) and cutting forces (Fa, Fr and Ft) for coated and uncoated inserts.

3.2 Impact of coating material

The coating layers' effect on the surface roughness and cutting force was another aim of this study. For this purpose, the experiments were repeated for two types of inserts with and without coating. Cermet tools had completely the same geometry and substrate, the only difference was the coating layer. The inserts employed in the experiments had an identical nose radius, and its effect was not investigated in this study. The effect of tool wear was neglected using a fresh cutting edge for each experiment. In addition, the effect of workpiece material hardness was not investigated in this study.

The effects of coating layers on the surface roughness and cutting forces are depicted in Fig. 10(a)-(d). These figures show a graphical comparison of the experimental values of surface roughness (Ra) and cutting forces (Fa, Fr and Ft) obtained by coated and uncoated inserts. In each graph, the axis from the center to outside shows the experimental values, whereas the run order is presented in the outside circle. The effects of coating layers on cutting force components (Fa, Fr and Ft) are shown in Fig. 10 (a)-(c). It can be seen that the presence of the (TiCN) layer played an important role in protecting the substrate. Its presence gave lower values of cutting force components (Fa, Fr and Ft) when compared to uncoated inserts, which may contribute to improve the surface quality. Furthermore, it can be concluded from Fig.10 (d) that high surface quality was achieved when employing PVD (TiCN/TiN) coated insert. This can be explained by an improvement in the contact friction at the tool-chip interface which contributes to decrease the cutting forces and contact temperature. Smaller cutting forces cause less vibration and provide better surface finish as demonstrated in previous papers (Chinchanikar and Choudhury 2013, Grzesik *et al*. 2009).

4. Conclusions

This paper presents an experimental investigation of the impact of coating material of cutting tools and cutting parameters on surface roughness and cutting forces in dry turning of AISI 52100 steel. The following conclusion can be drawn based on the experimental results obtained in the scope of this study:

- The ANOVA method in investigation of experimental results proved excellent fitting indicators, namely, the coefficients of determination and the significance level,
- According to the ANOVA analysis, the feed has the most significant effect on the surface roughness for coated and uncoated inserts. Its contributions were estimated as 85.17% and 85.67% for coated and uncoated inserts, respectively. Concerning the cutting force components namely (Fa, Fr and Ft), the ANOVA analysis showed that the cutting depth is the most significant factor which contributed (64.81%, 61.24% and 43.01%) and (88.23%, 55.09% and 71.73%) for inserts with and without coating, respectively.
- A second order regression model was developed. A statistical analysis method was added in this study in order to evaluate the accuracy of the proposed models. The coefficients of correlation (r) were in the range error of 0.95 to 0.97 and the root mean square of percent deviation values varied in the range of 0.85% to 2.64%. Consequently, a good agreement was found between the proposed theoretical models and the experimental data.
- Lower surface roughness values were obtained when employing PVD (TiCN-TiN) coated insert. The mean value of surface roughness was improved to 0.77 for the coated insert compared to 0.89 for the uncoated one.

References

Aouici, H., Bouchelaghem, H., Yallese, M.A., Elbah, M. and Fnides, B. (2014), "Machinability investigation in hard turning of AISI D3 cold work steel with ceramic tool using response surface methodology", *Int. J. Adv. Manuf. Techol.*, **73**(9-12), 1775-1788.

Aurich, J.C., Eyrisch, T. and Zimmermann, M. (2012), "Effect of the coating system on the tool performance when turning heat treated AISI 4140", *Procedia CIRP*, **1**, 214-219.

Azizi, M.W., Belhadi, S., Yallese, M.A., Mabrouki, T. and Rigal, J.F. (2012), "Surface roughness and cutting forces modeling for optimization of machining condition in finish hard turning of AISI 52100 steel", *J. Mech. Sci. Technol.*, **26**(12), 4105-4114.

Bouacha, K., Yallese, M.A., Khamel, S. and Belhadi, S. (2014), "Analysis and optimization of hard turning operation using cubic boron nitride tool", *Int. J. Refract. Metal. Hard Mater.*, **45**, 160-178.

Bouchelaghem, H., Yallese, M.A., Amirat, A., and Belhadi, S. (2007), "Wear behaviour of CBN tool when turning hardened AISI D3 steel", *Mechanika*, **65**(3), 57-65.

Bouzid, L., Boutabba, S., Yallese, M.A., Belhadi, S. and Girardin, F. (2014), “Simultaneous optimization of surface roughness and material removal rate for turning of X20Cr13 stainless steel”, *Int. J. Adv. Manuf. Techol.*, **74**(5-8), 879-891.

Cakir, M.C., Ensarioglu, C. and Demirayak, I. (2009), “Mathematical modeling of surface roughness for evaluating the effects of cutting parameters and coating material”, *J. Mater. Pr. Tech.*, **209**(1), 102-109.

Chinchanikar, S. and Choudhury, S.K. (2013), “Effect of work material hardness and cutting parameters on performance of coated carbide tool when turning hardened steel: An optimization approach”, *Measur.*, **46**(4), 1572-1584.

Chinchanikar, S. and Choudhury, S.K. (2015), “Machining of hardened steel-Experimental investigations, performance modeling and cooling techniques: A review”, *Int. J. Mach. Tool. Manuf.*, **89**, 95-109.

Das, S.R., Dhupal, D. and Kumar, A. (2015), “Experimental investigation into machinability of hardened AISI 4140 steel using TiN coated ceramic tool”, *Measurement*, **62**, 108-126.

Elbah, M., Yallese, M.A., Aouici, H., Mabrouki, T., and Rigal, J.F. (2013), “Comparative assessment of wiper and conventional ceramic tools on surface roughness in hard turning AISI 4140 steel”, *Measurement*, **46**(9), 3041-3056.

Grzesik, W. (1998), “The role of coatings in controlling the cutting process when turning with coated indexable inserts”, *J. Mater. Pr. Technol.*, **79**(1), 133-143.

Grzesik, W. and Nieslony, P. (2004), “Prediction of friction and heat flow in machining incorporating thermophysical properties of the coating-chip interface”, *Wear*, **256**(1), 108-117.

Grzesik, W., Rech, J., Żak, K. and Claudin, C. (2009), “Machining performance of pearlitic-ferritic nodular cast iron with coated carbide and silicon nitride ceramic tools”, *Int. J. Mach. Tool. Manuf.*, **49**(2), 125-133.

Hayajneh, M.T., Tahat, M.S. and Bluhm, J. (2007), “A study of the effects of machining parameters on the surface roughness in the end-milling process”, *Jordan J. Mech. Indus. Eng.*, **1**, 1-5.

Hessainia, Z., Belbah, A., Yallese, M.A., Mabrouki, T. and Rigal, J. F. (2013), “On the prediction of surface roughness in the hard turning based on cutting parameters and tool vibrations”, *Measur.*, **46**(5), 1671-1681.

Khuri, A.I. and Mukhopadhyay, S. (2010), “Response surface methodology”, *Wiley Interdisc. Rev.: Comput. Statist.*, **2**(2), 128-149.

Makadia, A.J. and Nanavati, J.I. (2013), “Optimisation of machining parameters for turning operations based on response surface methodology”, *Measur.*, **46**(4), 1521-1529.

Meddour, I., Yallese, M.A., Khattabi, R., Elbah, M. and Boulanouar, L. (2015), “Investigation and modeling of cutting forces and surface roughness when hard turning of AISI 52100 steel with mixed ceramic tool: cutting conditions optimization”, *Int. J. Adv. Manuf. Techol.*,**77**(5-8), 1387-1399.

Neşeli, S., Yaldız, S. and Türkeş, E. (2011), “Optimization of tool geometry parameters for turning operations based on the response surface methodology”, *Measur.*, **44**(3), 580-587.

Sahoo, A.K. and Sahoo, B. (2012), “Experimental investigations on machinability aspects in finish hard turning of AISI 4340 steel using uncoated and multilayer coated carbide inserts”, *Measur.*, **45**(8), 2153-2165.

Sahoo, A.K. and Sahoo, B. (2013), “Performance studies of multilayer hard surface coatings (TiN/TiCN/Al_2O_3/TiN) of indexable carbide inserts in hard machining: Part-I (An experimental approach)”, *Measur.*, **46**(8), 2854-2867.

Senthilkumar, N. and Tamizharasan, T. (2014), “Effect of tool geometry in turning AISI 1045 steel: experimental investigation and FEM analysis”, *Arabian J. Sci. Eng.*, **39**(6), 4963-4975.

Upadhyay, V., Jain, P.K. and Mehta, N.K. (2013), “In-process prediction of surface roughness in turning of Ti-6Al-4V alloy using cutting parameters and vibration signals”, *Measur.*, **46**(1), 154-160.

Yallese, M.A., Boulanouar, L. and Chaoui, K. (2004), “Usinage de l'acier 100Cr6 trempé par un outil en nitrure de bore cubique“, *Mécaniq. Indust.*, **5**(4), 355-368.

Yallese, M.A., Chaoui, K., Zeghib, N., Boulanouar, L, and Rigal, J.F. (2009), “Hard machining of hardened bearing steel using cubic boron nitride tool”, *J. Mater. Pr. Technol.*, **209**(2), 1092-1104.

Zhang, K., Deng, J., Meng, R., Gao, P. and Yue, H. (2015), “Effect of nano-scale textures on cutting performance of WC/Co-based Ti 55 Al 45 N coated tools in dry cutting”, *Int. J. Refract. Metal. Hard Mater.*, **51**, 35-49.

CC