ISSN 1392 - 1207. MECHANIKA. 2009. Nr.3(77)

Surface roughness model in turning hardened hot work steel using mixed ceramic tool

B. Fnides*, M. A. Yallese*, T. Mabrouki, J-F. Rigal****

**Mechanics and Structures Laboratory (LMS), Department of Mechanical Engineering, May 08th 1945 University, Guelma 24000, Algeria, E-mail: fbrahim@yahoo.fr*

***Laboratoire de Mécanique des Contacts et des Solides (LaMCoS), INSA de Lyon, 20 Avenue Albert Einstein, 69 621 Villeurbanne Cedex, France, E-mail: jean-francois.rigal@insa-lyon.fr*

Nomenclature

a_p - depth of cut, mm; f - feed rate, mm/rev; *HRC* - Rockwell hardness; R^2 - coefficient of determination; *Ra* - arithmetic mean roughness, µm; *Rt* - total roughness, µm; *Rz* - mean depth of roughness, µm; r_ε - tool nose radius, mm; V_c - cutting speed, m/min; α - relief angle, degree; γ - rake angle, degree; λ - inclination angle, degree; χ - major cutting edge angle, degree.

1. Introduction

Hard turning is a cutting process defined as turning materials with hardness higher than 45 HRC with appropriate cutting tools and under high cutting speed. Machining of hard steel using advanced tool materials, such as cubic boron nitride and mixed ceramic, has more advantages than grinding or polishing, such as short cycle time, process flexibility, compatible surface roughness, higher material removal rate and less environment problems as there is no use of cutting fluid. This process has become a normal practice in industry because it increased productivity and reduced energy consumption [1-3].

Alumina (Al_2O_3) based ceramics are considered to be one of the most suitable tool materials for machining hardened steels because of their high hot hardness, wear resistance and chemical inertness [4].

Surface roughness is classified among the most important technological parameters in machining process. It is in relation to many properties of machine elements such as wear resistance, the capacity of fit and sealing. Theoretical surface roughness achievable based on tool geometry and feed rate is given approximately by the formula: $Ra = 0.032 f^2 / r_\varepsilon$. In hard turning, surface finish has been found to be influenced by a number of factors such as feed rate, cutting speed, tool nose radius and tool geometry, cutting time, workpiece hardness, stability of the machine tool and the workpiece set up, etc [5-6].

In order to know surface quality values in advance, it is necessary to employ empirical models making it feasible to do predictions in a function of operation conditions. To calculate constants and coefficients of these models, we used software Minitab characterized by Analysis of Variance: ANOVA, multiple regression and Response Surface Methodology (RSM).

2. Experimental procedure

The material used for experiments is X38CrMoV5-1, hot work steel which is popular for the use in hot form pressing. Its resistance to high temperature and its aptitude for polishing enable it to meet the most severe requests in hot dieing and moulds under pressure [7]. Its chemical composition is as follows: 0.35% C; 5.26% Cr; 1.19% Mo; 0.5% V; 1.01% Si; 0.32% Mn; 0.002% S; 0.016% P; 1.042% other components and 90.31% Fe. The workpiece is of 270 mm length and 75 mm in diameter and it is machined under dry condition. It is hardened to 50 HRC. Its hardness was measured by a digital durometer DM2D. The lathe used for machining operations is TOS TRENCIN; model SN40C, spindle power 6.6KW. A roughness meter (2d) Surftest 201 Mitutoyo was selected to measure different criteria of surface roughness (*Ra*, *Rt* and *Rz*) as shown in Fig. 1. Roughness values were obtained without disassembling the workpiece in order to reduce uncertainties due to resumption operations.

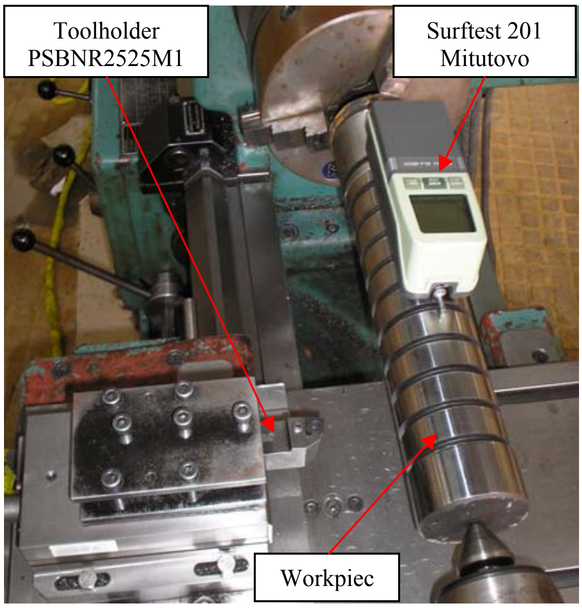

Fig. 1 Experimental configuration for measuring surface roughness criteria

Table 1

Assignment of the levels to the variables

Level	V_c, m/min	f, mm/rev	a_p, mm
1(low)	90	0.08	0.15
2(medium)	120	0.12	0.30
3(high)	180	0.16	0.45

The cutting insert used is a mixed ceramic (CC650), removable, of square form with eight cutting edges and having designation SNGA 120408 T01020. The insert is mounted on a commercial toolholder of designation PSBNR2525M12 with the geometry of active part characterized by the following angles: $\chi = 75°$; $\alpha = 6°$; $\gamma = -6°$; $\lambda = -6°$ [8]. Three levels were defined for each cutting variable as given in Table 1. The variable levels were chosen within the intervals recommended by the cutting tool manufacturer. Three cutting variables at three levels led to a total of 27 tests.

3. Results and discussion

Table 2 presents experimental results of surface roughness criteria (*Ra, Rt* and *Rz*) for various combinations of cutting regime elements (cutting speed, feed rate and depth of cut) according to 3^3 full factorial design. Minimal values of surface roughness criteria (*Ra, Rt* and *Rz*) were obtained at $V_c = 180$ m/min, $f = 0.08$ mm/rev and $a_p = 0.15$ mm (test number 19). That means increasing of cutting speed with the lowest feed rate and depth of the cut lead to decreasing of surface roughness.

Table 2

Design layout and experimental results for surface roughness criteria

Tests N°	Coded factors			Actual factors			Performance measures		
	X1	*X2*	*X3*	V_c, m/min	*f*, mm/rev	a_p, mm	*Ra*, µm	*Rt*, µm	*Rz*, µm
1	-1	-1	-1	90	0.08	0.15	0.41	3.44	2.36
2	-1	-1	0	90	0.08	0.30	0.43	3.47	2.39
3	-1	-1	1	90	0.08	0.45	0.44	3.48	2.40
4	-1	0	-1	90	0.12	0.15	0.53	3.95	3.11
5	-1	0	0	90	0.12	0.30	0.55	3.99	3.15
6	-1	0	1	90	0.12	0.45	0.56	4.02	3.16
7	-1	1	-1	90	0.16	0.15	0.69	4.50	3.81
8	-1	1	0	90	0.16	0.30	0.71	4.56	3.84
9	-1	1	1	90	0.16	0.45	0.72	4.59	3.88
10	0	-1	-1	120	0.08	0.15	0.35	3.32	2.19
11	0	-1	0	120	0.08	0.30	0.40	2.67	2.44
12	0	-1	1	120	0.08	0.45	0.41	3.07	2.33
13	0	0	-1	120	0.12	0.15	0.46	3.54	2.95
14	0	0	0	120	0.12	0.30	0.49	3.59	2.97
15	0	0	1	120	0.12	0.45	0.51	3.60	2.99
16	0	1	-1	120	0.16	0.15	0.56	3.75	3.50
17	0	1	0	120	0.16	0.30	0.59	3.97	3.45
18	0	1	1	120	0.16	0.45	0.62	4.16	3.55
19	1	-1	-1	180	0.08	0.15	0.30	2.80	2.10
20	1	-1	0	180	0.08	0.30	0.33	2.82	2.12
21	1	-1	1	180	0.08	0.45	0.34	2.85	2.15
22	1	0	-1	180	0.12	0.15	0.43	3.36	2.73
23	1	0	0	180	0.12	0.30	0.46	3.40	2.76
24	1	0	1	180	0.12	0.45	0.47	3.41	2.78
25	1	1	-1	180	0.16	0.15	0.54	3.67	3.37
26	1	1	0	180	0.16	0.30	0.56	3.76	3.36
27	1	1	1	180	0.16	0.45	0.58	3.81	3.38

Maximal values of surface roughness criteria (*Ra, Rt* and *Rz*) were registered at $V_c = 90$ m/min and $f = 0.16$ mm/rev and $a_p = 0.45$mm (test number 9). In order to achieve better surface finish, the highest level of cutting speed, 180 m/min, the lowest level of feed rate, 0.08 mm/rev, should be recommended.

3.1. ANOVA for *Ra*

The results of analysis of variance (ANOVA) for surface roughness *Ra* are shown in Table 3. This table also shows the degrees of freedom (DF), sum of squares (SS), mean square (MS), F-values (F-VAL.) and probability (P-VAL.) in addition to the percentage contribution (Contr. %) of each factor and different interactions.

Table 3

ANOVA for *Ra*

Source	DF	SS	MS	F-VAL.	P-VAL.	Contr. %
V_c	2	0.060289	0.030144	2170.40	<0.001	18.05
f	2	0.259267	0.129633	9333.60	<0.001	77.61
a_p	2	0.008289	0.004144	298.40	<0.001	2.48
$V_c \times f$	4	0.005444	0.001361	98.00	<0.001	1.63
$V_c \times ap$	4	0.000556	0.000139	10.00	0.003	0.17
$a_p \times f$	4	0.000111	0.000028	2.00	0.187	0.03
Error	8	0.000111	0.000014			0.03
Total	26	0.334067				100

A low P-value indicates statistical significance for the source on the corresponding response [9-10].

It is clear from the results of ANOVA that the feed rate is the dominant factor affecting surface finish *Ra*. Its contribution is 77.61%. The second factor influencing *Ra* is cutting speed. Its contribution is 18.05%. As for the depth of cut, its contribution is 2.48%. The interactions $V_c{\times}f$ and $V_c{\times}a_p$ are significant but interaction $a_p{\times}f$ is not significant. Respectively, their contributions are (1.63; 0.17 and 0.03) %.

To understand the hard turning process in terms of surface roughness *Ra*, mathematical model was developed using multiple regression method.

Ra model is given by equation (1). Its coefficient of correlation R^2 is 96.24%.

$$Ra = 0.19254 - 0.00075V_c + 3.54167f + 0.11667a_p - 0.00417V_c{\times}f + 0.00019V_c{\times}a_p \quad (1)$$

3. 2. 3D Surface plots of *Ra*

3D Surface plots of *Ra* vs. different combinations of cutting regime elements are shown in Figs. 2, 3 and 4. These figures were obtained using response surface methodology (RSM).

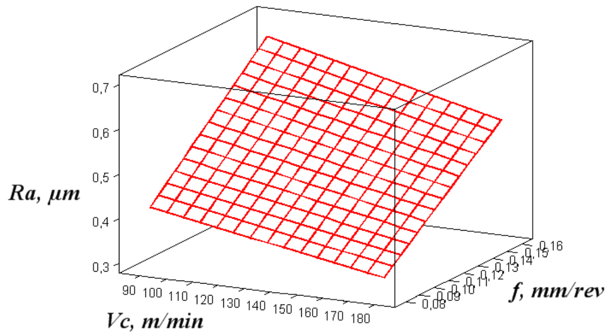

Fig. 2 3D Surface plot of *Ra* vs. V_c and *f*

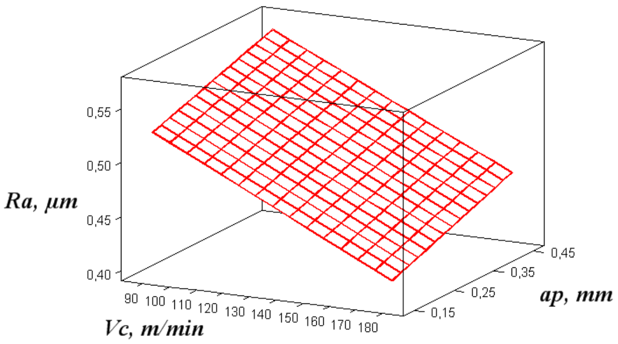

Fig. 3 3D Surface plot of *Ra* vs. V_c and a_p

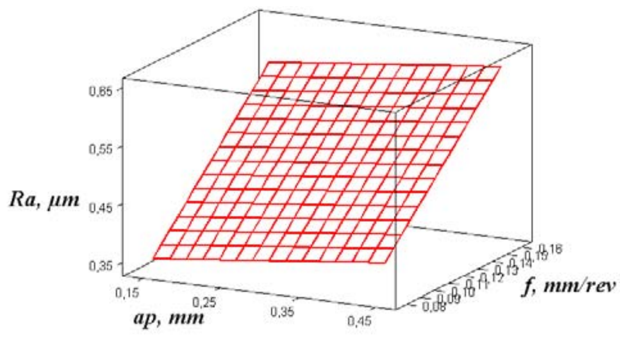

Fig. 4 3D Surface plot of *Ra* vs. a_p and *f*

3. 3. Effect graphs of the main cutting regime on *Ra*

Fig. 5 gives the main factor plots for *Ra*. Surface roughness *Ra* appears to be a decreasing function of V_c. This figure also indicates that *Ra* is an almost linear increasing function of *f*. But the depth of cut a_p has a little effect on *Ra*.

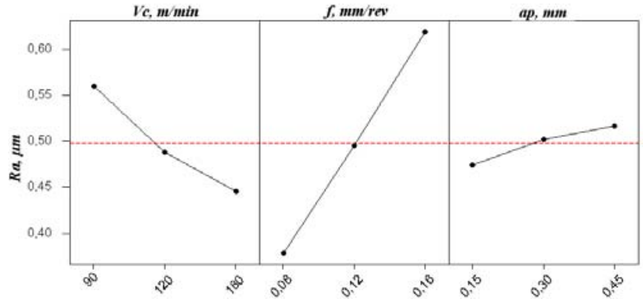

Fig. 5 Graphs of the main cutting variables effects on *Ra*

3. 4. ANOVA for *Rt*

Table 4 presents ANOVA results for *Rt*. It can be seen that the feed rate is the most important factor affecting surface finish *Rt*. Its contribution is 63.03%.

Table 4

ANOVA for *Rt*

Source	DF	SS	MS	F-VAL.	P-VAL.	Contr. %
V_c	2	2.20027	1.10014	61.80	<0.001	31.73
f	2	4.37090	2.18545	122.77	<0.001	63.03
a_p	2	0.03790	0.01895	1.06	0.389	0.55
$V_c \times f$	4	0.04246	0.01061	0.60	0.676	0.61
$V_c \times a_p$	4	0.04019	0.01005	0.56	0.696	0.58
$a_p{\times}f$	4	0.10104	0.02526	1.42	0.311	1.46
Error	8	0.14241	0.01780			2.05
Total	26	6.93516				100

The second factor influencing *Rt* is cutting speed. Its contribution is 31.73%. As for the depth of cut, its effect is not significant because its contribution is 0.55%. The interactions $V_c{\times}f$, $V_c{\times}a_p$ and $a_p{\times}f$ are not significant. Respectively, their contributions are (0.61; 0.58 and 1.46) %. *Rt* model is given by Eq. (2). Its coefficient of correlation R^2 is 89.42%.

$$Rt = 2.9681 - 0.0069V_c + 12.2917f + 0.2444a \quad (2)$$

3. 5. 3D Surface plots of *Rt*

Figs. 6, 7 and 8 illustrate 3D surface plots of *Rt* according to the response surface methodology.

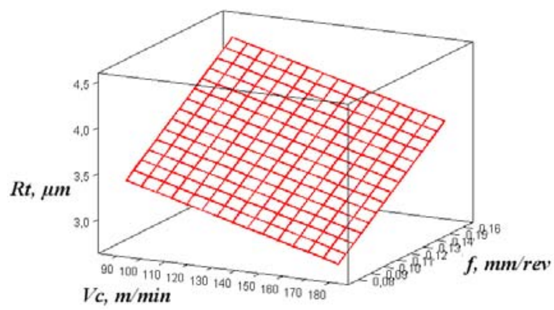

Fig. 6 3D Surface plot of *Rt* vs. V_c and *f*

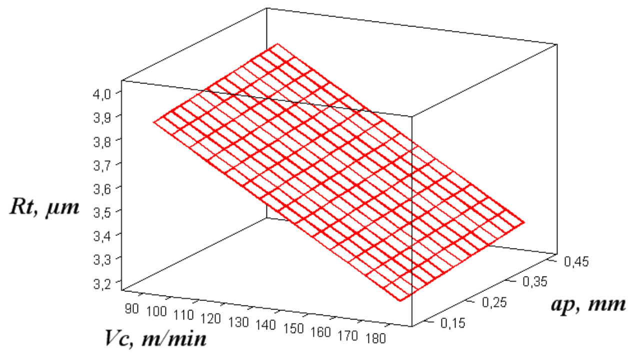

Fig. 7 3D Surface plot of *Rt* vs. V_c and a_p

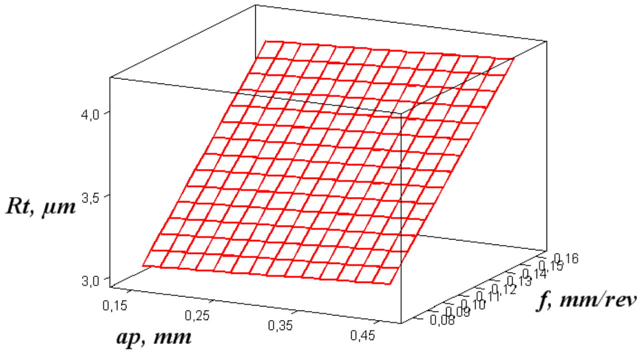

Fig. 8 3D Surface plot of *Rt* vs. a_p and *f*

3. 6. Effect graphs of the main cutting regime on *Rt*

Fig. 9 shows the main factor plots for *Rt*. Surface roughness *Rt* appears to be a decreasing function of V_c.

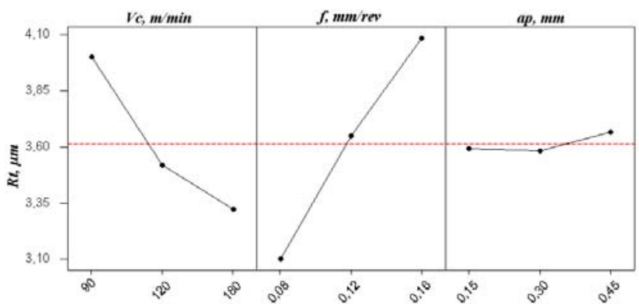

Fig. 9 Graphs of the main cutting variables effects on *Rt*

This figure also indicates that *Rt* is an almost linear increasing function of *f*. But the depth of cut a_p has not an effect on *Rt.*

3. 7. ANOVA for *Rz*

ANOVA results for *Rz* are indicated in Table 5. It can be noted that the feed rate affects *Rz* in a considerable way. Its contribution is 91.14%. The second factor influencing *Rz* is cutting speed. Its contribution is 7.52%. As for the depth of cut, its effect is not significant because its contribution is 0.18%. The interaction $V_c \times f$ is also significant. Its contribution is 0.80%. The interactions $V_c \times a_p$ and $a_p \times f$ are not significant. Respectively, their contributions are (0.03 and 0.12) %. *Rz* model is given by equation (3). Its coefficient of correlation R^2 is 98.69%.

Table 5

ANOVA for *Rz*

Source	DF	SS	MS	F-VAL.	P-VAL.	Contr. %
V_c	2	0.62370	0.31185	145.36	<0.001	7.52
f	2	7.55932	3.77966	1761.77	<0.001	91.14
a_p	2	0.01479	0.00739	3.45	0.083	0.18
$V_c \times f$	4	0.06677	0.01669	7.78	0.007	0.80
$V_c \times a_p$	4	0.00290	0.00073	0.34	0.845	0.03
$a_p \times f$	4	0.00981	0.00245	1.14	0.402	0.12
Error	8	0.01716	0.00215			0.21
Total	26	8.29445				100

$$Rz = 1.0865 - 0.0012V_c + 19.2381f + 0.1852a_p - 0.0234V_c \times f \quad (3)$$

3. 8. 3D Surface plots for *Rz*

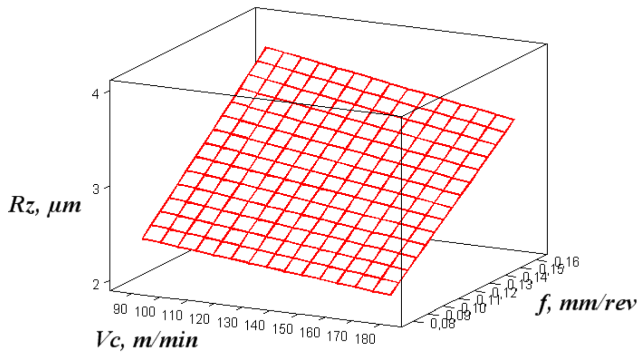

Fig. 10 3D Surface plot of *Rz* vs. V_c and *f*

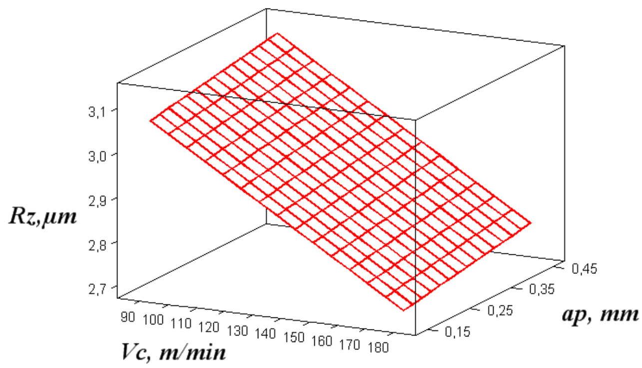

Fig. 11 3D Surface plot of *Rz* vs. V_c and a_p

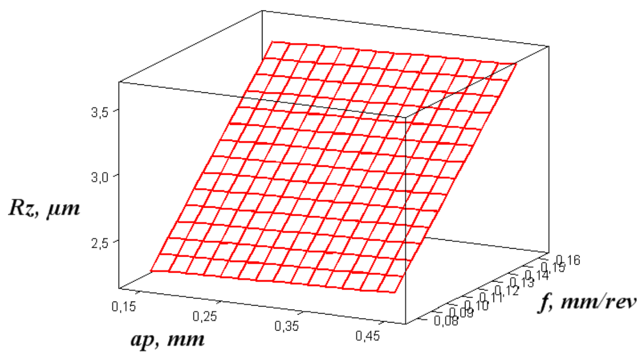

Fig. 12 3D Surface plot of *Rz* vs. a_p and *f*

Figs. 10, 11 and 12 show 3D surface plots for *Rz*. These figures were obtained by the response surface methodology for different combinations of cutting regime elements.

3. 9. Effect graphs of the main cutting regime on *Rz*

Fig. 13 highlights the main factor plots for *Rz*. Surface roughness *Rz* appears to be an almost linear decreasing function of V_c. This figure also indicates that *Rz* is an almost linear increasing function of *f*. But the depth of cut a_p has not an effect on *Rz*.

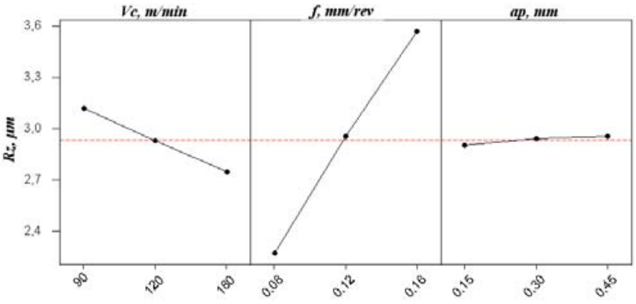

Fig. 13 Graphs of the main cutting variables effects on *Rz*

4. Conclusion

The tests of straight turning carried out on grade X38CrMoV5-1 steel treated at 50 HRC, machined by a mixed ceramic tool (insert CC650) enabled us to develop statistical models of surface roughness criteria. These models were obtained by the software Minitab using multiple regression method.

The results revealed that feed rate seems to influence surface roughness more significantly than cutting speed. However, the depth of cut is not significant. Thus, if we want to get good surface finish and much removed amount of chip, we must use the highest level of cutting speed, 180 m/min, the lowest level of feed rate, 0.08 mm/rev and the highest level of depth of cut, 0.45 mm.

Statistical models deduced defined the degree of influence of each cutting regime element on surface roughness criteria. They can also be used for the optimization of hard cutting process.

This study confirms that in dry hard turning of this steel and for all cutting conditions tested, the found roughness criteria are close to those obtained in grinding ($Ra < 0.73$ μm).

Acknowledgements

This work was completed in the laboratory LMS (University of Guelma, Algeria) in collaboration with LaMCos (CNRS, INSA-Lyon, France). The authors would like to thank the Algerian Ministry of Higher Education and Scientific Research (MESRS) and the Delegated Ministry for Scientific Research (MDRS) for granting financial support for CNEPRU Research Project – LMS: J-2401/03/80/06 (University of Guelma).

References

1. **Chen, W.** Cutting forces and surface finish when machining medium hardness steel using CBN tools. -International Journal of Machine Tools & Manufacture, 2000, 40, p.455-466.
2. **Singh, D., Rao, P.V.** A surface roughness prediction model for hard turning process. -Int. J. Adv. Manuf. Technol., 2007, 32, p.1115-1124.
3. **Fnides, B., Yallese, M.A., Aouici, H.** Hard turning of hot work steel AISI H11: Evaluation of cutting pressures, resulting force and temperature. -Mechanika. -Kaunas: Technologija, 2008, Nr.4(72), p.59-63.
4. **Dewes, R.C., Aspinwall, D. K.** A review of ultra high speed milling of hardened steels. -Journal of Materials Processing Technology, 1997, 69, p.1-17.
5. **Fnides, B., Aouici, H., Yallese, M.A.** Cutting forces and surface roughness in hard turning of hot work steel X38CrMoV5-1 using mixed ceramic. -Mechanika. -Kaunas: Technologija, 2008, Nr.2(70), p.73-78.
6. **Ozel, T., Hsu, T.K., Zeren, E**. Effects of cutting edge geometry, workpiece hardness, feed rate and cutting speed on surface roughness and forces in finish turning of hardened AISI H13 steel. -Int J Adv Manuf Technol, 2005, 25, p.262-269.
7. Site internet: http: //www. Buderus-steel.com.
8. SANDVIK Coromant, Catalogue Général, Outils de coupe Sandvik Coromant, Tournage – Fraisage – Perçage – Alésage - Attachements, 2009.
9. **Paulo Davim, J., Figueira, L.** Machinability evaluation in hard turning of cold work tool steel (D2) with ceramic tools using statistical techniques. -Journal of Materials & Design, 2007, 28, p.1186-1191.
10. **Sahin, Y., Motorcu, A. R.** Surface roughness model in machining hardened steel with cubic boron nitride cutting tool. -International Journal of Refractory Metals & Hard Materials, 2008, 26, p.84-90.

B. Fnides, M. A. Yallese, T. Mabrouki, J-F. Rigal

PAVIRŠIAUS ŠIURKŠČIO NUSTATYMO MODELIS TEKINANT SUKIETINTĄ, KARŠČIUI ATSPARŲ PLIENĄ MINERALŲ KERAMIKOS ĮRANKIU

R e z i u m ė

Šie eksperimentiniai tyrimai skirti paviršiaus šiurkščio parametrams nustatyti greitai tekinant gausiai legiruotą plieną X38CrMoV5-1. Iki 50 HRC kietumo užgrūdintas nevolframinis karščiui ir dilimui atsparus plienas, sukurtas Cr-Mo-V pagrindu apdirbamas mineralų keramikos įrankiu (plokštelės CC650 cheminė sudėtis 70%Al_2O_3+30%TiC). Jis naudojamas gaminti didelias apkrovas atlaikančioms formoms, tinkančioms lieti slegiant, ilgaamžėms kietlydinio plokštelėms, plastikiniams liejiniams, veikiamiems didelio slėgio, ir kaltų antgaliams.

Remiantis baigtiniu 3^3 faktorialiniu modeliavimu, atlikti 27 eksperimentiniai tyrimai. Kiekvieno parametro kitimo ribos nustatytos trijuose skirtinguose lygiuose: žemame, vidutiniame ir aukštame. Siekiant įvertinti kiekvieno pjovimo režimo įtakos laipsnį paviršiaus šiurkščiui, „Minitab" programine įranga (sudėtiniu regresijos metodu) paruošti matematiniai modeliai. Šie modeliai galėtų būti

naudingi parenkant pjovimo režimo kintamuosius pageidaujamiems paviršiaus šiurkščio parametrams užtikrinti. Jie gali būti panaudojami t greitojo pjovimo procesui optimizuoti.

Rezultatai rodo, kad paviršiaus šiurkščiui daugiausia įtakos turi pastūmos dydis ir pjovimo greitis. Pjovimo gylis ypatingos reikšmės neturi.

B. Fnides, M. A. Yallese, T. Mabrouki, J-F. Rigal

SURFACE ROUGHNESS MODEL IN TURNING HOT WORK STEEL USING MIXED CERAMIC TOOL

S u m m a r y

This experimental study is conducted to determine statistical models of surface roughness criteria in hard turning of high alloyed steel X38CrMoV5-1. This steel is hardened to 50 HRC, machined by a mixed ceramic tool (insert CC650 of chemical composition 70%Al_2O_3+30%TiC), free from tungsten on Cr-Mo-V basis, insensitive to temperature changes and having a high wear resistance. It is employed for the manufacture of highly stressed diecasting moulds and inserts with high tool life expectancy, plastic moulds subject to high stress and forging dies.

Based on 3^3 full factorial design, a total of 27 tests are carried out. The range of each parameter is set at three different levels, namely low, medium and high. Mathematical models were deduced by the software Minitab (multiple regression method) in order to express the influence degree of each cutting regime element on surface roughness. These models would be helpful in selecting cutting variables for the required surface roughness criteria. They can also be used for the optimization of hard cutting process.

The results indicate that feed rate is the dominant factor affecting surface roughness, followed by cutting speed. As for the depth of cut, its effect is not very important.

Б. Фнидес, М. А. Иаллесе, Т. Маброуки, J-F. Ригал

МОДЕЛЬ ДЛЯ ОПРЕДЕЛЕНИЯ ШЕРОХОВАТОСТИ ПОВЕРХНОСТИ ПРИ ТОЧЕНИИ ЖАРОСТОЙКОЙ СТАЛИ КЕРМЕТОМ

Р е з ю м е

Экспериментальные исследования предназначены для оценки параметров шероховатости поверхностей при скоростной обработке высоколегилированной стали.

Безвольфрамная 50 HRC твердости, жаро и износостойкая сталь, созданная на основе CrMoV, обрабатывается резцом с керметовой пластинкой (пластинка CC650, 70%Al_2O_3+30%TiC). Сталь CC650 используется при изготовлении литейных форм для литья под давлением, работающих под высокими нагрузками, износостойких твердотельных пластин, пластических сплавов, воздействуемых высоким давлением, и наконечников долота.

Используя полное 3^3 факториальное моделирование проведено 27 экспериментальных исследований. Предел изменения каждого параметра установлен при трех различных уровнях: низком, среднем и высоком. С целью установления уровня влияния на шероховатость поверхности каждого режима резания, с помощью Mintab программного оборудования (метод комплексной регрессии) созданы математические модели. Модели могут быть использованы при подборке режимов резания с целью обеспечения желаемых параметров шероховатости поверхностей и для оптимизации процесса скоростного резания.

Результаты показывают, что доминирующими факторами, оказывающими влияние на шероховатость поверхности, является величина подачи и скорость резания. Глубина резания существенного влияния не оказывает.

Received March 10, 2009
Accepted May 11, 2009