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Cutting forces and surface roughness in hard turning of hot work steel X38CrMoV5-1 using mixed ceramic

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Nomenclature

a_p - depth of cut, mm; f - *f*eed rate, mm/rev; F - resulting cutting force, N; Fa - *f*eed force, N; Fr - thrust force, N ; Fv - *t*angential cutting force, N ; HRC - Rockwell hardness; R^2 - coefficient of determination; Ra - *a*rithmetic mean roughness, µm; Rt - *t*otal roughness, µm; Rz - mean depth of roughness, µm; r_ε- tool nose radius, mm ; VB - flank wear, mm ; Vc - cutting speed, m/min ; α - relief angle, degree ; γ - rake angle, degree ; λ - inclination angle, degree ; χ - major cutting edge angle, degree.

1. Introduction

Cutting forces and surface roughness are classified among the most important technological parameters in machining process.

Cutting forces are the background for the evaluation of the necessary power machining (choice of the electric motor). They are also used for dimensioning of machine tool components and the tool body. They influence the deformation of the workpiece machined, its dimensional accuracy, chip formation and machining system stability.

During cutting process, the workpiece acts on the tool with a certain force F whose decomposition in three privileged directions can be used as a basis for the definition of cutting forces [1-4].

Surface roughness is in relation to many properties of machine elements such as wear resistance, the capacity of fit and sealing [5]. Theoretical surface roughness achievable based on tool geometry and feed rate is given approximately by the formula: $Ra = 0.032\, f^2 / r_\varepsilon$.

2. Experimental procedure

The material used for experiments is grade X38CrMoV5-1 steel, hot work steel which is popularly used in hot form pressing. Its resistance to high temperature and its aptitude for polishing enable it to answer the most severe requests in hot dieing and moulds under pressure [6, 7]. Its chemical composition is given in Table 1.

The workpiece is of 400 mm length and 75 mm in diameter. It is hardened to 50 HRC (quenching at 1020°C followed by oil tempering at 250°C). Its hardness was measured by a digital durometer DM2D. The lathe used for machining operations is TOS TRENCIN; model SN40C, spindle power 6.6 KW. The cutting insert used is a mixed ceramic CC650, removable, of square form having designation SNGN 120408 T01020. For three components measurement of cutting forces (Fa, Fv and Fr), we used a dynamometer KISTLER model 9257 B as shown in Fig. 1.

Table 1

Chemical composition of grade X38CrMoV5-1 steel

Composition	(wt. %)
C	0.35
Cr	5.26
Mo	1.19
V	0.5
Si	1.01
Mn	0.32
S	0.002
P	0.016
Other components	1.042
Fe	90.31

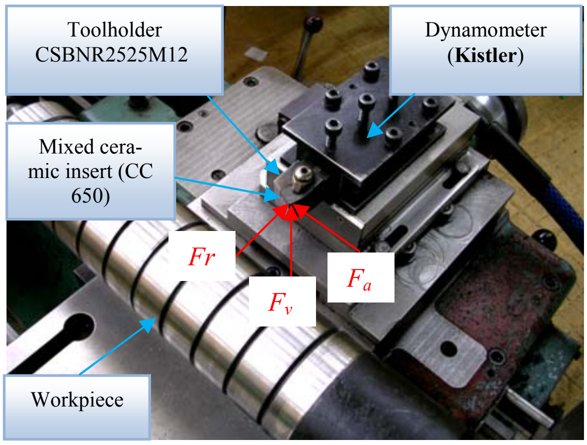

Fig. 1 Experimental configuration for measuring the components of cutting force

The toolholder adapted is of designation CSBNR2525M12 with the geometry of active part characterized by the following angles: $\chi = 75°$; $\alpha = 6°$; $\gamma = -6°$; $\lambda = -6°$ [8]. A roughness meter (2d) Surftest 301 Mitutoyo was selected to measure different criteria of surface roughness (Ra, Rz and Rt).

3. Experimental results and discussion

3.1. Effect of feed rate on cutting forces

The results presented on Fig. 2 show the evolution of the cutting forces according to the feed rate. If the feed rate increases, the section of sheared chip increases because the metal resists the rupture more and requires larger efforts for chip removal. It is noticed that the thrust force is dominating compared to both others and that for all the feed rates tested. The effects of the feed rate on the cutting forces are as follows: the increase in the feed rate from 0.08 to 0.24 mm/rev increases the components of the cutting forces (*Fr*, *Fv* and *Fa*) successively of (48.53%; 188.7% and 124%). It is noted that the tangential cutting force is very affected by the feed rate, follow-up of the feed force and lastly of the thrust force.

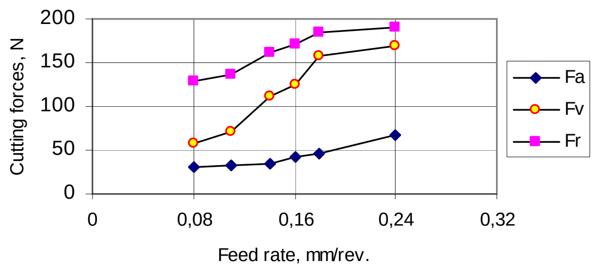

Fig. 2 Cutting forces vs. feed rate at $Vc = 125$ m/min; $a_p = 0.15$ mm

3.2. Effect of cutting speed on cutting forces

Fig. 3 shows that an increase in cutting speed generally leads to a reduction in the components of cutting forces.

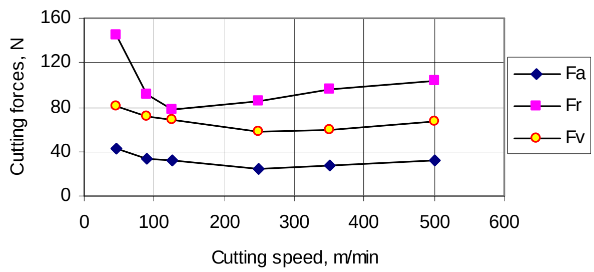

Fig. 3 Cutting forces vs. cutting speed at $f = 0.08$ mm/rev; $a_p = 0.15$ mm

This is due to the rise in the temperature in the cutting zone which makes the metal machined more plastic and consequently the efforts necessary for machining decrease. By examining the shape of the three curves, we record a very clear decrease of the thrust force until the speed of 125 m/min, beyond this limit; it stabilizes and takes again slightly an ascending pace. On the other hand the feed force and tangential cutting force decrease until the speed of 250 m/min, beyond this limit, they are stabilized slightly. It is noted that the maximum values of the cutting forces *Fa*, *Fr* and *Fv* are respectively 42.28; 81.47 and 144.53 N. They were recorded at the speed of 45 m/min.

3.3. Effect of depth of cut on cutting forces

The results obtained (Fig. 4) illustrate the evolution of cutting forces according to the depth of cut. With its increase, chip thickness becomes significant what causes the growth of the volume of deformed metal and that requires enormous cutting forces to cut the chip. For the cut depth of 0.1 to 0.8 mm, we successively record an increase in the components of the cutting forces *Fr*, *Fv* and *Fa* from 84%; 481% and 528%.

According to these results, the feed force is the most sensitive to the cutting depth increase, follow-up of the tangential cutting force and lastly of the thrust force. It is to be concluded that from the cutting parameters *f*, *Vc* and a_p, the depth of cut affects the cutting forces in a considerable way.

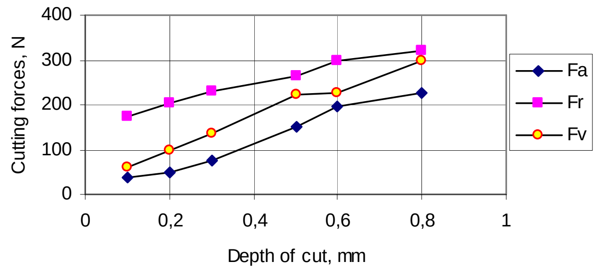

Fig. 4 Cutting forces vs. depth of cut at $Vc = 125$ m/min; $f = 0.08$ mm/rev

3.4. Effect of feed rate on surface roughness

The analysis of the effect of feed rate on surface roughness (Fig. 5) shows that this parameter has a very significant influence, because its increase generates helicoid furrows the result tool shape and helicoid movement tool-workpiece. These furrows are deeper and broader as the feed rate increases. For this reason, we must employ weak feed rate during turning.

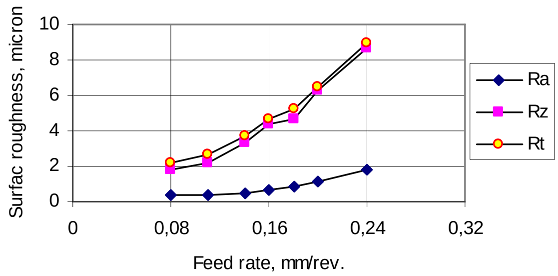

Fig. 5 Surface roughness vs. feed rate at $Vc = 125$ m/min; $a_p = 0.15$ mm

In practice, the consequences of the influence of the feed rate on surface roughness are as follows: the increase in the feed rate from 0.08 to 0.24 mm/rev makes respectively increase the criteria of roughness *Ra*, *Rz* and *Rt* from 432.54%; 387% and 309.63%. It is to be concluded that the feed rate contributes largely to the evolution of surface roughness.

3.5. Effect of cutting speed on surface roughness

Fig. 6 expresses the evolution of surface roughness criteria versus cutting speed. The increase in cutting

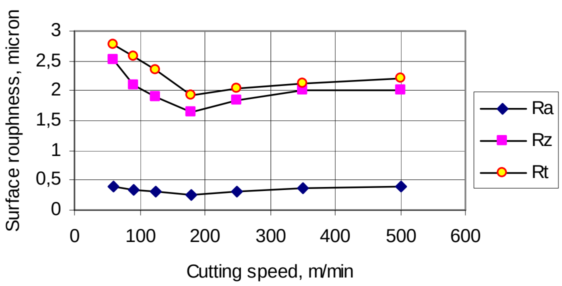

Fig. 6 Surface roughness vs. cutting speed at $f = 0.08$ mm/rev; $a_p = 0.15$ mm

speed improves the machined surface quality. For the speed from 60 to 125 m/min, the criteria of surface roughness *Ra*, *Rz* and *Rt* fall successively of 27%, 25% and 15%. When the speed is between 125 and 350 m/min, surface roughness is stabilized slightly because of the reduction in cutting forces stabilizing the machining system. If the speed is higher than 350 m/min, the curves related to surface roughness take ascending forms because of the vibrations related to high speeds.

3.6. Cutting depth effect on surface roughness

Evolution of surface roughness according to the depth of cut (Fig. 7) shows that this parameter has a very weak effect compared to that of the feed rate. This is due to the increased length of contact between the tool and the workpiece. This improves the conditions of heat flow from the cutting zone and consequently slows down the process wear. For the depths of cut from 0.05 to 0.6 mm, we record an increase in *Rz* and *Rt* respectively of 9.96% and 16.45%. On the other hand roughness *Ra* remains practically stable.

This enables to conclude that, if we want to increase the removed amount of chip, it is recommended the increase depth of cut instead of the feed rate.

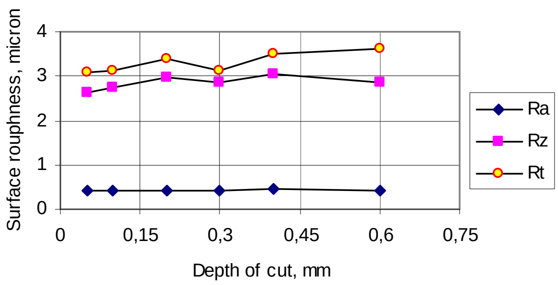

Fig. 7 Surface roughness vs. depth of cut at $Vc = 125$ m/min; $f = 0.08$ mm/rev

3.7. Effect of flank wear on cutting forces

Fig. 8 shows the evolution of cutting forces according to flank wear (*VB*). Shape analysis of the curves shows that the cutting forces are not stable during machining but they evolve according to the flank wear. Three parts are seen in the evolution of the cutting forces. The first in the part where the flank wear reaches the value of 0.2mm, the increase in cutting forces *Fa*, *Fr* and *Fv* is 84.94%; 183.87% and 35.95%. The second is characterized by a light stability, the value of wear reaches 0.28 mm, which generates an increase in the cutting forces, in 35.85%; 23.83% and 2.75%. The last in the part where the flank wear reaches the value of 0.44 mm, a total rise in the cutting forces of 448.28%; 621% and 107.11% was recorded. The major cutting force is the thrust force. This synthesis confirms that the increase in cutting forces is in direct connection with the degradation of cutting edge of the tool.

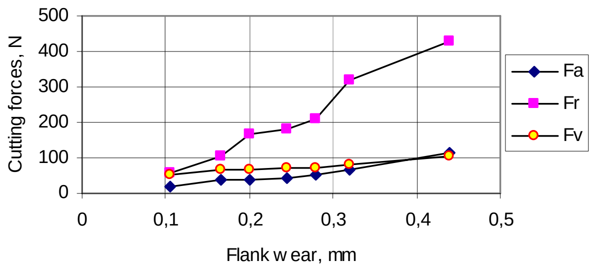

Fig. 8 Cutting forces vs. flank wear at $Vc = 125$ m/min; $f = 0.08$ mm/rev; $a_p = 0.15$ mm

3.8. Effect of flank wear on surface roughness

Fig. 9 presents the effect of flank wear *VB* on surface roughness. On the experimental plan, for a flank wear of 0.105 mm, the values of roughness criteria *Ra*, *Rz* and *Rt* are respectively 0.32; 2.15 and 2.78 µm. For the wear of 0.20 mm, the increase in roughness criteria is 81.25%; 59.07% and 28.42%. When the flank wear reaches 0.44 mm, the increase in roughness criteria is significant 197%; 179% and 132%.

Surface roughness is proportional and closely related to the flank wear.

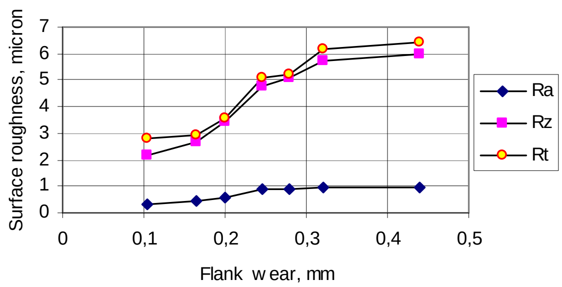

Fig. 9 Surface roughness vs. flank wear at $Vc = 125$ m/min; $f = 0.08$ mm/rev; $a_p = 0.15$ mm

4. Mathematical models

Table 2 presents the results of cutting force components and the criteria of surface roughness for various

Table 2

Components of cutting force and roughness criteria vs. various combinations of cutting regime elements

Tests N°	*f*, mm/rev	a_p, mm	*Vc*, m/min	*Fa*, N	*Fr*, N	*Fv*, N	*Ra*, µm	*Rz*, µm	*Rt*, µm
1	0.08	0.15	125	54.08	167.03	101.06	0.35	2.19	3.32
2	0.16	0.15	125	62.90	191.00	117.00	0.56	3.50	3.75
3	0.08	0.30	125	93.14	232.61	136.02	0.40	2.44	2.67
4	0.16	0.30	125	108.83	274.93	212.00	0.59	3.45	3.97
5	0.08	0.15	250	30.93	148.72	88.48	0.30	1.87	2.04
6	0.16	0.15	250	49.01	152.00	109.26	0.50	3.39	3.41
7	0.08	0.30	250	73.54	179.80	132.69	0.35	2.12	2.48
8	0.16	0.30	250	89.91	219.42	192.43	0.53	2.87	3.62

combinations of the elements of cutting regime (feed rate, cutting speed and depth of cut) according to the multifactorial method.

Treatment of these experimental results defines statistical mathematical models (Tables 3, 4, 5 and 6).

To calculate the values of constants of these mathematical models and the coefficients of determination R^2, we used a turbo Pascal program. These models make predictions to optimize the cutting process [9-16]

4.1. Mathematical models of cutting regime influence on cutting forces

The detailed analysis of the derived mathematical models (Table 3) confirms that the increase in cutting speed leads to the reduction in cutting forces and the increase in chip section ($f \times a_p$) induces the cutting forces growth. The order of classification of the exponents of the determined models, in absolute value, highlights the degree of the influence of each factor of cutting regime on cutting forces. Indeed, the depth of cut is the most influential factor.

Table 3

Mathematical models of cutting forces vs. cutting regime

Mathematical models	Coef. of det.
$Fr = e^{8.164} f^{\ 0.127}\ a_p^{\ 0.512}\ Vc^{-0.358}$	$R^2 = 0.937$
$Fv = e^{7.437} f^{\ 0.423}\ a_p^{\ 0.761}\ Vc^{-0.116}$	$R^2 = 0.956$
$Fa = e^{8.531} f^{\ 0.320}\ a_p^{\ 0.953}\ Vc^{-0.417}$	$R^2 = 0.948$

4.2. Mathematical models of cutting regime influence on surface roughness

Table 4

Mathematical models of surface roughness vs. cutting regime

Mathematical models	Coef. of det.
$Rt = e^{3.684} f^{\ 0.509}\ a_p^{\ 0.033}\ Vc^{\ -0.269}$	$R^2 = 0.837$
$Rz = e^{3.310} f^{\ 0.618}\ a_p^{\ 0.019}\ Vc^{\ -0.185}$	$R^2 = 0.927$
$Ra = e^{1.741} f^{\ 0.644}\ a_p^{\ 0.143}\ Vc^{\ -0.183}$	$R^2 = 0.988$

The mathematical models presented in Table 4, confirm that the feed rate is the most influential factor on different criteria of surface roughness because it has the highest exponent. The second parameter which influences the roughness is cutting speed. As for the depth of cut, its effect is not very significant.

4.3. Mathematical models of flank wear influence on cutting forces and on surface roughness

Table 5

Mathematical models of cutting forces vs. flank wear

Mathematical models	Coef. of det.
$Fr = 41.51\ e^{5.7536VB}$	$R^2 = 0.921$
$Fv = 42.10\ e^{1.8849VB}$	$R^2 = 0.905$
$Fa = 14.05\ e^{4.7663VB}$	$R^2 = 0.972$

The mathematical models of the cutting force components and criteria of surface roughness according to flank wear VB expressed in Tables 5 and 6 were obtained starting from the tests worked out under the following cutting conditions: $f = 0.08$ mm/rev, $Vc = 125$ m/min and $a_p =$ $= 0.15$ mm.

Table 6

Mathematical models of surface roughness vs. flank wear

Mathematical models	Coef. of det.
$Rt = 2.103\ e^{2.9175VB}$	$R^2 = 0.850$
$Rz = 1.738\ e^{3.3204VB}$	$R^2 = 0.834$
$Ra = 0.276\ e^{3.4591VB}$	$R^2 = 0.744$

They show that the increase in flank wear leads to the increase in cutting forces and in criteria of roughness, because the surface of contact between the tool and the workpiece increases, what generates friction. This latter degrades the surface quality and increases the forces of friction which are added to cutting forces.

5. Conclusion

The tests of slide-lathing carried out on grade X38CrMoV5-1 steel treated at 50 HRC, machined by a mixed ceramic tool (insert CC650), enabled us to study the influence of the following parameters: feed rate, cutting speed, depth of cut and flank wear on cutting forces and on surface roughness.

It is to be noted that tangential cutting force is very sensitive to the variation of cutting depth what affects the cutting forces in a considerable way. It is also noted that surface roughness is very sensitive to the variation of feed rate and that flank wear has a great influence on the evolution of cutting force components and on the criteria of surface roughness. Thus, the ranges of best cutting conditions adapted, were given.

Mathematical models established defined the degree of influence of each cutting regime element on the studied technological parameters.

This study confirms that in dry hard turning of this steel and for all cutting conditions tested, the major force is the thrust force and the roughness criteria found are close to those obtained in grinding.

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PJOVIMO JĖGA IR PAVIRŠIAUS ŠIURKŠTUMAS KERMETU TEKINANT KARŠČIUI ATSPARŲ PLIENĄ X38CrMoV5-1

R e z i u m ė

Darbo tikslas – nustatyti pjovimo jėgą ir paviršiaus šiurkštumą tekinant karščiui atsparų plieną X38CrMoV5-1 [AISI H11]. Užgrūdintas iki 50 HRC kietumo nevolframinis, Cr-Mo-V pagrindu sukurtas karščiui ir dilimui atsparus plienas apdirbamas pjovimo įrankiu su kermetine plokštele (plokštelė CC650, jos cheminė sudėtis – 70%Al_2O_3+30%TiC). Jis naudojamas dideles apkrovas atlaikančioms formoms, ilgaamžių įrankių detalėms ir kalimo mašinų puasonams gaminti.

Tekinimo bandymai buvo atlikti naudojant eksperimento planavimo metodiką. Gauti rezultatai įgalino analizuoti pjovimo kintamųjų (pastūmos dydžio, pjovimo greičio ir gylio) įrankio antgalio nusidėvėjimo (*VB*) įtaką pjovimo jėgoms ir paviršiaus šiurkštumui. Siekiant nustatyti įvairių pjovimo režimų komponentų įtaką nagrinėjamiems technologiniams parametrams, buvo sudarytas matematinis modelis. Juo naudojantis parinktas geriausių pjovimo sąlygų diapazonas.

Šie tyrimai patvirtino, kad esant įvairioms bandymų sąlygoms, sausai tekinamą plieną veikianti didžiausia jėga yra nukreipta radialine kryptimi, o gautas paviršiaus šiurkštumo kriterijus artimas gaunamam šlifuojant.

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CUTTING FORCES AND SURFACE ROUGHNESS IN HARD TURNING OF HOT WORK STEEL X38CrMoV5-1 USING MIXED CERAMIC

S u m m a r y

The aim of this work is to evaluate cutting forces and surface roughness in hard turning of hot work steel X38CrMoV5-1 [AISI H11].

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.

The tests of slide-lathing were carried out according to the method of planning experiments. The results made it possible to study the influence of cutting variables (feed rate, cutting speed and depth of cut) and flank wear (*VB*) on cutting forces and surface roughness. Mathematical models were established to express the influence degree of each cutting regime element on the studied technological parameters. Thus, the ranges of the best cutting conditions adapted, were given.

This study confirms that in dry hard turning of this steel and for all cutting conditions tested, the major force is the thrust force and the found roughness criteria are close to those obtained in grinding.

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СИЛА РЕЗАНИЯ И ШЕРОХОВАТОСТЬ ПОВЕРХНОСТИ ПРИ ТОЧЕНИИ ЖАРОСТОЙКОЙ СТАЛИ X38CrMoV5-1 КЕРМЕТОМ

Р е з ю м е

Цель работы установить силу резания и шероховатость поверхности при точении жаростойкой стали X38CrMoV5-1 [AISI H11]. Эта безвольфрамная жаро и износостойкая сталь твердостью 50 HRC создана на основе Cr-Mo-V обрабатывается резцом с кермето-

вой пластинкой (пластинка CC650, ее химический состав 70%Al_2O_3+30%TiC). Эта сталь используется для изготовления высокопрочных литейных форм и пуасонов, а также других деталей долговечных инструментов.

Эксперименты по точению проводились по методу планирования экспериментов. Полученные результаты позволили анализировать влияние режимов резанья (величины подачи, скорости и глубины точения), на износ наконечника инструмента (*VB*), изменение силы точения и шероховатость поверхности. С целью установления влияния режимов резания на исследуемые технологические параметры, разработана соответствующая математическая модель. С ее помощью определен наилучший диапазон режимов резания.

Исследования подтвердили, что при разных условиях сухого точения стали, максимальная составляющая силы резанья действует по радиальному направлении а определен критерий шероховатости поверхности близок к полученному при шлифовании.

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