Machinability investigation in hard turning of AISI H11 hot work steel with CBN tool

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1. Introduction

In hard turning, ferrous metal parts that are hardened usually between (45-70 HRC) are machined with the single point cutting tools. This has become possible with the availability of the new cutting tool materials (cubic boron nitride (CBN) and ceramics). Since a large number of operations is required to produce the finished product, if some of the operations can be combined, or eliminated, or can be substituted by the new process, product cycle time can be reduced and productivity can be improved. The traditional method of machining hardened materials includes rough turning, heat treatment, and then grinding process. Hard turning eliminates the series of operations required to produce a component and thereby reduces the cycle time resulting in productivity improvement [1-3].

Various studies have been conducted to investigate the performance of CBN tool in machining of various hard materials. Dilbag and Venkateswara [1] have conducted the study on the influence of rake angle, cutting speed, feed rate and nose radius are primary influencing factors which affect the surface finish. The results indicated that feed rate is the dominant factors affecting the surface roughness. Sahin and Motorcu [2] show that feed rate was the main factor influencing the surface roughness. It increased with increasing the feed rate but decreased with increasing the cutting speed and the depth of cut, respectively. In their experimental research work, Bouacha et al. [4] investigated the effect of cutting speed, feed rate and depth of cut on surface roughness and cutting forces using three level factorial design (3^3) during machining of bearing steel (AISI 52100) with CBN tool. The results show how much the surface roughness is influenced by feed rate and cutting speed and that the depth of cut exhibits maximum influence on the cutting forces as compared to feed rate and cutting speed. Horng et al. [5] presented a model to evaluate the machinability of Hadfield steel by applying response surface methodology (RSM) and analysis of variance (ANOVA) techniques. The study indicated that the flank wear is influenced principally by the cutting speed and the interaction effect of feed rate with nose radius of the tool. Lima et al. [6] investigated the machinability of hardened steels at different levels of hardness using a range of cutting tool materials. More specific is the machinability of hardened AISI 4340 high strength low alloy steel and AISI D2 cold work tool steel. The results indicated that when turning AISI 4340 steel surface roughness of the machined parts was improved as cutting speed was elevated and deteriorated with feed rate. Depth of the cut presented little effect on the surface roughness values. Flank wear of mixed alumina tool increased with cutting speed

and depth of the cut increasing. Chou et al. [7] experimentally investigated the performance and wear behaviour of different CBN tools in finish turning of hardened AISI 52100 steel (DIN 100Cr6). In this study, it was established that low CBN content materials provide the best performance in hard turning in terms of tool life and surface finish. Zhou et al. [8] in their investigation revealed that chamfer angle has a great influence on cutting force and tool life. All the three force components increase with the increase in chamfer angle. The optimized chamfer angle for maximum tool life, as suggested by this study, is 15°. Luo et al. [9] studied the wear behaviour in hard turning of the same alloy steel by CBN and ceramic tools and they found that the flank wear was reduced as work material hardness increased up a critical value of 50 HRC. In addition, wear mechanisms by diffusion, abrasion and adhesion were discussed by Poulachon et al. [10] and usually it is concluded that these mechanisms are prevalent during the wear process of CBN tools. The major influencing factor on the tool wear is the presence of various carbides in the steel microstructure. Hardness of these carbides varies significantly, causing different wear rates when turning 100Cr6, X155CrMoV5, X38CrMoV5 and 35NiCrMo16 steels. In these cases, the flank wear on the tool has resulted in grooves caused by the major abrasive action of carbides.

Fnides et al. [11] found that the temperature increases, which is due to mechanical energy conversion into thermal energy because of elastic strain friction of the chip on rake and relief surfaces of the tool. The knowledge of the variation in temperature in the entire insert and particularly to the interface tool chip will allow a better adequacy between the cutting parameters, the characteristics of material to be machined like those of the tool.

The current article investigates the influence of cutting parameters (cutting speed, feed rate and depth of cut) on cutting forces, surface roughness and tool wear in turning of hot work steel AISI H11 with CBN tools. Tool life model was obtained by the sowftwere Design-Expert using RSM.

2. Experimental procedure

Turning experiments were performed in dry conditions using the lathe type SN 40C with 6.6 KW spindle power. The workpiece material was AISI H11, 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 [12]. Its chemical composition is given in Table 1.

Chemical composition of AISI H11

Composition	(Wt %)
C	0.35
Cr	5.26
Mo	1.19
V	0.50
Si	1.01
Mn	0.32
S	0.002
P	0.016
Other components	1.042
Fe	90.31

The workpiece is of 80 mm in diameter. It is hardened to 50 HRC. Cutting insert is removable and offered eight squared working edges. The chosen CBN tool in commercially known as CBN7020 and it is essentially made of 57% CBN and 35% Ti(C, N). Its designation is SNGA12 04 08 S01020 and was manufactured by Sandvik. Physical properties of the CBN7020 tool are summarized in Table 2. Tool holder is codified as PSBNR25×25M12 with a common active part and tool geometry described by $\chi_r = +75°$, $\lambda = -6°$, $\gamma = -6°$ and $\alpha = +6°$. Three component cutting force in X, Y and Z directions as recorded using a standard quartz dynamometer (Kistler 9257B) allowing measurements from -5 to 5KN. Instantaneous roughness criteria (Ra, Rt and Rz) for each cutting condition were obtained by a Surftest 201 Mitutoyo roughness meter coupled with a radius and moved linearly on the working surface. The length examined is 2.4 mm with a basic span of 3 mm. The measured values of Ra are within the range 0.05 to 40 μm while for Rt and Rz, they lay between 0.3 and 160 μm.

Physical properties of CBN

Material	Hardness V, daN/mm^2	Tenacity, MPa m$^{1/2}$	Young's modulus, GPa	Density, g/cm^3	Grain size, μm
CBN 7020	2800	4.2	570	4.3	2.5

Roughness measurements were directly performed on the same without disassembling the turned part in order to reduce uncertainties due to resumption operations. The measurements were repeated 3 times out of 3 generatrices equally positioned at 120° and the result is the average of these values for a given machining pass. To measure maximum temperatures in the cutting zone, we used a pyrometer with infra-red model Raynger 3I, its interval is -30 to 1200°C.

3. Results and discussion

3.1. Evolution of the cutting forces

a) Effect of cutting speed

It can be seen in Fig. 1 that all components of the cutting force decreased as the cutting speed was increased, with different slopes. This is due to the rise in temperature in the cutting zone which makes the metal machined more plastic and consequently the efforts necessary for machining decrease [13].
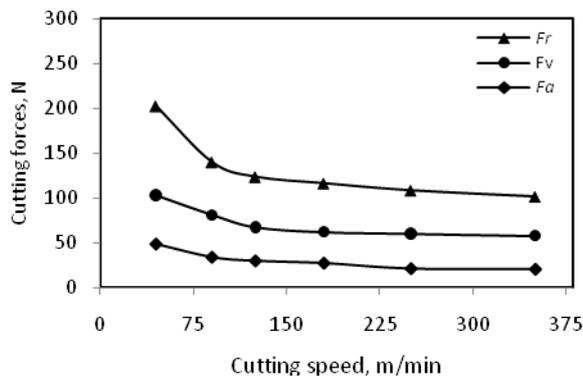
Fig. 1 Variation of cutting forces with cutting speed at $f = 0.08$ mm/rev; $ap = 0.15$ mm

It is noticed that the thrust force is dominating compared to both others and that for all the cutting speed tested, probably due to the work of tool exclusively with its nose radius is equal to 0.8 mm ($r_e > ap$) and the negative rake angle ($\gamma = -6°$). The effects of cutting speed on the cutting forces are as follows: the increase in cutting speed from 45 to 125 m/min increase the components of the cutting force (Fr, Fv and Fa) successively of 39; 34.19 and 37.91%.

b) Effect of feed rate

The effect of feed rate on cutting forces is shown in Fig. 2. It can be noted that the increase in feed rate resulted in the increase in cutting forces.
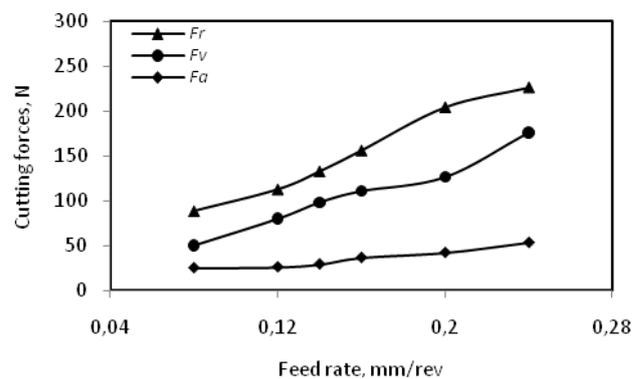
Fig. 2 Variation of cutting forces with feed rate at $Vc = 180$ m/min; $ap = 0.15$ mm

If the feed rate increases, the section of sheared chip increases because the metal resists rupture more and requires large efforts for chip removal [14]. The effects of feed rate on the cutting forces are as follows; the increase in feed rate from 0.08 to 0.24 mm/rev, increases components of the cutting forces (Fr, Fv and Fa) successively of 156.24; 250.6 and 114.31%. It is noted that the tangential cutting force is very affected by the feed rate.

c) Effect of depth of cut

Fig. 3 represents the influence of the depth of cut on the cutting forces. 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 depth of 0.05 to 0.75 mm, we successively recorded the increase in components of the cutting forces (Fr, Fv and Fa) from 380.46; 559.20 and 915.15%. It is noted that the axial force is very affected by the depth of cut.
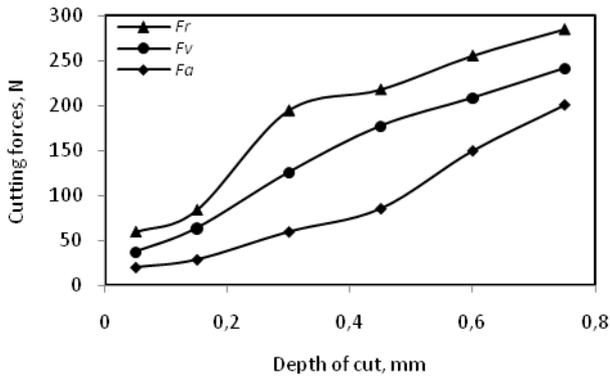
Fig. 3 Variation of cutting forces with depth of cut at $Vc = 80$ m/min; $f = 0.08$ mm/rev

3.2. Evolution of the surface roughness

Characterization of the machined surface quality was limited to the criteria of total roughness (Rt), arithmetic mean roughness (Ra) and mean depth of roughness (Rz).

a) Effect of cutting speed

Fig. 4 shows the evolution of surface roughness according to the cutting speed.
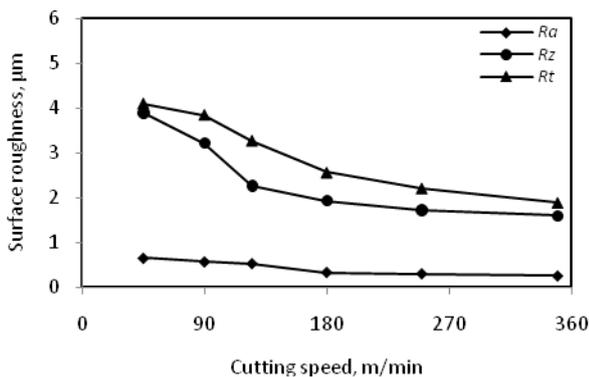
Fig. 4 Variation of surface roughness with cutting speed at $f = 0.08$ mm/rev; $ap = 0.15$ mm

The three criteria of roughness present a decrease when the cutting speed increases. This can be related to the growth of temperature in cutting zone and consequently, friction becomes less important. This graph indicated that at cutting speeds lower than 180 m/min (zone I), the criteria of roughness (Rt, Rz and Ra) fall successively from 37.73; 50.25 and 48.50%.

In the second zone, surface roughness is stabilized slightly because of reduction in the cutting forces stabiliz-

ing the machining system. Chen [15] explains this stability which returns to the weak deformation of the workpiece for higher speed (this is with the rise in temperature in the zone of cut which makes metal machined more plastic and consequently the efforts necessary to the cut decrease).

b) Effect of feed rate

Fig. 5 illustrates the evolution of surface roughness according to the feed rate. The analysis of the graphs shows that this parameter has a very significant influence, because its increase generates helicoids furrows the result of tool shape and helicoids 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. In practice it is noted that roughness's (Rt, Rz and Ra) are minimal for the weakest feed rate. But they increase with the rise in this one. We note the increase of approximately 159% of Rt, and 173.71% for Rz and 197% for Ra, when the values of the feed rate pass for 0.08 to 0.24 mm/rev.
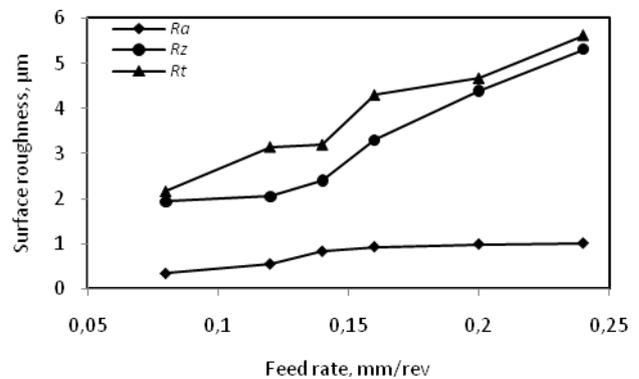
Fig. 5 Variation of surface roughness with feed rate at $Vc = 180$ m/min; $ap = 0.15$ mm

Table 3
Comparison of measured and predicted values of the surface roughness

	f, mm/rev	Roughness measured		Roughness predicted	
		Rt, µm	Ra, µm	Rt, µm	Ra, µm
$Vc = 180$ m/min $ap = 0.15$ mm $r_\varepsilon = 0.8$ mm	0.08	2.17	0.34	1	0.25
	0.16	4.30	0.93	4	1
	0.24	5.62	1.01	9	2.25

In the literature, Habak [16] and Remadna [17] show that the equations $R_a = f^2/32r_\varepsilon$ and $R_t = f^2/8r_\varepsilon$ are not appropriate to hard turning. This is shown though the results presented in Table 3. The experimental results are either lower, or higher than the computed values. One can conclude that in hard turning, the value of roughness depends on several parameters: geometry of tool (major cutting edge angle, rake angle, ...), the process of machining, and hardness of the workpiece [3].

c) Effect of depth of cut

Fig. 6 shows the evolution of surface roughness

according to the depth of cut. The three parameters of roughness show that this parameter has a very weak effect compared to that of feed rate.
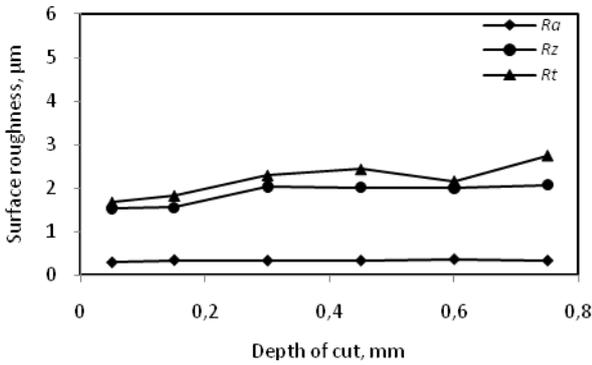
Fig. 6 Variation of surface roughness with depth of cut at $Vc = 180$ m/min; $f = 0.08$ mm/rev

For cut depth 0.05 to 0.75 mm, we recorded the increase in (Rt and Rz) respectively in 64.67 and 35.30%. On the other hand roughness (Ra) remains stable 13.79%.

3.2. Evolution of the cutting temperature

a) Effect of cutting speed

Fig. 7 presents the change of temperature in cutting zone according to the cutting speed for the machining time of 25 seconds. With the increase of the cutting speed, frictions increase, this induces temperature increase in the cutting zone. It is noted that for the speed of 45 m/min, the maximum temperature is 114°C. For the variation of cutting speed of 45 to 335 m/min, we record the increase in temperature in the cutting zone of 240.5%.
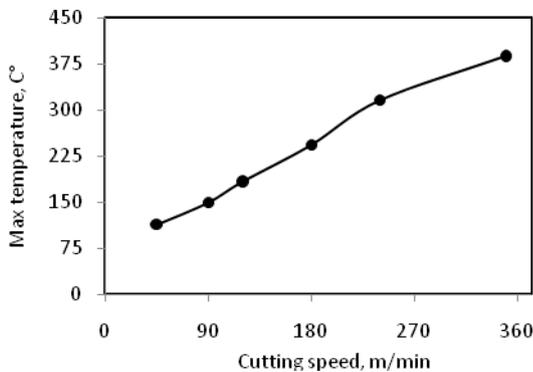
Fig. 7 Variation of cutting temperature with cutting speed at $f = 0.08$ mm/rev; $ap = 0.15$ mm
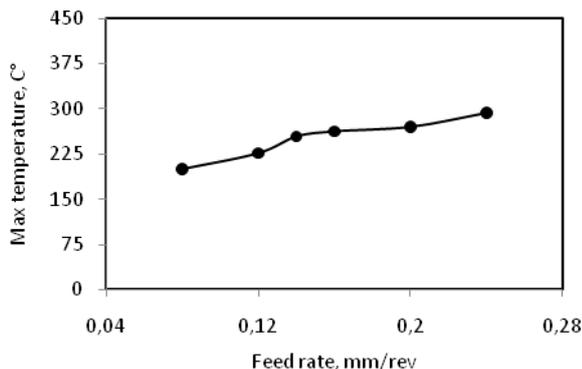
Fig. 8 Variation of cutting temperature with feed rate at $Vc = 180$ m/min; $ap = 0.15$ mm

b) Effect of feed rate

Fig. 8 presents the change of temperature in the zone of cut according to the feed rate. The results of the influence of the feed rate on temperature, show an increase in this last. With the increase in the feed rate section of the chip increases and consequently friction increases, which involves an increase in the temperature. For the feed rate from 0.08 to 0.24 mm/rev, we record temperatures which vary from 200.5°C to 293.5°C. It represents the increase of 46.38%.

c) Effect of depth of cut

Fig. 9 shows the maximum temperature in the cutting zone according to the depth of cut. We record an increase which is worth ~176% when the depth of cut varies from 0.05 with 0.70 mm.
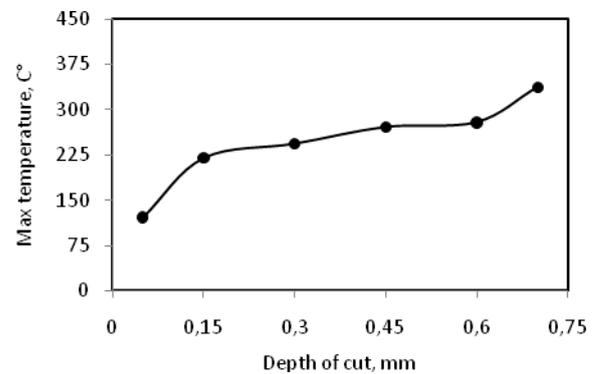
Fig. 9 Variation of cutting temperature with depth of cut at $Vc = 180$ m/min; $f = 0.08$ mm/rev

- For the depth of cut of 0.05 mm the maximum temperature recorded in the zone of cut is 122°C. If the depth of cut increases up to 0.15 mm, (either 3 times), the value of the maximum temperature becomes 220°C, which represents the increase in temperature of 81.96%.
- For the depth of cut of 0.45 mm, (that is to say 9 times), the value of the maximum temperature in the zone of cut reached 271°C, which represents the increase in temperature of 122.13%.
- For the depth of cut of 0.70 mm, (that is to say 14 times), the value of the maximum temperature in the zone of cut reached 337°C, which represents the increase in temperature of 176.22%. It is noted, if the depth of cut increases, the section of the chip increases and friction chip tool increases, which leads to an increase in temperature.

3.3. Evaluation of the tool life

Tool life is a crucial factor for evaluating machinability of materials. In order to determine this important factor, we have realized wear tests according to machining time at three cutting speeds and three feed rates.

Table 4 presents experimental results of tool life (T) for various combinations of cutting regime elements (cutting speed and feed rate) according to 3^2 full factorial design. Minimal values of tool life (T) were obtained at $Vc = 240$ m/min and $f = 0.16$ mm/rev. Maximal values of tool life were registered at $Vc = 120$ m/min and $f = 0.08$ mm/rev. In order to achieve better tool life, the low-

est level cutting speed and lowest level feed rate are recommended.

Table 4

Tool life for $VB = 0.30$ mm and $ap = 0.15$ mm (AISI H11)

Vc, m/min	F, mm/rev	Tool life T, min
180	0.08	40.00
120	0.08	76.00
180	0.12	37.00
180	0.16	32.67
120	0.16	56.60
240	0.12	20.00
240	0.16	18.34
120	0.12	67.50
240	0.08	20.50

3.4. Modeling of the machining parameters for tool life

The response surface methodology (RSM) is the procedure for determining the relationship between the independent process parametres with the desired response and exploring the effect of these parametres on responses.

In the current study, the relatioship between the cutting conditions and the machinability aspect is given as

$$Y = \phi(V_c, f) \qquad (1)$$

where Y is the desired machinability aspect and ϕ is the response function.

The approximation of Y is proposed by using a non-linear mathematical model, which is suitable for studying the interaction effects of process parameters on machinability characteristics.

In the present work, the RSM based second order mathematical model is given by

$$Y = a_0 + a_1 V_c + a_2 f + a_{12} V_c \times f + a_{11} V_c^2 + a_{22} f^2 \qquad (2)$$

where Y is the desired response of the tool life $a_0, a_1, a_2, a_{12}, a_{11}$ and a_{22} regression coefficients to be determined for each response.

The resultas of analysis of variance (ANOVA) for tool life (T) are shown in Table 5. This Table also shows the degrees of freedom (df), sum of squares (SC sq.), mean square (MS), F-values and probabilty (P-value), in addition to the contribution (Cont. %) of each factor.

Table 5

Analysis of variance for tool life

Source	df	SC sq.	MS	F-value	Prob>F	Cont. %	Remark
Model	5	3627.59	725.52	528.53	0.0001	-	Signifiant
f, mm/rev	1	139.11	139.11	101.34	0.0021	3.83	Signifiant
Vc, m/min	1	3325.73	3325.73	2422.75	<0.0001	91.57	Signifiant
$f \times Vc$	1	74.30	74.30	54.13	0.0052	2.04	Signifiant
f^2	1	1.33	1.33	0.97	0.3978	0.036	Not signifiant
Vc^2	1	87.12	87.12	63.47	0.0041	2.398	Signifiant
Residual	3	4.12	1.37			0.113	
Total	8	3631.77				100	

ANOVA results for T are indicated in Table 5. It can be noted that the cutting speed affects T in a considerable way. Its contribution is 91.57%. The second factor influenceing T is feed rate. Its cobtribution is 3.83%. The interactions feed rate/cutting speed and cuting speed/cutting speed are significant but the interaction feed rate/feed rate is not significant. Respectively, their contributions are 2.04; 2.398 and 0.036%. (Values of $Prob > F$ less than 0.0500 indicate model terms are significant.

Using the data presented in Table 4, a quadratic model regression can be obtained by equation (3), which gives the time required to reach $VB = 0.30$ mm as a function of cutting speed (Vc) and feed rate (f) with $R^2 = 0.9862$

$$T = 213.03 - 1.269V_c - 321.375f + 1.796V_c f +$$
$$+ 1.833 \times 10^{-3} V_c^2 - 509.375 f^2 \qquad (3)$$

The obove mathematical model can be used to predict the values of tool life (T) within in the limites of the factors studied.

The differences between measured and predicted responses are illustrated in Fig. 10.

The results of comparison were proved to predict the values of tool life close to those readings recoreded

exprementally with a 95% confidence interval. Good agreement is observed between these values as seen in Fig. 11.
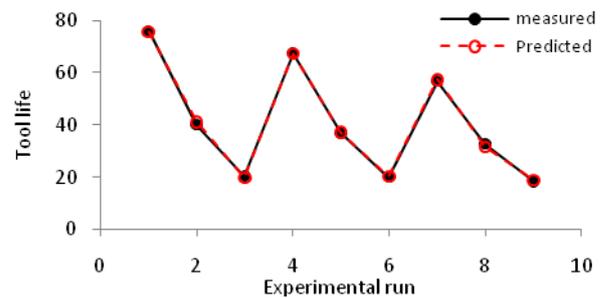
Fig. 10 Comparison of measured and predicted value for tool life

Fig. 12 gives the main factor plots. The tool life appears to be an almost-linear decreasing function of cutting speed. This result contradicts with common expectation that tool life usually decreases with increasing cutting speed. But the feed rate has little effect on tool life.

The effect of feed rate (f) and cutting speed (Vc) on the tool life (T) is shown in Fig. 13. This figure displays that the value of tool life (T) decrease with the increase of cutting speed and feed rate. The decrease is approximately 75.86% of T,
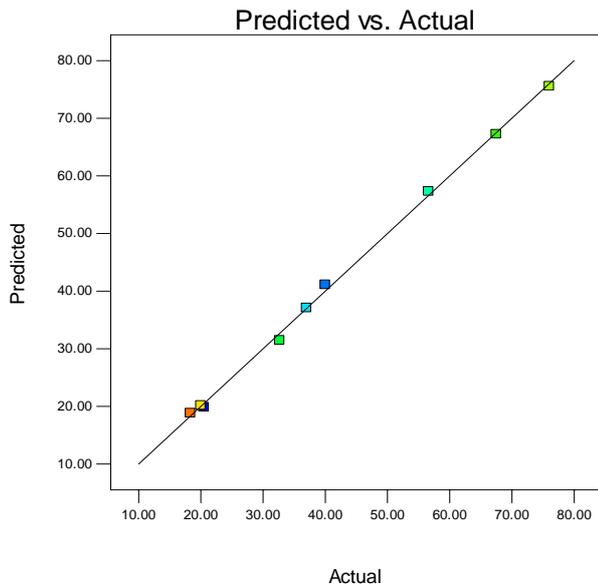
Fig. 11 Comparison of measured and predicted value of tool life
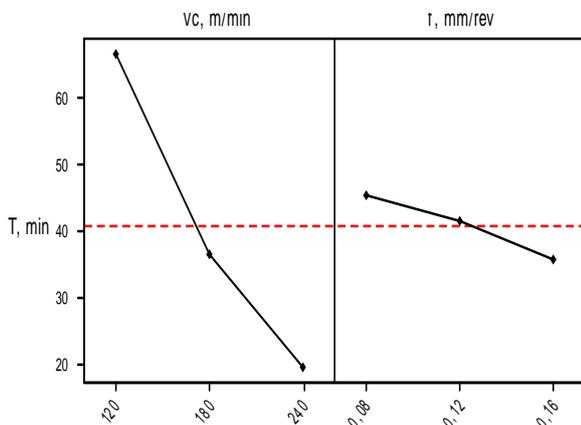
Fig. 12 Main factor plots: averages for *T*
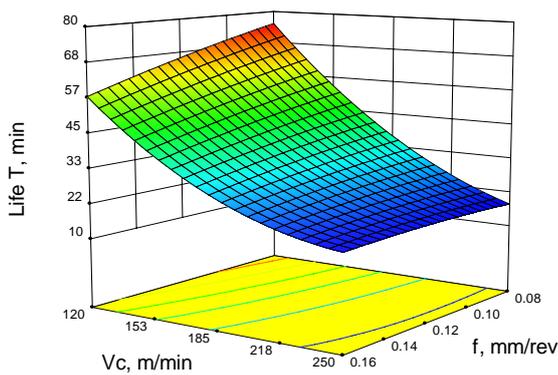
Fig. 13 Response surface of tool life according to the change of cutting speed and feed rate

4. Conclusions

The tests of straight turning carried out on grade AISI H11 steel treated at 50 HRC, machined by a Cubic Boron Nitride tool (CBN7020), enabled us to study the influence of the following parameters: feed rate, cutting speed and depth of cut on cutting force, surface roughness, temperature in the cutting zone and tool life. The conclusions of research are as follows.

- Tangential cutting force is very sensitive to the variation of cutting depth what affects the feed (axial) forces in a considerable way.
- Thrust force is dominating compared to both others and that for the entire cutting regime.
- Surface roughness is very sensitive to the variation of the feed rate. We record the increase of approximately 159% of *Rt*, 173.71% for *Rz* and 197% for *Ra* when the values of the feed rate passed from 0.08 to 0.24 mm/rev.
- Temperature is strongly influenced by the cutting speed (240.50%).
- RSM technique has the advantage of investigating the influence of each machining variable on the values of technological parameters.
- Cutting speed is the most significant factor with 91.57% contribution in the total variability of model (*T*), whereas feed rate has a secondary contribution of 3.83% in the model.

Acknowledgements

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KARŠČIUI ARSPARAUS PLIENO AISI H11 APDIRBAMUMO RUPIAI TEKINANT CBN ĮRANKIU TYRIMAS

R ė z i u m ė

Straipsnyje aprašomas detalus karščiui atsparaus plieno AISI H11 rupiojo aptekinimo pjovimo jėgų, paviršiaus šiurkštumo, maksimalios temperatūros, įrankio išsidėvėjimo tyrimas. Šis plienas yra užgrūdintas iki 50 HRC ir apdirbtas kubiniu boro nitridu (CBN7020), pagamintu Cr-Mo-V pagrindu ir neturinčiu volframo, nejautriu temperatūros pokyčiams ir labai atspariu dilimui. Jis yra naudo-jamas malūnsparnių rotoriaus menčių ir štampų detalių apdirbimui. Aptekinimo bandymai buvo atlikti taikant eksperimento planavimo metodiką. Gauti rezultatai buvo panaudoti pjovimo kintamųjų (pastūmos ir pjovimo greičio, pjovimo gylio) įtakai pjovimo jėgoms, paviršiaus šiurkštumui, pjovimo zonos temperatūrai ir įrankio išsidėvėjimui nustatyti.

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MACHINABILITY INVESTIGATION IN HARD TURNING OF AISI H11 HOT WORK STEEL WITH CBN TOOL

S u m m a r y

This paper reports an extensive characterization of cutting forces, surface roughness, evaluate maximum temperature and tool wear in hard turning of hot work steel AISI H11. This steel is hardened to 50 HRC, machined by cubic boron nitride (CBN 7020). It is free from tungsten on Cr-Mo-V basis, insensitive to temperature changes and has a high wear resistance. It is employed for the manufacture of helicopter rotor blades and forging dies. The tests of straight turning 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) on cutting forces, surface roughness, temperature in the cutting zone and tool wear.

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ИССЛЕДОВАНИЕ ОБРАБАТЫВАЕМОСТИ ЧЕРНОВОЙ ОБТОЧКОЙ ТЕПЛОУСТОЙЧИВОЙ СТАЛИ AISI H11 CBN РЕЗЦОМ

S u m m a r y

В настоящей статье представлено детальное исследование сил резания, шероховатости поверхности, максимальной температуры и износа резца при черновой обточке теплоустойчивой стали AISI H11 закаленной до 50 HRC и обработанной безвольфрамовым кубическим нитридом бора (CBN7020) созданным на основе Cr-Mo-V, являющимся малочувствительным изменениям температуры и обладающим большой износостойкостью. Этот материал применяется для обработки лопастей ротора вертолетов и деталей штампов. Исследования обточки проводились по методике планирования эксперимента. Полученные результаты позволили оценить влияние переменных резания (скорости подачи и резания, глубины резания) на силы резания, шероховатость поверхности, температуру зоны резания и износ резца.