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Wear behaviour of CBN tool when turning hardened AISI D3 steel

H. Bouchelaghem*, M. A. Yallese, A. Amirat***, S. Belhadi******
**Laboratoire LMS, Université du 8 Mai 1945, BP 401, Guelma 24000, Algérie, E-mail: b_hadjer2@yahoo.fr*
***Laboratoire LMS, Université du 8 Mai 1945, BP 401, Guelma 24000, Algérie, E-mail: yalese@yahoo.fr*
****Laboratoire LR3MI Université Badji Mokhtar, BP. 12, Annaba 23000, Algérie, E-mail: amirat_abd@yahoo.fr*
*****Laboratoire LMS, Université du 8 Mai 1945, BP 401, Guelma 24000, Algérie, E-mail: belhadi23@gmail.com*

1. Introduction

In a cutting process there is always emergence of great cutting forces, friction and high temperatures due to continuous and intensive contact between the active cutting part surface and the workpiece machined surface. This obviously generates wear on the tool faces leading to damage on surface roughness quality and precision decrease in the machined workpiece. The generated wear processes is very complex as it is followed by physicochemical phenomena appearing on the contact surfaces between tool part, workpiece and chip. In other words, the wear is a destructive process of surface layers of the active tool part leading to progressive modifications in machined forms of the workpiece and surface quality, through changes in tool geometrical parameters (angles and nose radius), temperature, cutting force, macro and microgeometrical precision of the machined surface. Depending on the machining conditions, the wear process can significantly affect one, two or all faces of the active tool part [1-6].

It should be noted that the tool wear, particularly when machining harder material appears under much more sever working conditions than under those traditionally used for machine components. In fact, the specific contact pressure in a workpiece of a machine component does not exceed some MPa, and temperature is usually below 100°C whereas in the active cutting tool part surface, pressure goes up to 10^3 to $2x10^3$ MPa and temperature reaches 100°C to 1000°C and even more [7-12].

The physical nature of wear mechanism in tools working under different conditions is elucidated by a series of assumptions [4, 5, 12-17] that include crumbling, abrasion, adhesion and the diffusion. With regards to working conditions (physico-mechanical properties of both the material properties to be machined and tool material, cutting parameters, cooling and lubrication liquid, machining system rigidity) the cutting tool wear evolutes in various ways. Basically, the wear appears on the rake and flank tool surfaces otherwise there could be a dominating wear surface [1, 6, 9, 13, 18, 19].

On the basis of the point outlined above, as the main technological parameters are concerned, the behaviour of machining precision, surface quality, cost price, and productivity are directly related to tool wear. Therefore more and deep tool wear investigations are continuously required particularly in machining harder steels using performance high tool material (CBN) that is of great importance to economic and technological task in mechanical manufacturing. The present work lays out experimental results on the cubic boron nitride (CBN) wear behaviour when machining aggressive hardened AISI D3 steel. In addition, surface quality degradation, cutting forces and temperature evolution are related to the tool wear. Then, a relationship between wear VB and roughness Ra is proposed in order to gather information about cutting edge quality and to intend the tool wear through measured roughness.

2. Experimental procedure

Long term tests according to ISO 3685 [20] standard have been conducted in order to evaluate the CBN tool life. Straight turning operations have been carried out on 80 mm diameter and 400 mm length bars made of heat treated AISI D3 steel with the chemical specification given in Table 1, to generate wear in the cutting tool. Because of its wear resistance, AISI D3 steel is usually used for the manufacture of matrices, punches blanking, stamping, drawing die, rollers profilers, wood tools, combs for nets rolling [21].

Table 1

Chemical composition of AISI D3 steel in weight %

C	Mn	Si	P
2	0.29	0.31	0.011
S	Cr	Ni	
0.009	1.14	0.259	

The test specimens have been hardened to the required hardness of 60 HRC through quenching to 940°C and tempered at 280°C. Machining operations have been achieved on a 6.6 KW power TOS TRENCIN model SN40 lathe. A TiN layer covered cutting insert (57% CBN), of the standard designation SNGA120408 T01020 is mounted on PSBNR2525K12 (Fig. 1), tool holder with an active part tool geometry characterised by the following angles: χ_r = 75°; α = 6°; γ = -6°; λ = -6°. Wear has been measured using a CCD camera equipped HUND optical microscope (W-AD).

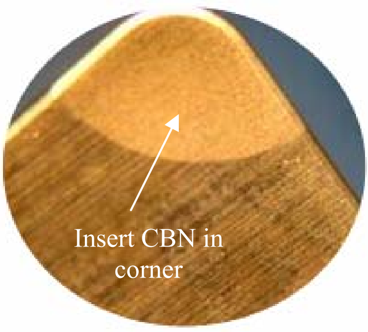

Fig. 1 CBN insert

All roughness measurements have been obtained directly on the machine and without disassembling the workpiece (Fig. 2) by means of a Surftest 301 Roughness meter. The cutting forces have been measured in real time within the three components according the directions *X*, *Y* and *Z*, using a quartz KISTLER 9257B standard dynamometer. A distance IR pyrometer with, Rayner models 3I, (-30 to 1200°C) has allowed to record temperatures in the cutting zone. Wear has been investigated without lubrication under the following cutting parameters: feed rate (*f*) of 0.08 mm/rev, cut depth (a_p) of 0.5 mm and a cutting speed (v_c) range of 85 to 310 m/min. An allowable wear value [*VB*] of 0.3 mm is adopted for the CBN tool life. However wear values have been obtained beyond this limit in order to observe the global CBN tool behaviour, under extreme conditions.

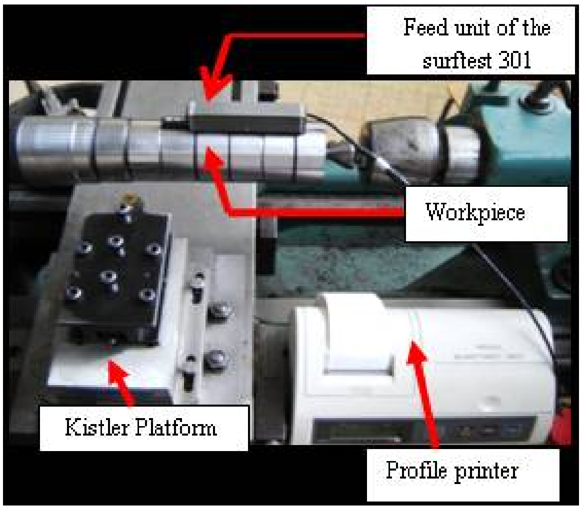

Fig. 2 Layout of the equipment for Roughness measurement on the machine

3. Results and discussion

3.1. Effect of cutting speed on wear

Long term wear tests according to ISO 3685 have been carried out through straight turning in order to evaluate CBN tool life for various cutting speeds. These tests provide reliable results closer to industrial reality [22, 23]. Results on CBN tool wear evolution (flank and crater) as a function of cutting time for a cutting speed range of 85, 115, 150, 200, 240 and 310 m/min, are illustrated in Fig. 3 and Fig. 4. It can be clearly seen that the wear trend obey the universal wear law of any mechanical workpiece (wearing, normal wear, accelerated wear). However the cutting speed has a great effect on the wear behaviour as a rapid increase of the wear started from the cutting speed of 115 m/min. As a consequence the extent of the normal wear zone is considerably reduced; this is justified when testing at 85, 150 and 310 m/min. At 85 m/min, the normal wear zone extends during 35 min, at 150 m/min; it requires only 15 min, whereas at 310 m/min the normal wear zone is almost nonexistent. Moreover, Fig. 4 reveals that the crater trend of wear *KT* is relatively weak comparing to wear *VB* therefore the principal criterion of tool life is the wear *VB* resistance [21].

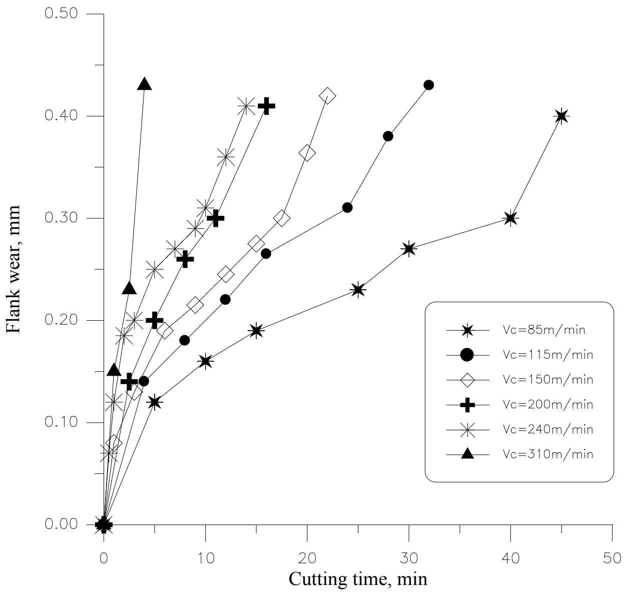

Fig. 3 Evolution of flank wear (*VB*) as the function of cutting time

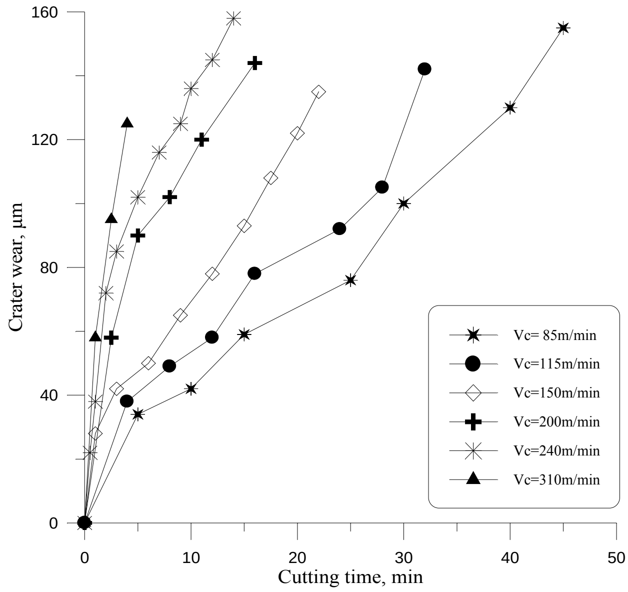

Fig. 4 Evolution of crater wear (*KT*) as the function of cutting time

3.2. Microscopic observations of wear morphology

Microscopic observations have been of practical use to following the *VB* and *KT* wear morphology as a function of time and various cutting speeds.

For cutting speeds of 85 m/min and 115 m/min, there was no difficulty in machining. The wear on flank surface is regular; at the beginning, it is manifested by the appearance of a grooved and shining band. When increasing the machining time, the *VB* value increases generating discontinuous chip. It is worth noting that the machining system is stable within these cutting speeds. The crater wear appears by a small cup on the rake surface in the first machining minutes and it extents with time (Fig. 5, a).

When increasing the cutting speed to 150 m/min, mechanical and thermal solicitations on the cutting edge increase allowing small grooves to be formed after 3 min on the flank surface along the cutting speed direction. Af-

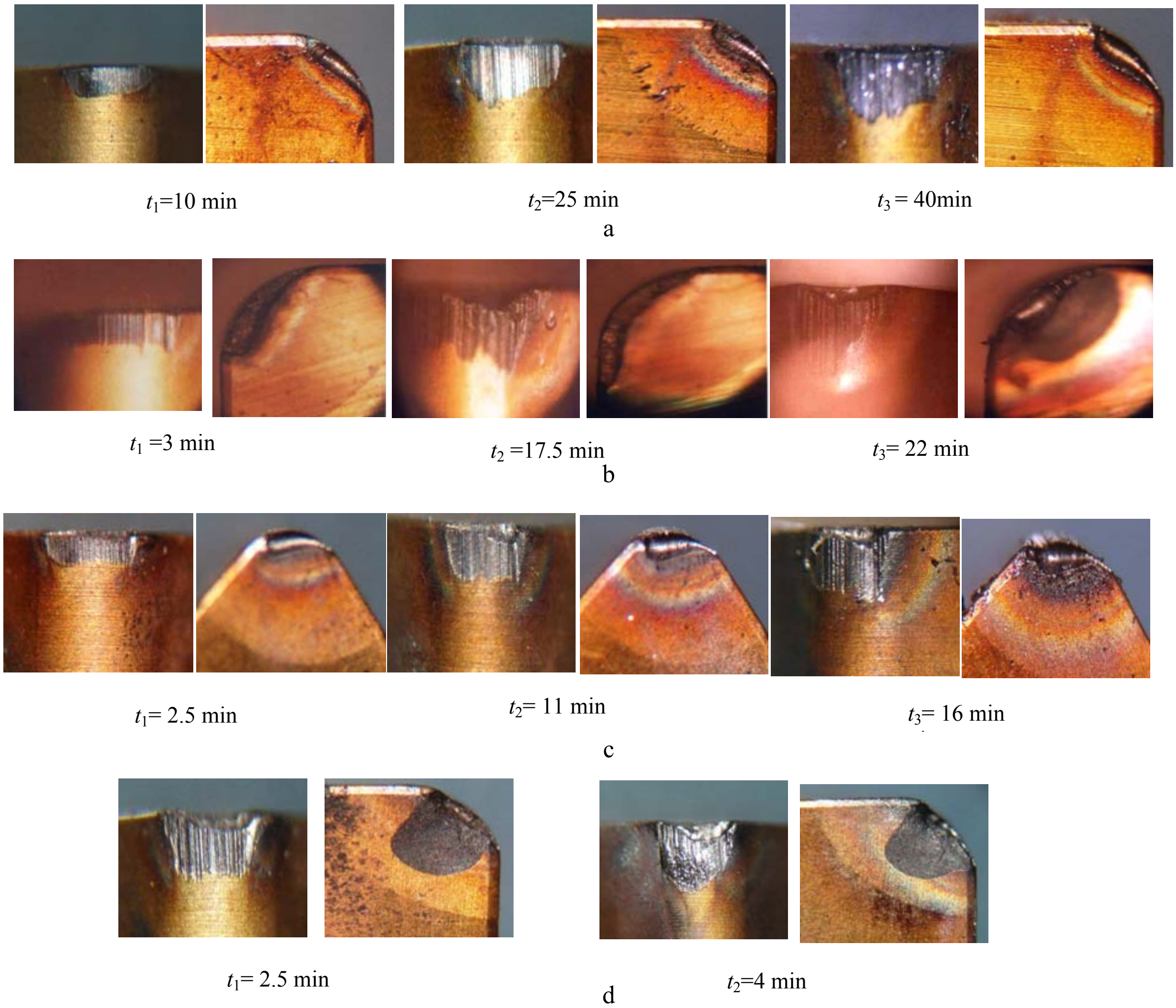

Fig. 5 Micrographs of flank and crater wear at various cutting speeds f = 0.08 mm/rev and a_p = 0.5 mm: a - v_c= 85 m/min ; b - v_c = 150 m/min ; c - v_c = 200 m/min ; d - v_c = 310 m/min

ter 17.5 min of machining, the wear *VB* expands in width and increases to becoming irregular. On the 22nd minute of work, machining becomes difficult showing fairly red colour discontinuous chips (Fig. 6). Chippings on the tool rake surface following the high stresses generated from the cutting process are observed. The rapid evolution of *VB* and *KT* has lead to the collapse of CBN tool nose (Fig. 5, b).

Fig. 6 A vue of the chip form

At 200 m/min, at the beginning the machining is characterized by stability, by no chipping on the flank surface and the crater of the CBN insert, and by discontinuous red chip. After 2.5 min the flank wear appears with regular band (Fig. 5, c). At the 11th minute the *VB* value increases in width and the crater becomes wider. At the end, 16 min of machining, wear *VB* becomes irregular allowing small collapse on the CBN tool nose.

At 310 m/min within 2.5 min of machining, the insert chamfer undergoes an accelerated wear caused by temperature increase, and chipping is observed on the rake surface. After 4 min, small collapse of the tool nose is noted. Machining lasted with chipping on the rake surface that propagates along the diagonal direction of the insert. There have also been grooves while wear *VB* is generating on tool flank, resulted from high abrasive wear (Fig. 5, d).

It is worth noting that for all cutting speeds considered in this work, there have been grooves on tool flank surface. These grooves are oriented along the cutting speed direction. The latter seems to be the results of high abrasive wear. Grooves usually appear at the beginning of the machining and never disappear (Fig. 5), and this is in good agreement with what is reported in literature [24, 25]. The origin of these grooves is attributed to the tool binder damage caused by hard carbide particles of the workpiece leading to CBN tool grains fall out. However deep studies of the worn areas show than the wear phenomenon due to diffusion generated with great cutting speeds takes part in wear process of the rake surface of CBN tool [12, 13, 26]. When combined these two wear mechanisms (abrasion and diffusion) lead to acceleration of the chipping process of tool surfaces and degradation of the cutting edge.

3.3. Effect of wear on tool life and productivity

Graphic analysis of the flank wear results (*VB*) (Fig. 3) as a function of cutting time in the investigated cutting speeds allows to determine different CBN tool lives. It should be noted that the tool life (*t*) has been obtained for the flank wear as the latter is very much higher than the crater wear specifically when the speed is increased. On the basis of two allowable wear criteria [*VB*] = = 0.3 mm and [*VB*] = 0.4 mm, the obtained values of tool live are summarized in Fig. 7.

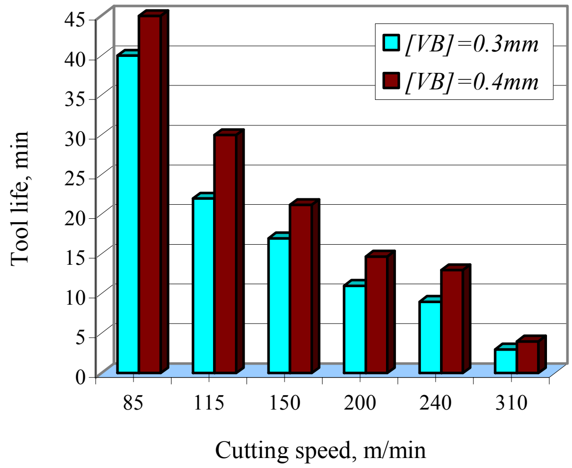

Fig. 7 Effect of cutting speed on CBN tool life

For the cutting speeds 85 to 115 m/min and the speed ratio of 1.35, the tool life falls by 45%. Increasing the speed range 115 to 150 m/min, for the speed ratio of 1.3, it is observed 23% of tool life fall. The corresponding tool life reduction, for the next three speed ranges 150 to 200, 200 to 240 and 240 to 310 m/min have been found respectively of 36%, 19%, and 67%. There is obviously a great sensitivity of lifetime to cutting speed variation. For higher speed ranges 240 to 310 m/min, this effect is even more significant on the tool life that dropped down by 67%. This can be explained by the presence of high temperatures generated by the cutting process around the tool nose, supporting various wear mechanisms (abrasion and diffusion) and consequently the cutting tool capacity decreases. Even more when working at high cutting speeds, the mechanical and thermal solicitations increase on the cutting edge. As a consequence frictions and high pressures that are exerted on the interface chip-tool and tool-workpiece generate wear [9, 18, 21].

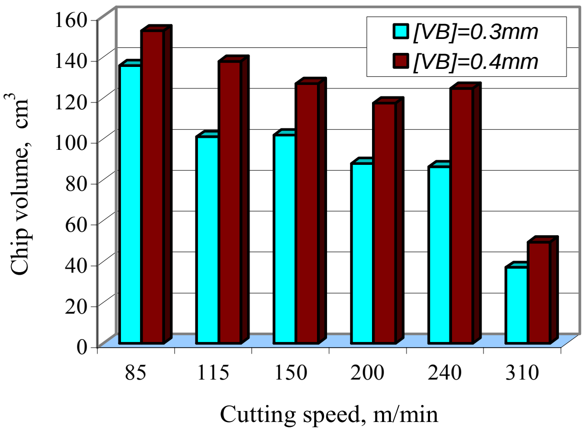

Fig. 8 Effect of cutting speed on the generated chip volume

Fig. 8 illustrates the chip volume produced during AISI D3 steel machining at various cutting speeds for the two wear criteria [*VB*]=0.3 mm and 0.4 mm. It can be clearly seen from the results that for the cutting speed of 85 m/min there have been better performance as the volume *V* respectively to the values of wear criteria is equal to 136 cm^3 and 153 cm^3. The smallest chip volume values *V* = =37.2 cm^3 and *V*=49.6 cm^3 corresponding to the allowed values of wear are obtained for the cutting speed of 310 m/min.

3.4. Effect of wear on roughness

Results on roughness evolution as a function of wear VB are illustrated in Fig. 9 and Fig. 10, for 115 and 160 m/min cutting speeds. There is neither stable nor uniform roughness value for criteria (*Ra*, *Rz*, *Rt*) during the cutting, but roughness is subjected to sudden increase as a function of machining time, i.e. with wear resistance. Therefore superficial damage obtained on of the faces and cutting edges of the active tool part leads to the degradation of surface roughness of machined material. The curves also show that CBN ensure good surface quality during a large spare machining time. At 115 m/min and after 32.5 min of cutting roughness *Ra* has not exceeded 1 µm, similarly at higher speed v_c=160 m/min, *Ra* remains lower than 1 µm within 20 min of machining.

The change in the roughness behaviour as the function of *VB* wear can be explained through microscopic observations of the tool nose. Fig. 10 shows increasing wear micrographics describing the transition from low roughness value (*VB*=0.14 mm), to high value (*VB*=0.31 mm) and the zone with higher roughness value (*VB*=0.43 mm), for the cutting speed of 160 m/min. 4 min machining generate a weak wear bandwidth that is appreciable with constant total roughness (*Rt*=2.75 µm). 8 min machining reveals an increase in the width of wear band with the formation of small grooves on the flank face (abrasion wear). After 12 min of machining, the thermomechanical solicitations increase on the cutting edge, causing various forms of the CBN tool wear resulting in a total roughness value *Rt* of 3.44 µm and a *VB* of 0.25 mm. When machining ended after 20 min, the tool undergoes rapid wear degradation (*VB*=0.43 mm), where a small collapse on the tool CBN nose is observed leading to the machined surface quality drop (*Rt*=5.01 µm). Finally at v_c=160 m/min, the *VB* wear increase from 0.14 to 0.43 mm led to roughness values increase (*Ra*; *Rz*; *Rt*) respectively by 130.76%; 110.61%; 82.18%.

3.5. Effect of wear on cutting forces

Fig. 11 and Fig. 12 show the evolution of cutting forces as a function of cutting time and wear. There is an increase in the cutting force components as a function of cutting time. This is due to wear evolution on the attack and flank surfaces of the tool. As a consequence the workpiece-tool contact surface increases together with the friction forces generating higher cutting forces.

The first stage lasted 6.5 min and corresponded to *VB* wear of 0.15 mm, the cutting forces (*Fr*, *Fa* and *Fv*) recorded were respectively 137.82, 61.5 and 85.22 N. The

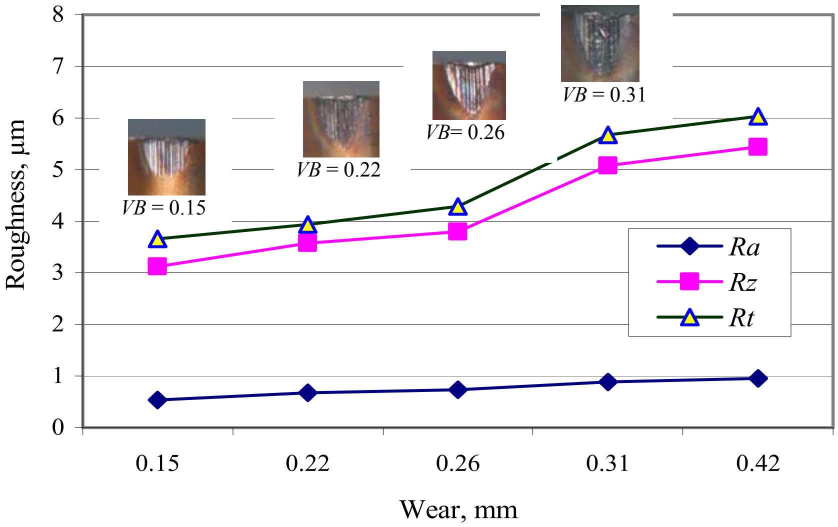

Fig. 9 Influence of wear on roughness at v_c = 115 m/min; f = 0.08 mm/rev; a_p = 0.2 mm

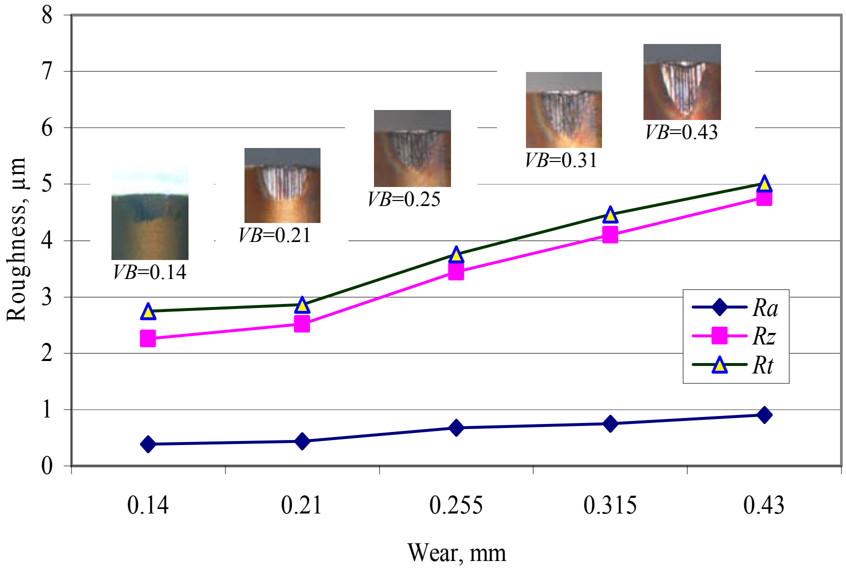

Fig. 10 Influence of wear on Roughness at v_c = 160 m/min; f = 0.08 mm/rev; a_p = 0.2 mm

second stage varied from 6.5 to 26 min of machining, where the measured wear *VB* increased from 0.15 to 0.31 mm, causing an increase in the cutting forces (*Fr*, *Fa* and *Fv*) of respectively 87.96, 39.77 and 76.07%. In this stage the evolution of the cutting forces is more accentuated than during the first stage. The third stage was characterized by a fast evolution of wear *VB* value passing from 0.31 to 0.42 mm during a spare time of 26 to 32.5 minutes of machining. At this stage the cutting forces reached maximum values with an increase of 20.47, 19.11 and 4.84. When comparing the evolution of the cutting forces (*Fr*, *Fa* and *Fv*) from the beginning to the end of machining, there has been respectively 126.44, 66.48 and 84.60%, increase. Fig. 5 shows micrographics of the CBN tool flank taken at various wear stages.

3.6. Correlation between wear and cutting temperature

The cutting tool wear is the most influencing parameter during machining of hard materials [10, 15, 19, 21, 26]. Fig. 13 illustrates the evolution of cutting temperature as a function of wear *VB*. The longer the cutting time the larger the wear therefore the temperature generated in the cutting zone increases significantly. Within 4 minutes temperature reaches 548°C while the flank wear is weak, *VB*=0.14 mm. As contact surface between the workpiece and tool increases in 12 minutes, because of increases in wear (*VB*=0.25 mm), there is a rise in frictions and heating allowing the deterioration of cutting edges by physico-chemical phenomena [12]. The acceptable wear limit is reached after 16min of machining when small collapse of the CBN tool nose occurs and maximum temperature of 597°C is recorded. Later on after 20 min, catastrophic collapse of the nose is observed when *VB*=0.43 mm.

Hence a mechanism of abrasion and diffusion [25, 26] occurs due to the amount of heating and higher values of cutting forces. At this stage, the maximum temperature of 615°C is recorded and the tool loses its cutting qualities by thermal fatigue. Finally it can be said that the three parameters (friction, temperature and wear) are closely related and mutually affecting each other. As a consequence when cutting frictions increase there a is rise in cutting

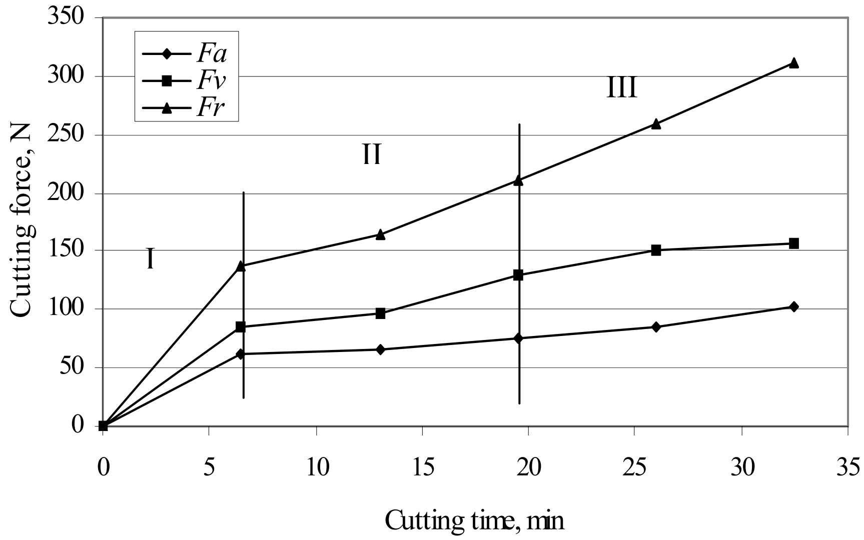

Fig. 11 Effect of cutting time on cutting force at v_c = 115 m/min; f = 0.08 mm/rev; a_p = 0.2 mm

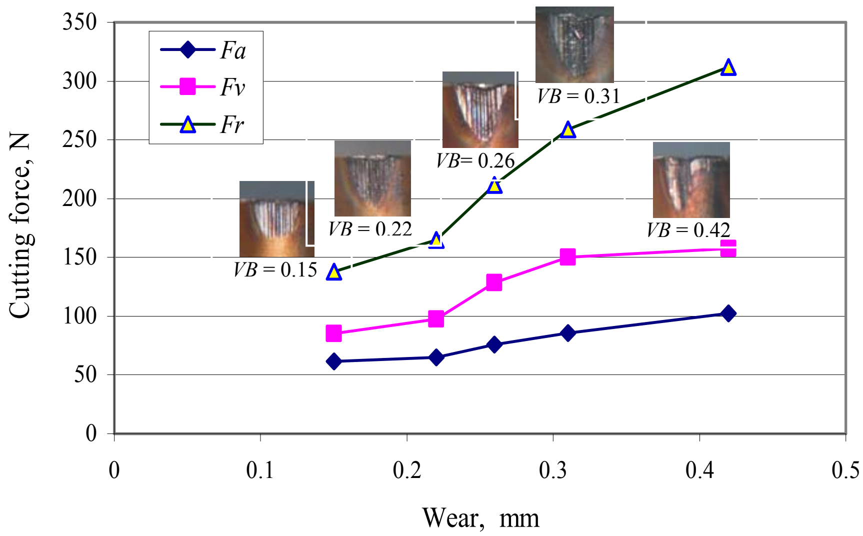

Fig. 12 Influence of wear on cutting force at v_c = 115 m/min; f = 0.08 mm/rev; a_p = 0.2 mm

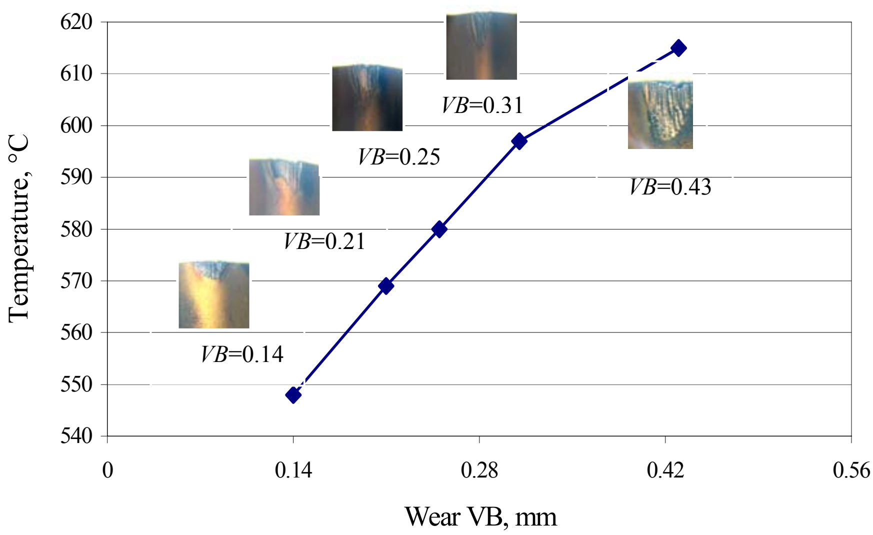

Fig. 13 Influence of wear on maximum recorded value of temperature in the cutting zone at v_c =160 m/min, f=0.08 mm/rev, a_p = 0.2 mm

temperature and heat diffusion in the tool, decreasing tool mechanical characteristics by accelerated wear phenomena, thus the tool life is affected. In fact there could be invaluable information on the importance of heating effects associated to cutting through temperature investigation [4, 26, 27], particularly when the tool life is concerned.

3.7. Mathematical models

From the above analysis, mathematical models can be deduced. As a result the tool life models can be established as a function of cutting speeds using the least squares method. The former equations are then written as expressed in (1) and (2) for the two allowable *VB* criteria:

$$t=exp^{11.667}v^{-1.781} \quad R^2=0.991 \ \text{for} \ [VB]=0.3 \text{ mm} \quad (1)$$

$$t= exp^{11.296}v^{-1.657} \quad R^2=0.986 \ \text{for} \ [VB]=0.4 \text{ mm} \quad (2)$$

These models allow to determine the CBN tool life as the function of expected cutting speed. As it can be seen, the cutting speed has a great influence on the tool life: the higher the cutting speed the lower the tool life. In addition these models are of great interest in eventual optimisation of cutting processes. The determination coefficients R^2 of the proposed models converge towards the unit, which give a good correlation with the experimental results.

Then from equations (1) and (2) Taylor straight lines can be drawn on a bi-logarithmic scale (Fig. 14) for the two wear criteria [*VB*]=0.3 and 0.4 mm. These lines are economically very important since they allow to know the CBN tool life when machining AISI D3 steel hardened to 60 HRC, at any selected cutting speed ranging from 85 to 310 m/min.

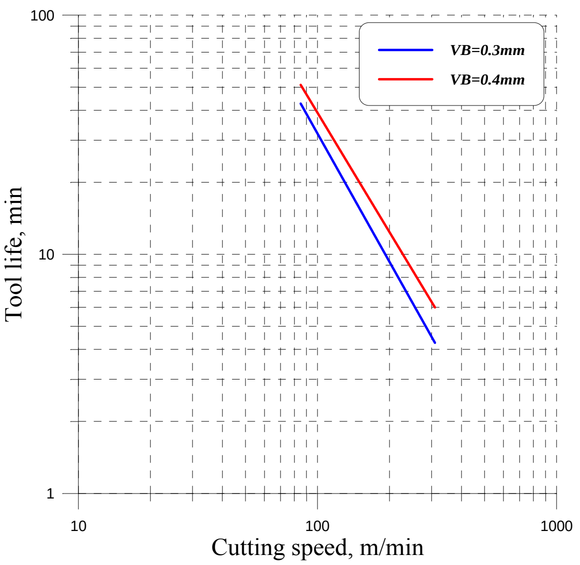

Fig. 14 Effect of cutting speed on tool life using Taylor straight lines

In addition with regard to roughness-wear *VB* curves (Fig. 9 and Fig. 10) a general mathematical model is proposed in the equation

$$R_i = K\, e^{\alpha (VB)} \quad (3)$$

Table 2 presents various models of roughness as the function of wear in given cutting conditions.

Table 2

Roughness mathematical models as the function of wear *VB* for f = 0.08 mm/rev and a_p = 0.2 mm

Cutting material	v_c, m/min	Mathematical models	R^2
CBN 7020	115	Ra=0.489 $e^{0.1388VB}$	0.967
		Rt=2.647 $e^{0.1465VB}$	0.951
	160	Ra=0.310 $e^{0.2206\,VB}$	0.951
		Rt=1.815 $e^{0.1976\,VB}$	0.979

The proposed models can be now used to evaluate roughness (*Ra* and *Rt*) as a function of wear *VB* and vice versa. In all cases the determination coefficients R^2 are greater than 0.95.

4. Conclusions

The main conclusions of this work are.

1. The most distinguished wear phenomenon is abrasion wear that appears by grooving on the tool flank face. The abrasion is due to pull out of tool particles by hard particles existing in the machined material.

2. In low cutting speed range, the wear of CBN tool appears through grooving on flank surface and the formation of a crater on attack surface. With time, an increase in wears *VB* and *KT* is observed which leads to the tool nose collapse because of the combined action of the two wears. In high cutting speed range, the tool nose collapse occurs within the first minutes of machining and the tool nose retraction follows after blunting. In this case a particular attention should be paid since the dimensional accuracy and machined surface quality can be significantly affected.

3. Above 240 m/min the cutting speeds are not recommended because of the fast tool wear which leads to too much short tool life not interesting to industrial applications. Therefore this can be as the highest cutting speed for optimal cutting speed range for CBN tools exploitation particularly when cutting hardened AISI D3 steel.

4. The wear is one of the main factors to be considered, since it has a great detrimental effect on surface quality of the workpieces. However, even when the VB reaches 0.3 mm, the majority of the recorded values or *Ra* does not exceed 1 µm.

5. The CBN wear increase induces a rise in temperature and cutting forces. This is observed when *VB* reached 0.42 mm after 32.5 min of machining allowing respectively significant increase of 126.44, 66.48 and 84.60% in the cutting forces components *Fr*, *Fa* and *Fv*.

6. A relationship between *VB* and *Ra* is proposed in the form $R_a = Ke^{\alpha(VB)}$. The parameters K and α, are coefficients that are respectively varying, from 0.489 to 0.310 and 0.138 to 0.220. In the given conditions, the correlation allows getting information on cutting edge state and easily following the tool wear from measured roughness.

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H. Bouchelaghem, M.A. Yallese, A. Amirat, S. Belhadi

IŠ KUBINIO BORO NITRIDO PAGAMINTO ĮRANKIO DILIMAS TEKINANT SUKIETINTĄ PLIENĄ AISI D3

R e z i u m ė

Atlikti įrankio, pagaminto iš kubinio boro nitrido atsparumo dilimui tyrimai, tekinant sukietintą AISI D3 plieną. Ilgai trunkančiais dilimo tyrimais siekta išsiaiškinti įrankio, pagaminto iš KBN dilimo pobūdį, jo patvarumo bei produktyvumo priklausomybę nuo pjovimo greičio. Atlikta eksperimentų serija tyrinėjant apdirbamo paviršiaus šiurkštumo, pjovimo jėgų bei temperatūros įtaką įrankio dilimui (*VB*). Gauti rezultatai rodo, kad, nepaisant plieno AISI D3 kietumo (60 HRC), KBN įrankiai yra atsparūs dilimui. Didelis šilumos kiekis, susidaręs pjovimo metu, išsklaidomas per drožles. Viršijus 240 m/min pjovimo greitį, dėl įrankio dilimo spartėjimo apdirbimo sistema tampa nestabili, sukeliamos kibirkštys bei vibracija. Pastebėta, kad iki leistinos įrankio nusidėvėjimo ribos [*VB*]=0.3 mm apdirbamo paviršiaus šiukštumas *Ra* neviršijo 1 μm. Vėliau šiurkštumas išaugo, bet liko visiškai priimtinas (*Ra*<1.2 μm). Sudarytas matematinis modelis, įgalinantis įvertinti įrankio patvarumo priklausomybę nuo pjovimo greičio, o kartu ir šiurkštumo *Ra* ir nusidėvėjimo *VB* tarpusavio ryšį.

H. Bouchelaghem, M.A. Yallese, A. Amirat, S. Belhadi

WEAR BEHAVIOUR OF CBN TOOL WHEN TURNING HARDENED AISI D3 STEEL

S u m m a r y

Investigations on wear resistance of cubic boron nitride tool during turning of hardened AISI D3 steel have been conducted. Initially, long term wear tests were planned to elucidating the effects of cutting speed on the various forms of CBN tool wear and also to make in evidence wear consequences on the tool life and the productivity. Then, a second series of experiments has been carried out to study the influence of wear (VB) on surface roughness, cutting force and temperature. Results show that the CBN tool presents a good wear resistance despite the aggressiveness of AISI D3 steel (60 HRC). A great part of heat generated during cutting is dissipated within the chip. Beyond 240 m/min cutting speed, the machining system becomes unstable, producing sparks and vibrations caused by intensive wear evolution. Meanwhile, up to the admissible wear value [*VB*] =0.3 mm, roughness *Ra* did not exceed 1 μm but beyond, roughness increased, but it remained extremely acceptable (*Ra* <1.2 μm). Finally, in one hand a mathematical model has been obtained to predict the tool life as a function of the cutting speed and in the other hand a correlation between roughness *Ra* and wear *VB* is proposed.

Г. Боухелагем, М.А. Яллесе, А. Амират, С. Белгади

ИЗНОС ИНСТРУМЕНТА, ИЗГОТОВЛЕННОГО ИЗ КУБИЧЕСКОГО НИТРИДА БОРА, ПРИ ТОЧЕНИИ ЗАКАЛЕННОЙ СТАЛИ AISI D3

Р е з ю м е

Исследовано сопротивление к износу инструмента, изготовленного из кубического нитрида бора (КНБ), при точении закаленной стали AISI D3. Произведены долговременные эксперименты инструмента, изготовленного из КНБ, с целью выяснения характера его износа, производительности и износостойкости в зависимости от скорости точения. Проведена серия экспериментов изучения влияния на износ инструмента шероховатости обрабатываемой поверхности, сил точения и температуры. Полученные результаты показывают, что инструменты, изготовленные из КНБ, износостойкие, несмотря на твердость стали AISI D3 (60 HRC). Большое количество теплоты, сгенерированной при точении, отводится через стружку. При превышении скорости точения 240 м/мин из-за быстрого роста износа, иследуемая система становится неустойчивой, появляются искры и вибрация. Установлено, что до допустимого предела износа инструмента [*VB*]= = 0.3 mm шероховатость обрабатываемой поверхности не превышала 1 μm. Далее шероховатость увеличивалась, но оставалась полне приемлемой (*Ra* < 1.2 μm). Разработана математическая модель, позволяющая оценить зависимость износостойкости инструмента от скорости точения, а также установили взаимную связь между шероховатостью *Ra* и износом *КВ*.

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