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On machining of hardened AISI D2 steel with PCBN tools

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Abstract

This paper describes an experimental investigation on machining of a difficult-to-cut material, AISI D2 steel of hardness 62 HRC with PCBN tools. It was found that the most feasible feeds and speeds fall in the ranges 0.08–0.20 mm/rev and 70–120 m/min, respectively and that most of the tested PCBN tools reached the end of life mainly due to flank wear. The highest acceptable values of tool life and volume of material removal were obtained at the lowest speed tested (70 m/min), indicating that this speed is more suitable for machining the selected tool/work material combination. While the highest feed used resulted in the highest volume of material removal, lower feeds resulted in higher tool life values. It was also found that the most appropriate feeds for this type of hardened steel are 0.14 mm/rev for finishing operations and 0.20 mm/rev for roughing operations. It is shown that for the considered conditions, the relationship between tool life and cutting conditions can be represented by a Taylor type tool life equation, while that between forces and cutting conditions can be represented by power function type equations.

Keywords: Machining; PCBN tools; Hardened AISI D2 steel; Tool life

1. Introduction

Since the introduction of PCBN in 1970s, hard turning technology has made rapid advances and provided an alternative to grinding in the manufacture of many high precision, high hardness components. In addition to the ability-to-machine using defined cutting edges, hard turning has other advantages such as elimination of coolant, higher metal removal rates, greater flexibility and the ability to manufacture complex part geometries in a single set-up. This process differs from conventional turning in that relatively low depths of cut, feeds and cutting speeds are normally used. Moreover, because of the high strength/hardness of the work materials and the brittleness of PCBN, the tools are normally used with a chamfered cutting edge which offers increased cutting edge strength, and wear and chipping resistance. However, this chamfer leads to a large negative tool rake angle resulting in higher plastic strains and hence higher cutting temperatures during machining which can adversely affect the tool performance.

Despite the aforementioned advantages of hard turning of steels compared to grinding, there is a clear need for further research to clarify the issues in the areas of tool wear/life, surface integrity, work piece quality, process reliability and process modelling [1–3]. This is particularly important with wider applications of PCBN tools to machine ferrous work materials. In addition, before a part is put into production, most suitable cutting conditions for the process must be determined in order to minimise/eliminate the possibility of scrapping an expensive part.

This paper describes an experimental investigation with PCBN tools in turning hardened AISI D2 steel of 62 HRC, aiming at determining the most suitable cutting conditions based on tool life and volume of material removal. In addition, tool wear, variations of cutting forces, chip form and appropriate equations for tool life and cutting forces will be

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Nomenclature

A_c, A_f, A_r	constants in force Eq. (4)
A_t	constant in tool life Eq. (2)
b_c, b_f, b_r	exponents in force Eq. (4)
b_t	exponent in tool life Eq. (2)
c_c, c_f, c_r	exponents in force Eq. (4)
c_t	exponent in tool life Eq. (2)
d	depth of cut (mm)
f	feed (mm/rev)
F_c	force acting in the cutting direction (N)
F_f	force acting in the negative feed direction (N)
F_r	force acting in the radially outward direction (N)
T	tool life (min)
V	cutting speed (m/min)
VB_B	average width of flank wear land (mm)
VB_{Max}	maximum width of flank wear land (mm)
W	volume of material removal (cm^3)

investigated. AISI D2 steel is a high chromium, high carbon, tool and die steel with hardness in the range 54–62 HRC used for cold working operations. It has a high strength, very high resistance to cracking and high resistance to softening and wear. Its toughness and machinability are considered to be low [4]. A typical composition of this special alloy steel is: 1.55% C, 0.3% Si, 0.4% Mn, 11.8% Cr, 0.8% Mo and 0.8% V.

2. Review of previous work

During the past 30 years or so, many investigations that involve machining of hardened steels with PCBN tools have been reported. These include research on the mechanics of the chip removal process, tool materials, tool wear/life, determination of optimal tool geometry, cutting forces, cutting temperatures, surface roughness/integrity, machine tools, dimensional/form accuracy, residual stresses and work piece microstructure. In addition, some investigations have been carried out for obtaining the high temperature, high strain rate flow stress data [5] which were then used for modelling the hard turning process [6]. Two major reviews of research on machining of hardened steels have been presented by Tonshoff et al. [1] and Konig et al. [7]. Some of the more recent investigations considered to be relevant to the present investigation are discussed in some detail below.

Konig et al. [8] pointed out that PCBN tools (with metal carbide binders) could economically be used not only for turning hardened steels but also for milling and drilling of these materials. Their turning test results showed that PCBN gave much longer tool life values compared to ceramic tools.

Zhou et al. [9] investigated the effect of tool chamfer angle on cutting forces, tool flank wear and tool life when turning hardened AISI-52100 steel of hardness 60–62 HRC. The tools used were low CBN content PCBN, having cutting edge radius 0.01 mm and chamfer width 0.1 mm with chamfer angle varied from 0° to 30°. The tests were carried out at depth of cut 0.05 mm, feed 0.05 mm/rev and cutting speed 160 m/min. Their results showed that, with increase in chamfer angle, all three force components increased while tool life first increased and reached a maximum value at chamfer angle 15°. Tool life then decreased with further increase in chamfer angle, indicating an optimum angle of 15°.

Kishawy and Elbestawi [10] investigated the surface integrity of AISI D2 steel of 62 HRC machined using PCBN tools under high speed conditions. They used cutting speeds in the range 140–500 m/min, feeds 0.05–0.2 mm/rev, depths of cut 0.2–0.6 mm and tools with edge preparations, sharp, chamfered (20° × 0.1 mm) and honed (radius 0.0125 mm). Their results showed that, at cutting speeds above 350 m/min, the surface roughness increased with increase in tool wear and this was attributed to material side flow. In addition, defects such as micro-cracks and cavities were observed on the machined surface. The density of these micro-cracks was found to depend on the cutting speed and feed used. Their study of machined surface structure revealed a thermally affected white layer formed due to phase transformation when machined with chamfered or worn tools but not with sharp tools.

Narutaki and Yamane [11] investigated tool wear when machining hardened tool steel, casehardening steel and high speed steel work materials of hardness in the range 10–66 HRC. They used PCBN tools with high CBN content (∼90% with metallic binder) and low CBN content (60–70% with ceramic binder). When machining softer steels (e.g. 10 HRC), low CBN content tools performed better in terms of flank wear. This was attributed to lower attrition wear due to greater bonding strength of the tool which consisted of a higher volume of binder. These tools also showed better wear resistance when machining hardened tool steel and case hardening steel. However, when machining high speed steels, high CBN content tools performed better. This was attributed to the greater volume of CBN in the tool resisting abrasion by hard carbide particles in the work material.

Chou et al. [2] investigated the performance and wear behaviour of high CBN content (92% with metallic (cobalt) binder) and low CBN content (70% CBN with ceramic (TiN) binder) PCBN tools when turning hardened AISI-52100 steel of 61–63 HRC. Their test results showed that low CBN content tools generated better surface finish and had lower flank wear rates than high CBN content ones. From an SEM study of built-up layers[1] on the flank wear scars of these tools, they suggested that built-up layers on low CBN content tools are not as strongly bonded as those on high CBN content tools

[1] These relatively thin layers are observed on wear scars of PCBN tools and seem to be formed as a result of reactions among elements/compounds in work material, tool material, etc.

and that adhesion interacted with built-up layer as a dominant wear mechanism. The observed greater adhesion on high CBN content tools was attributed to a higher affinity of the metallic binder to the built-up layer while the accelerated abrasive wear was attributed to plucked out CBN particles due to loss of binder.

Poulachon et al. [12] studied the wear behaviour of low CBN content PCBN tools when turning hardened steels AISI D2, AISI H11, 35NiCrMo16 and AISI-52100, each steel with hardness 54 HRC. During their tool wear tests, these four steels showed different flank wear rates under identical conditions. Based on a study of worn tool flanks and the microstructure of the steel work materials, they identified presence of various hard carbides in the steel as the major influencing factor on tool wear which caused wear grooves on tool flank by abrasion. The observed differences in wear rates were attributed to different hardness values of the various carbides in the steels. Luo et al. [13] machined AISI-4340 steel with hardness values 35, 45, 50 and 55 HRC using PCBN tools (with TiC and Al_2O_3 binder) and concluded that the main tool wear mechanism is due to abrasion of the binder by hard carbide particles in the steel work material.

Barry and Byrne [14] investigated the wear mechanism of low CBN content (50% CBN with TiC binder) PCBN tools when machining three heats of AISI-4340 steel of 52 HRC. Considering the presence of different elements on the crater and flank wear surfaces of the used tools (these elements were originally present in the work materials in small or very small quantities), they suggested that the dominant wear mechanism of PCBN tools was chemical in nature. Based on the observed higher wear rate of CBN phase than TiC phase, they suggested that the products of the reaction between the BN phase and certain work material inclusionary deposits may afford a degree of protection to the TiC phase against dissolution/diffusion wear. This was used to account for the widely acknowledged superior wear resistance of low CBN content tools compared to high CBN content ones.

More recent developments/applications of CBN/PCBN include PCBN tools with TiN and TiAlN coatings, PCBN tools with wiper edge, composite CBN coatings on carbide substrate and pure or binderless CBN tools. Experimental tool life results obtained using AISI-52100 steel of 62 HRC with coated (TiN and TiAlN) and uncoated (low CBN content) PCBN tools by Dawson and Kurfess [15] have confirmed that, in general, coated tools performed better in terms of tool wear/life. They suggested that the coating possibly provided a ‘break-away’ layer that delayed the exposure and wear of PCBN substrate thus increasing tool life. Knuefermann et al. [16] reported an investigation carried out using an ultra-precision lathe with redesigned spindle and specially designed and manufactured PCBN inserts and holders to achieve greater rigidity in the machining system. Tool inserts were submicron grain low CBN content (∼45%) PCBN with cutting edge chamfer $20^\circ \times 0.1$ mm and hone radius 0.01 mm. The work material was AISI-52100 steel of hardness 60 HRC. During their machining tests with wiper tools, surface roughness values as low as 22 nm R_a were achieved. Yadave et al. [17] described the development and testing of tools with a CBN–TiN composite coating for machining hardened steels. The performance of these coated tools (in terms of tool wear) were shown to be comparable to PCBN tools. Such tool coatings have the potential for application on tools with chip breaker grooves. Neo et al. [18] used both binderless CBN (CBN content > 99.9%) and high CBN content PCBN tools for ultra-precision machining of a stainless steel (prehardened 215 BHN) and found that binderless CBN performed better in terms of wear resistance. These recent developments/applications clearly indicate the continuing advancement of hard turning technology with CBN/PCBN tools.

As noted earlier Shatla et al. [5] determined the flow stress data for hardened AISI P20 and AISI H13 steel work materials by applying the Oxley machining theory [19] in reverse. In Ref. [5], the Johnson-Cook constitutive equation was used to relate the flow stress with strain, strain-rate and temperature. The constants of this equation were determined using an iterative procedure which adjusted these constants until reasonable agreement between predicted (using Oxley theory) and experimental cutting forces was obtained. Thus there is no guarantee that obtained constants for the constitutive equation were unique. While Oxley theory has been used in reverse for obtaining the work material flow stress data in conventional turning of plain carbon steels [20] and aluminium alloys [21], these analyses have used experimental cutting forces, chip thicknesses, secondary deformation zone thicknesses, etc. Considering that in hard turning saw-tooth chips are often produced under non-steady state conditions, major difficulties are encountered when applying Oxley theory (which assumes steady state conditions) for obtaining the flow stress data.

From the above brief review of PCBN tool wear, it can be seen that different wear mechanisms (based on mechanical and physical properties as well as chemical and microstructural aspects) have been used to explain the flank wear of PCBN tools when machining hardened steels. This indicates that wear of PCBN tools is not fully understood yet and is one of the major difficulties encountered when developing a fundamental approach for predicting tool life in hard turning. Because of these difficulties, an experimental approach is adopted in the present work to determine the most suitable cutting conditions for machining AISI D2 steel based on tool life and volume of material removal. In addition, possible wear mechanisms for the tested tools are discussed. Finally, an attempt is made to present empirical tool life and cutting force relations that can be used in an optimisation procedure for hard turning similar to the one described in Ref. [22] for conventional turning.

In order to obtain the experimental values of tool life, cutting forces, etc. required for the present investigation, the following experimental procedure was used.

3. Experimental procedure

During the preparation and actual tool life testing stages, attempts were made to follow as closely as possible the recommendations made by the ISO [23]. The experiments were made on a lathe using a bar turning process under dry conditions. For each test condition, it was necessary to measure the average width of flank wear land VB_B and maximum width of flank wear land VB_{Max} after machining for a predetermined time interval. It was also necessary to measure the three force components: cutting force F_c, feed force F_f and radial force F_r. The above parameters are affected by the work material, tool material, tool geometrical parameters, cutting conditions, etc. The selected conditions/values of each of these variables are given below.

(a) *Work material*: This was a hardened AISI D2 steel bar of hardness 62 HRC with 97 mm diameter and 300 mm length.
(b) *Tool insert and holder*: SNMA-120408 PCBN inserts (with ∼85% CBN) were used with tool holder MSDNN2525-M12.
(c) *Tool geometrical parameters*: Average T-land width in the range 0.12–0.15 mm, nose radius 0.8 mm, rake angle 5°, inclination angle −7° and approach angle 45°.
(d) *Cutting conditions*: Cutting speeds 70, 95 and 120 m/min; feeds 0.08, 0.14 and 0.20 mm/rev; depth of cut 0.5 mm. Selection of these cutting conditions is based on a preliminary investigation [24] carried out using the above work material and cutting tool. It was found that, at feeds 0.315 and 0.2 mm/rev and cutting speeds 120 and 170 m/min, the obtained tool life values were short and uneconomical due to high tool wear and/or cutting edge chipping.

The machine tool used was a Heidenreich and Harbeck VDF precision lathe having a variable speed motor with speeds 0–5600 rpm rating up to 37 kW. The available feed range was 0.01–1.4 mm/rev. The conditions were oblique since the cutting edge inclination angle was non-zero and, at the chosen depth of cut, the nose radius part of the cutting edge was mainly involved in cutting thus varying the thickness of the cut. For increased rigidity of the machining system, the D2 steel bar was held between (three jaws) chuck and (live) tailstock and the tool overhang was maintained at the minimum possible value 31 mm. Required cleanup cuts were taken at depth ∼0.25 mm, feed 0.1 mm/rev and cutting speed 100 m/min with a PCBN insert. By using these conditions, it was expected that the cleanup cuts would have the minimum influence (in terms of surface integrity) on the subsequent test cuts.

After randomly selecting within the prescribed range a tool and the cutting conditions, machining was carried out for predetermined time intervals and tool wear was allowed to build up gradually. A chip breaker was not used in order to prevent its influence on cutting forces, tool life, etc. An attempt was also made to test each tool at different positions within the bar, so that wear variations caused by possible work piece inhomogeneity could be averaged out. After each machining test, the resulting wear land was examined for possible adhering work material, etc. that can hinder accurate measurement of wear land widths VB_B and VB_{Max}. There were no lumps of adhering work material, however, a thin shiny layer on some parts of the wear scar which did not cause difficulties in measuring wear land widths was noted (Fig. 1). The wear scars were cleaned using methylated spirit and the average width of flank wear land, VB_B, as recommended in Ref. [23], and the maximum width of the flank wear land VB_{Max} were then measured using a Nikon microscope which allowed these measurements to be made within ±0.005 mm. In order to obtain a clear image of the wear land, it was illuminated with filtered light. During each test, the force components were measured using a Kistler type 9257A three component piezoelectric dynamometer and a PC based data acquisition system that consisted of Kistler type 5011 charge amplifiers, RTI-815 ADC card, 486 DX2-66 personal computer and inhouse developed data acquisition software. During selected tests, chip samples were collected for subsequent examination of their shape, underside, etc. After each test, insert rake faces were also examined under the microscope for possible chipping, etc.

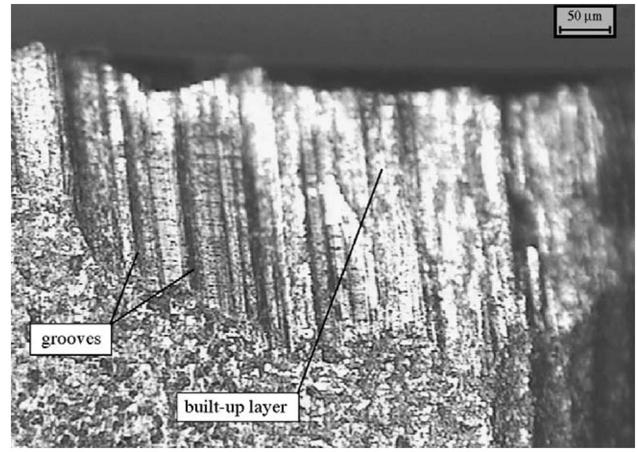

Fig. 1. A typical flank wear scar with grooves and built-up layer.

Based on preliminary work [24] and assuming that the speed would have the greatest influence on tool life, machining time intervals were selected depending on the cutting speed of a test. Thus, longer machining time intervals for lower speeds and shorter ones for higher speeds were chosen. Accordingly, the chosen time intervals for VB_B measurements at speeds 70, 95 and 120 m/min were 0.4, 0.6 and 0.75 min, respectively. For some tests, these initial time intervals were later increased to speed up the testing procedure.

As noted earlier, machining was carried out for predetermined time intervals given above and flank wear widths VB_B and VB_{Max} together with cutting forces were measured. This procedure was continued until flank wear land width reached ∼0.35 mm and/or considerable chipping was noticed at the cutting edge thus indicating the end of useful life of the tool. Although crater wear was also observed on tools it was not measured. Observed progression of crater wear was similar to that depicted in Refs. [11,15] in that on the rake face contact zone, the chamfer was gradually worn off and a groove and/or an obstruction (similar to a back-wall) formed. During most of the tests, cutting force signals were found to be steady. However, in a few cases, particularly with high levels of tool wear, decreasing force signals with higher forces at the initial part of the cut were seen.

No measurements of surface roughness of the machined surface were made during the tests. However, during some of the tests, unbroken chips produced with inserts having low levels of tool wear were found to scratch the newly generated surface. Hence, after each cut the new surface was examined and its surface condition (e.g. excellent/good surface finish, surface damaged by entangling chips, etc.) was recorded.

Initially, it was planned to carry out at least three replication tool life tests because of the possible high variability of tool life results. However, due to time constraint only one replication test (at speed 120 m/min and feed 0.20 mm/rev) became possible. Thus, in total, 10 full tool life tests were carried out. In addition, when an insert was prematurely failed (e.g. due to rake face chipping), the complete test was repeated using a new insert. Premature tool failure due to rake face chipping occurred at two feed/speed combinations: feed 0.08 mm/rev and speeds 70 and 120 m/min. Under no test condition was total fracture of CBN inserts experienced.

4. Results and discussion

4.1. Tool wear, tool life and volume of material removed

In this section, the values of tool life and total volume of material removal (during the life of a tool involving progressive tool wear) obtained under different cutting conditions are first compared. The volume of metal removal, W, was calculated using equation

$$W = TVfd \quad (1)$$

where T is the tool life, V the cutting speed, f the feed and d is the depth of cut.

Fig. 2 shows the variation of tool life with cutting speed and feed. As expected, with increases in feed and cutting speed, tool life can be seen to decrease. The highest tool life was obtained at speed 70 m/min and feed 0.08 mm/rev, i.e., at the lowest feed/speed combination used. It is also interesting to note that, as the feed is increased from 0.08 to 0.2 mm/rev (an increase of 150%), the decrease in tool life at speeds 70, 95 and 120 m/min are 30.6, 37.1 and 59.8%, respectively. Thus, it can be seen that the rate of decrease in tool life with increase in feed becomes greater as the speed increases. On the other hand, as the speed is increased from 70 to 120 m/min (i.e. an increase of 71.4%) the decrease in tool life at feeds 0.08, 0.14 and 0.20 mm/rev are 60.5, 70.9 and 77.1%, respectively. Thus, it can be seen that, within the tested range of conditions, speed has a much greater influence on tool life than feed. As a result tests carried out at low speeds have resulted in higher tool life values.

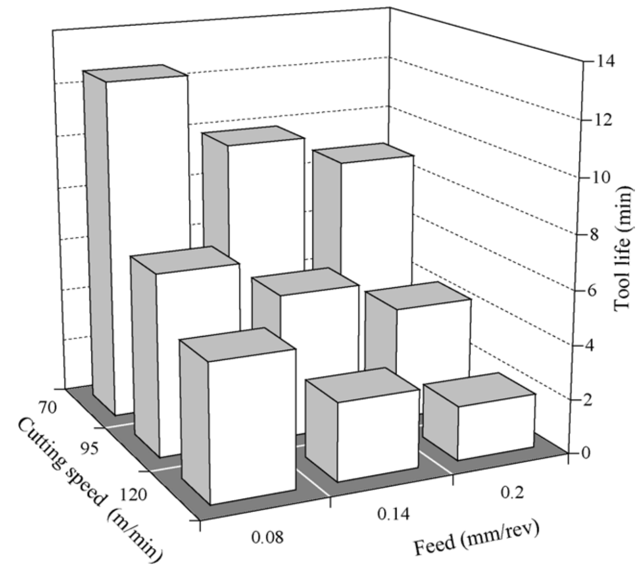

Fig. 2. Variation of tool life with cutting speed and feed.

Fig. 3 shows the variation of volume of material removal, W with cutting speed and feed. It can be seen that, at a given feed, with increase in cutting speed W decreases. The highest value for W was obtained at speed 70 m/min and feed 0.20 mm/rev, i.e. at the lowest speed and highest feed used. It can also be seen that, as the feed is increased from 0.08 to 0.20 mm/rev (an increase of 150%), the increases in W at speeds 70, 95 and 120 m/min are 73.5, 57.3 and 0%,

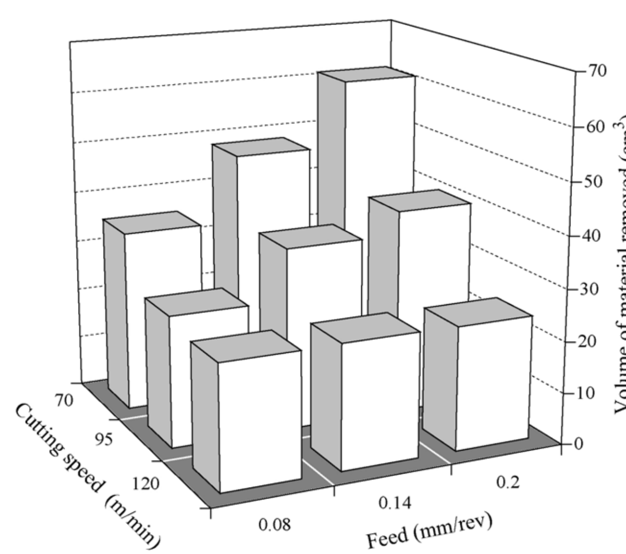

Fig. 3. Variation of the volume of material removal W with cutting speed and feed.

respectively. Thus, it can be seen that the rate of increase in W with increase in feed becomes less as the speed increases. On the other hand, as the speed is increased from 70 to 120 m/min (i.e. an increase of 71.4%) the decrease in W at feeds 0.08, 0.14 and 0.20 mm/rev are 32.3, 50.1 and 60.8%, respectively. Thus, the rate of decrease in W with increase in speed becomes greater as the feed increases. It can be seen that, within the tested range of conditions, low speed and high feed combinations have resulted in higher W values.

From the above results, it can be concluded that when machining hardened D2 steel with the selected PCBN inserts, the most suitable speed is 70 m/min. At this speed, higher and economical tool life and W values were obtained at all three feeds used. When rake face chipping did not occur, use of lower feeds resulted in higher tool life values (and possibly better surface roughness R_a), and higher feeds resulted in higher volumes of material removal W. Overall, a feed 0.14 mm/rev can be recommended for finishing operations and 0.20 mm/rev for roughing operations. Since feeds higher than 0.20 mm/rev were not tested at speed 70 m/min, there is a possibility that a higher feed (e.g. 0.25 mm/rev) may also be suitable for roughing.

4.2. Cutting forces and tool wear

Fig. 4 shows the variations of the average flank wear land width VB_B and, the cutting (F_c), feed (F_f) and radial (F_r) force components with machining time until the end of useful life of a tool as determined by flank wear land width and/or cutting edge chipping (width) at four different speed/feed combinations. In these graphs the early starting and ending of force lines than VB_B lines reflect the measurement of forces during the early part of a machining time interval and measurement of VB_B at the end of a machining time interval. It can be seen that, for all speed/feed combinations considered, VB_B shows a marked increase with machining time while F_c, in general shows a little increase with machining time and/or tool wear. It is also found that F_f is the smallest force and in most cases, F_c is the largest force while F_r lies between F_c and F_f, at times approaching/exceeding F_c. Generation of a larger F_r than F_f which is common in hard turning, is due to the smaller depth of cut (0.5 mm) and the tool geometry (approach angle 45° and nose radius 0.8 mm) used. This high radial force is known not only to cause dimensional inaccuracies (due to greater radial deflection of the work piece) but also to cause chatter if the dynamic loop stiffness of the

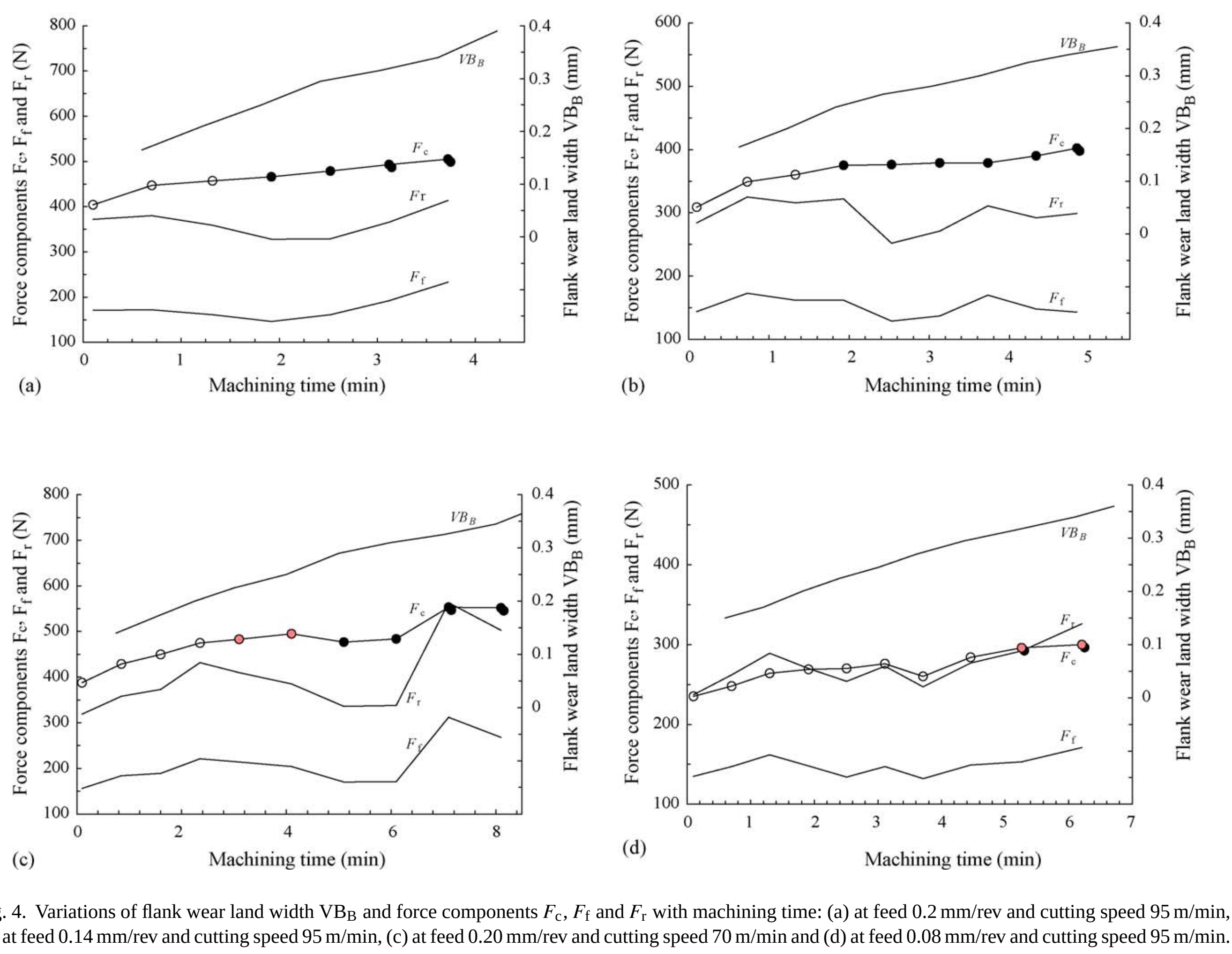

Fig. 4. Variations of flank wear land width VB_B and force components F_c, F_f and F_r with machining time: (a) at feed 0.2 mm/rev and cutting speed 95 m/min, (b) at feed 0.14 mm/rev and cutting speed 95 m/min, (c) at feed 0.20 mm/rev and cutting speed 70 m/min and (d) at feed 0.08 mm/rev and cutting speed 95 m/min.

machining system is low [16]. The cutting force F_c can be seen to increase with increasing machining time or tool wear (except for the sudden drop and rise in all three force components in Fig. 4(d) which may be due to possible variation in the depth (which was set manually) during this particular cut). On the other hand, F_f and F_r does not show such consistent trend with time. However, these two forces indicate similar variations in that if one decreases/increases within a certain time interval the other would follow. In contrast, according to Ref. [1], when machining AISI-5115 steel of 60–62 HRC with PCBN tools, all three force components were found to increase with increase in machining time and/or tool wear.

In Fig. 4, the circles on F_c line indicate the chip form and/or cutting edge chipping, if observed, during a cut. An open circle indicates no or very little chip breaking; light filled in circle indicates partial chip breaking; dark filled in circle indicates good chip breaking; circle with shadow indicates excessive cutting edge chipping (chipped width ~0.1 mm or greater). These results also indicate that, for the tested conditions, chip breaking has improved with increase in machining time/tool wear. Generally chips produced with unworn or less worn tools were found to be unbroken but when the insert rake face was worn, broken chips were produced due to the influence of the rake face groove and/or obstruction generated by tool wear. However, since the chips produced by D2 steel broke relatively easily (compared to chips produced by plain carbon steels), chip breaking (due to obstruction) does not seem to contribute to an increase in forces (note that, in general, forces do not show an increase as the chip form changes from unbroken to broken (Fig. 4)). Thus, the variations in the forces with time seen in Fig. 4 can be attributed to: (i) increase in the effective rake angle due to rake face wear (with tool wear, rake angle gradually increases from an initial large negative rake to a small negative or positive rake); (ii) stresses acting on the gradually increasing flank and nose wear scar areas; (iii) cutting edge chipping (observed towards the end of tool life). Note that, while (i) tends to decrease the forces (ii) and (iii) tend to increase them. As stated earlier, cutting edge chipping was only observed at high levels of flank wear ($VB_B > 0.3$ mm). Under some conditions, the rise in F_f and F_r towards end of life of tool (e.g. Fig. 4(a, c and d)) may be associated with excessive cutting edge chipping. However, only in a few cases substantial increases in force components (in particular F_f and F_r) were seen towards the end of life of tool (e.g. Fig. 4(c)). Hence, for the considered tool/work material combination, it may not be possible to use the variations of cutting force(s) for tool condition monitoring, i.e. for on-line determination of the end of useful life of a tool.

4.3. Tool life and cutting forces

The possibility of representing the obtained tool life results using an extended Taylor type tool life equation (in which the effects of cutting speed and feed on tool life are considered independently) is now explored. Since a constant depth of cut (0.5 mm) was used in the present investigation, the type of equation used is

$$T = \frac{A_t}{V^{b_t} f^{c_t}} \qquad (2)$$

This form of tool life equation has been used in an optimisation procedure for conventional turning [22]. From the method of least squares, the constant A_t and exponents b_t and c_t of Eq. (2) were determined using four experimental tool life results. The obtained equation is

$$T = \frac{71853}{V^{2.292} f^{0.431}} \qquad (3)$$

As expected, the exponent of cutting speed is much greater than that of feed indicating a greater influence of cutting speed on tool life.

For the conditions used in the experiments discussed in Section 3, a comparison between predicted and experimental tool life results is given in Fig. 5. In this figure the experimental results are represented by symbols and the predicted results using Eq. (3) are represented by lines. The symbols with a hatched background represent the four data points used for obtaining the constant and exponents in Eq. (3). It can be seen that the experimental results show the same trends as the predicted results and the quantitative agreement between the measured and predicted tool life values is reasonable, particularly when the general scatter associated with experimental tool life values is taken into account. This indicates that the relationship between tool life and cutting conditions (cutting speed and feed) can be represented by a Taylor type tool life equation.

The possibility of representing the three force components F_c, F_f and F_r generated during hard turning using a power function type force equation is now explored. Since a constant depth of cut (0.5 mm) was used in the present investigation,

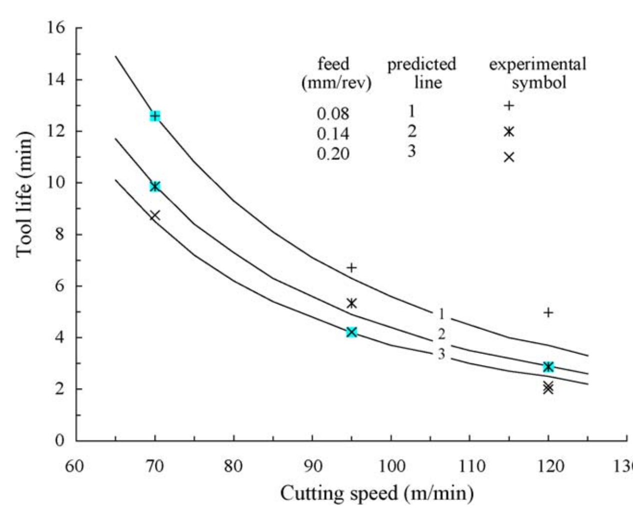

Fig. 5. Variation of tool life with cutting speed and comparison between predicted and experimental results.

Table 1
Comparison between predicted and measured forces

Test no.	Feed (mm/rev)	Cutting speed (m/min)	F_{cm}	F_{cc}	%Diff	F_{fm}	F_{fc}	%Diff	F_{rm}	F_{rc}	%Diff
1	0.08	70	229	228	−0.4	133	132	−0.5	234	225	−4.0
2	0.08	95	235	219	−7.0	135	133	−1.4	237	214	−9.9
3	0.08	120	206	212	2.7	110	134	21.6	202	205	1.7
4	0.14	70	330	331	0.2	153	154	0.4	284	303	6.8
5	0.14	95	309	317	2.6	144	155	7.3	284	288	1.5
6	0.14	120	307	307	0.0	155	155	0.1	268	277	3.5
7	0.20	70	388	419	8.0	156	169	8.3	319	367	15.2
8	0.20	95	404	402	−0.6	171	170	−0.6	372	349	−6.1
9	0.20	120	385	389	1.0	154	171	10.8	309	336	8.7
10	0.20	120	379	389	2.6	145	171	17.7	302	336	11.2

the type of equation used is

$$F_c = A_c V^{b_c} f^{c_c}$$
$$F_f = A_f V^{b_f} f^{c_f} \quad (4)$$
$$F_r = A_r V^{b_r} f^{c_r}$$

This form of force equations which can be used to predict forces with reasonable accuracy in conventional turning have been used in an optimisation procedure [22]. From the method of least squares, the constants A_c, A_f, A_r, and exponents b_c, c_c, b_f, c_f, b_r and c_r of Eq. (4) were determined using four experimental cutting force results (that is, in Table 1, those corresponding to tests 1, 4, 6 and 8). The obtained equation is

$$F_c = 2192 V^{-0.138} f^{0.664}$$
$$F_f = 239 V^{0.019} f^{0.266} \quad (5)$$
$$F_r = 1765 V^{-0.166} f^{0.537}$$

It can be seen that, in Eq. (5), the exponents of cutting speed are small indicating relatively smaller influence of cutting speed on the three force components. Thus, the influence of cutting speed on forces can be neglected. However, for a more general form of force equation, the effect of depth of cut should be incorporated. This can be done in the same way as feed is considered.

The accuracy of the constants and exponents in Eq. (5) is now checked by comparing the predicted forces with the experimentally measured values. The results are given in Table 1. The first column gives the test number while second and third columns give feed and cutting speed used in these tests. The fourth, seventh and tenth columns give the measured cutting, feed and radial force components while fifth, eighth and eleventh columns give the corresponding predicted force components. The sixth column gives the percentage difference between the measured and the predicted cutting force with reference to the measured force. These percentage differences for the feed and radial force components are given in the 9 and 12 columns, respectively. It can be seen that most of these percentage differences are within ±10%, indicating that Eq. (5) can be used to predict forces with reasonable accuracy.

4.4. PCBN tool wear

In Section 2, it was noted that Poulachon et al. [12] observed grooves on the flank wear scars of the low CBN content PCBN tools used to machine D2 steel in their tests. They attributed these grooves and flank wear to abrasion by hard carbide particles/clusters in the D2 steel work material. Grooves similar to those observed by Poulachon et al. have also been observed on the flank wear scars of all the tools used in the present investigation. A typical flank wear scar with these grooves (up to 40 μm in width) and a built-up layer is shown in Fig. 1. The PCBN tools used in this work have ~85% CBN and the CBN grains are much harder than any hard carbide particles/clusters in the D2 steel work material. Thus, it is highly unlikely that the observed flank wear on the tested PCBN tools is due to the abrasion by the hard carbide particles in the D2 steel. It is more likely that the observed flank wear is mainly due to dissolution/diffusion wear of BN and/or binder. The observed grooves were possibly caused either by loose CBN grains (which were swept away due to chemical/dissolution/diffusion wear of the binder) or by hard carbide particles in the steel work material when both binder and BN were subjected to dissolution/diffusion wear. To clarify this further research is needed. Considering the marked influence of cutting speed on tool life (in Eq. (3), $b_t \gg c_t$) and the influence of cutting speed on cutting temperature in hard turning [1], it appears that wear of tested PCBN tools is temperature dependant.

In Section 2, it was also noted that Kishawy and Elbestawi [10] investigated the surface integrity of AISI D2 steel (62 HRC) machined using PCBN tools at high cutting speeds in the range 140–500 m/min. Compared to lower cutting speeds (e.g. 140 m/min), higher speeds (e.g. 500 m/min) were found to decrease the magnitudes of the maximum tensile residual stresses on the surface and compressive stresses beneath the surface. Thus, in terms of surface integrity, higher cutting speeds appear to have an advantage over lower ones. However, in Ref. [10], obtained tool wear/life values were not given. Based on the results obtained in the present study, tools tend to wear rapidly at speeds above 140 m/min resulting in very low and uneconomical tool life values.

5. Conclusions

For the selected AISI D2 steel work material and PCBN tools, it was shown that both the highest tool life and volume of material removal *W* were obtained at the lowest speed used (70 m/min). However, the corresponding feed values were different—while the highest feed tested resulted in the highest *W* value, lower feeds resulted in the higher tool life values. Overall, a feed 0.14 mm/rev has been recommended for finishing operations and 0.20 mm/rev for roughing operations. The obtained tool life and *W* values were somewhat lower than those obtained in conventional turning, e.g. plain carbon or low alloy steel work materials with carbide/coated tools. However, these values can be considered reasonable when it is recalled that due to the high hardness of the D2 steel work material, grinding is the only other material removal process applicable. While surface integrity was not considered in the present work, it will be incorporated in future investigations, particularly for finishing operations. It was also shown that, for the considered conditions, the relationship between tool life and cutting conditions can be represented by a Taylor type tool life equation, while that between forces and the cutting conditions can be represented by power function type equations. In spite of the grooves observed on the flank wear scars of the tested PCBN tools, flank wear seemed to be temperature dependent. Work is already underway for developing suitable constitutive equation(s) for hardened steel work materials that can be used in a machining theory for predicting cutting forces, tool life, etc. using the fundamental work material properties and cutting conditions which also accounts for the variations of flow stress with strain, strain-rate and temperature.

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