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Investigation of TiN Coated CBN and CBN Cutting Tool Performance in Hard Milling Application

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Cubic Boron Nitride (CBN) and TiN Composite Coated CBN combines the thermal stability, super abrasiveness and cost effectiveness for hard machining applications. This paper reports the results of a study addressing wear performance of these CBN and TiN based coated CBN inserts (SNMN090308) for face milling of 61 HRC hardened 90MnCrV8 tool steel. Machining test conditions are obtained after dynamic stability simulation of cutting tools and machine tools. The tool wear and cutting forces are also analyzed and the results are presented.

Keywords: tool wear, hard milling, CBN tools, coated CBN

0 INTRODUCTION

Hard milling has been recently employed to hardened steels (> 30 HRC) used for dyes and mould making industry [1].

Generally, in hard milling research fields have focused on tool life [2], surface integrity [3], white layer effects [4], chip formation [5], cutting force models [6], stability of hard milling [6] and optimal cutting parameters [7]. However, very few studies have dealt specially with the dynamic cutting mechanisms induced by hard milling such as the effects of machine tool stability. Better understanding of machining stability can lead to a better process economics, increased process stability, improved tool life, reduced tooling costs and enhanced surface integrity and component performance.

Many researchers have studied cubic boron nitride (CBN) tools in the hard milling of steel alloys [8] to [12]. Generally CBN cutting tools have greater wear resistance than other tool materials due to their high degree of hardness [8]. Raghavan [10] was used PCBN to face mill AIS1 HI3 (48 to 50 HRC) tool steel at cutting speeds of 100 to 200 m/min, feed of 0.1 mm/tooth and 1.0 mm depth of cut. Heath et al. [11] recommended the use of PCBN at a cutting speed of 180 m/min, a feed of 0.2 mm/tooth and 1.0 mm depth of cut to face mill cold work tool steel (60 HRC). Nakagawa et al. [12] has reported the effect of cutting fluid when high speed ball nose end milling 57 HRC tool steel AISI D2 using polycrystalline cubic boron nitride (PCBN) tools. The application of a water-based cutting fluid led to catastrophic tool failure due to thermal shock, however, indirect supply of oil on the surface of the work material, rather than directly at the cutting edge, resulted in a longer tool life as compared to dry cutting. They have reported a feed/tooth of 0.05 mm, and axial/radial depths of cut of 0.05 and 0.2 mm, respectively, a length cut of 400 m for a flank wear of approximately 0.1 mm using oil as the cutting fluid at a cutting speed of 222 m/min.

58 HRC AISI D2 hardened tool steel is face milled by Koshy et al. [13] with a round CBN insert. They found acceptable tool life (43 cm^3 of removed material) together with excellent surface finish in the range of 0.1 to 0.2 μm in Ra. This study points out that tool life would need to be extended to make the process economically viable.

CBN and coated CBN tools are still very expensive and it is difficult to find better cutting performance [14]. In our study the use of different CBN Grade is proposed.

In this study, cutting performance of the TiN coated CBN and CBN cutting tools for 61 HRC hardened 90MnCrV8 cold work tool steel face milling is investigated with considering hard milling stability analysis. Wear performance

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of CBN and TiN based coated CBN inserts (SNMN090308) for face milling of the hardened tool steel is examined. The tool wear formation and cutting forces are also analyzed and the results are presented.

1 EXPERIMENTAL METHODOLOGY

Machining experiments are performed on a Harford VMC 1020 machining centre to ensure precisely computer controlled cutting conditions. The depth of cut, the feed rate and cutting speed are selected by simulating analytical chatter stability analysis. Stability analysis procedure of hard face milling test is shown in Fig. 1.

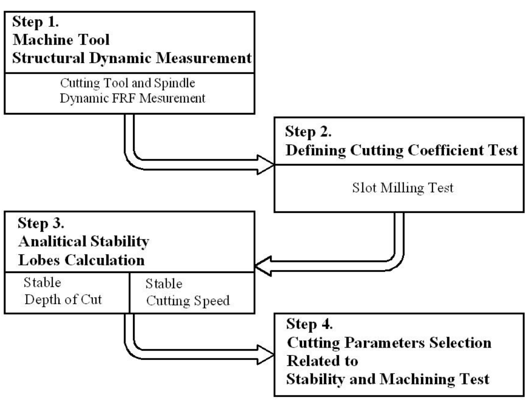


Fig. 1. *Procedures of face milling stability analysis*

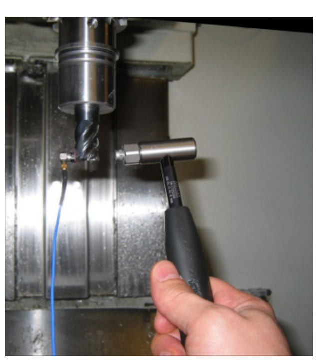


Fig. 2. *Structural dynamic measurement of cutting tool*

From Fig. 1 it is seen that Step-1 machine tool-workpiece structural dynamic measurement is done using the tap testing method. Fig. 2 shows tap testing of cutting tool.

X and Y direction of cutting tool dynamic characteristics is measured with tap testing. 2000 N Kistler 9722A Hammer and 100 g/V sensitivity accelerometer is used for tap testing. Frequency response function calculation (FRF) cutting tool is calculated in both directions using CutPRO MALTF software.

In Step-2 cutting coefficients are defined. In this step, the slot milling test is done to define the average cutting coefficient. Table 1 shows the test conditions of hard milling.

Table 1. *Average cutting coefficient test conditions [15]*

Test no	Feed rate [mm/ tooth]	Spindle speed [rpm]	Cutting speed [m/min]	Axial depth of cut [mm]
1	0.05	850	50.87	0.3
2	0.075			
3	0.1			
4	0.125			
5	0.150			

Average cutting forces are calculated by using measured cutting forces in three dimensions for each test condition. Average cutting forces are used for calculating average cutting coefficient model [16] which is given in Eq. (1).

$$K_{tc}=\frac{4\bar{F}_{yc}}{Na},\quad K_{te}=\frac{\pi\bar{F}_{ye}}{Na},$$
$$K_{rc}=\frac{-4\bar{F}_{xc}}{Na},\quad K_{re}=\frac{-\pi\bar{F}_{xe}}{Na}, \qquad (1)$$
$$K_{ac}=\frac{\pi\bar{F}_{zc}}{Na},\quad K_{ae}=\frac{2\bar{F}_{ze}}{Na}.$$

In Eq. (1), N is the number of teeth, a is axial depth of cut [mm], $\bar{F}_{xc}$, $\bar{F}_{yc}$, $\bar{F}_{zc}$ are average cutting force in x, y and z directions respectively (Newton), $\bar{F}_{xe}$, $\bar{F}_{ye}$, $\bar{F}_{ze}$ are average edge cutting force in x, y and z directions (Newton), K_{rc}, K_{tc}, K_{ac} are cutting coefficients of tool-material interface in radial, tangential and axial directions [N/mm2], K_{re}, K_{te}, K_{ae} are cutting tool edge cutting coefficients in radial, tangential and axial directions [N/mm].

After the slot milling test, the average cutting coefficient of 90MnCrV8 is found. Sub indices (c) and (e) represent shear and edge force components, respectively. The edge cutting K_{re}, K_{te} and K_{ae} are constants and related to the cutting edge length dS given in an infinitesimal length (ds) of a helical cutting edge. The shear force coefficients K_{rc}, K_{tc} and K_{ac} are identified either mechanistically from milling tests conducted at a range of feed rate. Table 2 shows average cutting coefficients.

In Step-3 stability of hard face milling experiment is simulated by using cutting tool frequency response function calculation (FRF) (Step-1) and average cutting coefficients (Step-2). Stability simulation is calculated using Eq. (2) [16].

$$a_{\lim} = -\frac{2\pi\Lambda_R}{NK_t}(1+\kappa^2)\ . \qquad (2)$$

Stability lobe diagram is given Fig. 3.

In Step-4 the tool wear test condition which is given Table 3 is determined after stability simulation. Axial depth of cut is fixed as 0.6 mm related to stability simulation which is shown in Fig. 3.

The chemical properties of workpiece material are given in Table 4. Workpiece material, steel 90MnCrV8 (AISI – O2, EU – 90MnCrV8) is a cold work tool steel, with high dimensional stability at heat treatment, very high resistance to cracking, high machinability, medium toughness and resistance to wear. Hardness after annealing is max 229 HB. After quenching, the hardness achieved may be from 63 to 65 HRC. The field of application of 90MnCrV8 is compress measuring tools, machine knives for the wood, paper and metal industry, cold cutting shear blades, thread cutting tools [17].

Table 2. *Average cutting coefficients of 62 HRC 90MnCrV8 tool steel [15]*

	K_{te} [N/mm]	K_{re} [N/mm]	K_{ae} [N/mm]	K_{tc} [N/mm²]	K_{rc} [N/mm²]	K_{ac} [N/mm²]
Average Cutting Coefficients	581.35	-724.47	158.96	3689.11	-5804.89	2257.14

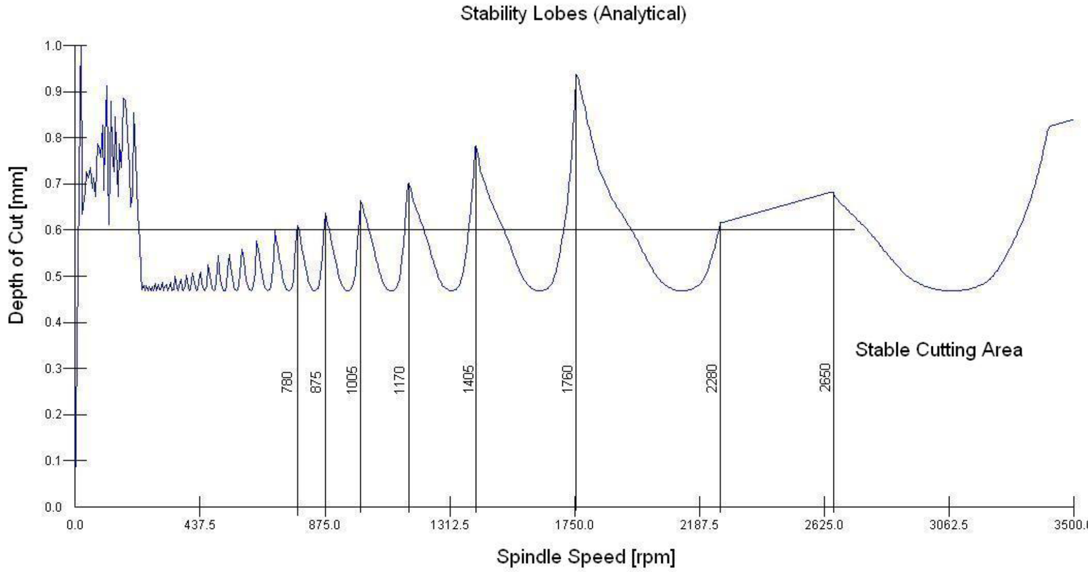


Fig. 3. *Analytical Stability Lobes diagram of hard milling test*

Table 3. *Stable tool wear test conditions for 90MnCrV8 Face milling [15]*

Spindle speed	rpm	2650	2280	1760	1405	1170	1005	875	780
Feed rate	mm/tooth	0.05	0.075	0.1	0.15				

The tests were discontinued when a flank wear criterion *VB* of 700 µm was reached. For cutting tool wear test chip volume is fixed 5896.8 mm³. Flank wear measurements were taken in accordance with the International Standard ISO 8688-1 [19] and using the Olympus TM optical microscope and SEM. Cutting forces were recorded for every test in F_x, F_y and F_z directions. For this purpose, a 9257B-type Kistler dynamometer was used.

Two type CBN tool is tested in a hard milling test. Properties of cutting tools are given in Table 5.

Table 4. *Chemical compositions of 90MnCrV8 [18]*

Chemical Composition (% weight)						
C	Si	Mn	Cr	P	S	V
0.88	0.29	2.07	0.26	0.024	0.009	0.08

2 RESULTS AND DISCUSSION

2.1 Tool Wear

Damage of the cutting tools over the entire range of cutting conditions was mainly in the form of chipping. Chipping tool wear measurement ISO 8688 standard of face milling conditions is given in Table 6.

Hard milling of 90MnCrV8 cold work tool steel by CBN is characterized by the flow of chips at very high temperature and extremely deformed signs of intensive shearing at cutting edge (Fig. 4).

In this study a different type of chipping tool wears is investigated. This wear formation is given in Table 7. As seen from Table 7 TiN Composite Coated CBN grade cutting tools are four times braked than CBN grades. Milling operations are known as interrupt cutting so that TiN Composite Coated CBN grades is not useful for hard milling application.

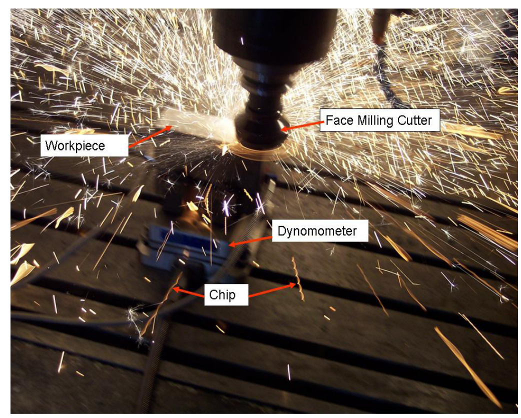


Fig. 4. *Heat dissipation through chip while machining, Vc = 278.1 m/min*

Fig. 5a shows the change in depth of the chipping wear with a cutting distance for the

Table 5. *Cutting tools properties [20]*

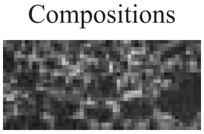
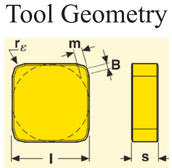
Tool Properties	CBN300 Grade	CBN300P Grade
ISO CODE	SNEN0903ENE-M06	SNMN090308
Compositions 	CBN content approx. 90 vol % Average starting grain size (µm) – 22 Binder – Al ceramic Format – Solid	CBN content approx. 90 vol % Average starting grain size (µm) – 22 Binder – Al ceramic Format – Solid Coated Ti(C,N) + (Ti, Al) N + TiN with a total thickness of 2-4 µm
Physical Properties	Knoops hardness GPa – 30.4 Thermal conductivity [Wm^{-1}K^{-1}] (20 °C) – 130	Knoops hardness GPa – 30.4 Thermal conductivity [Wm^{-1}K^{-1}] (20 °C) – 130
Tool Geometry 	Size *L* – 9.525 mm *s* – 3.18 mm *B* – 0.9 mm r_e – 0.8 mm Rake angle – 0°	Size *L* – 9.525 mm *s* – 3.18 mm *B* – 0.9 mm r_e – 0.8 mm Rake angle – 0°

Table 6. *ISO 8688 Face milling chipping measurement standard*

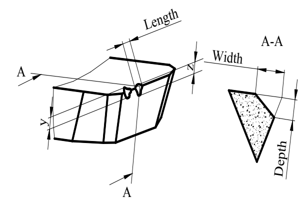
	Tool Deterioration Phenomena		Criteria [mm] S (small)	N (normal)	L (large)	Illustration
CH	**Chipping** (breakage)		For y or z with corresponding length values			
1	Uniform					
2	Non-uniform					
3	Localized					
		Length [mm]				
A	Micro-chipping	<0.3	0.2	0.25	0.3	
B	Macro-chipping	0.3-1	0.25	0.4	0.5	
C	Breakage	>1	-	-	-	

Table 7. *Tool wear type of TiN coated CBN and CBN tool in hard milling conditions*

	Breakage ISO type C	Macro chipping ISO type B
CBN tool	2 tools	30 tools (1 Small, 13 Normal, 16 Large)
TiN Composite Coated CBN	9 tools	23 tools (2 Small, 10 Normal, 11 Large)

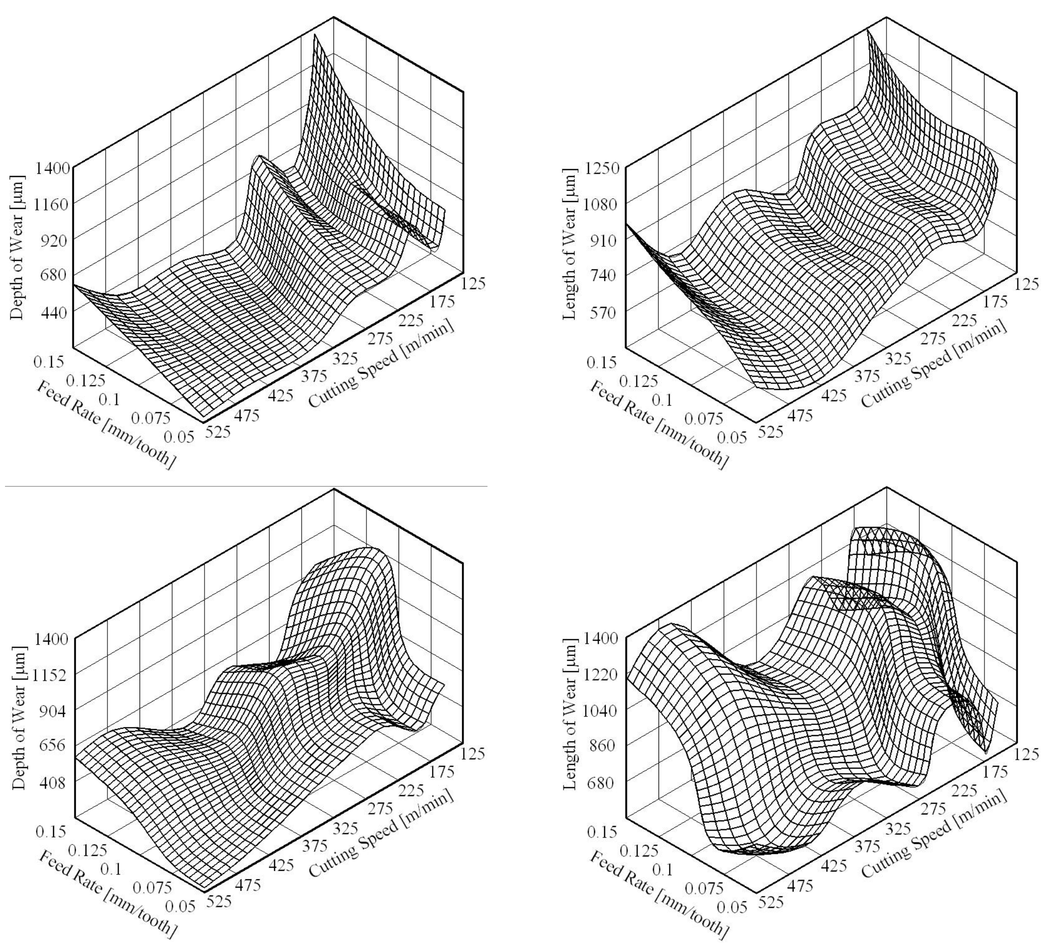


Fig. 5. *Wear depth and length in the hard milling tests at various feed [mm/tooth] and cutting speeds [m/min]; a) CBN tools, b) coated Ti(C,N) + (Ti, Al) N + TiN CBN tools*

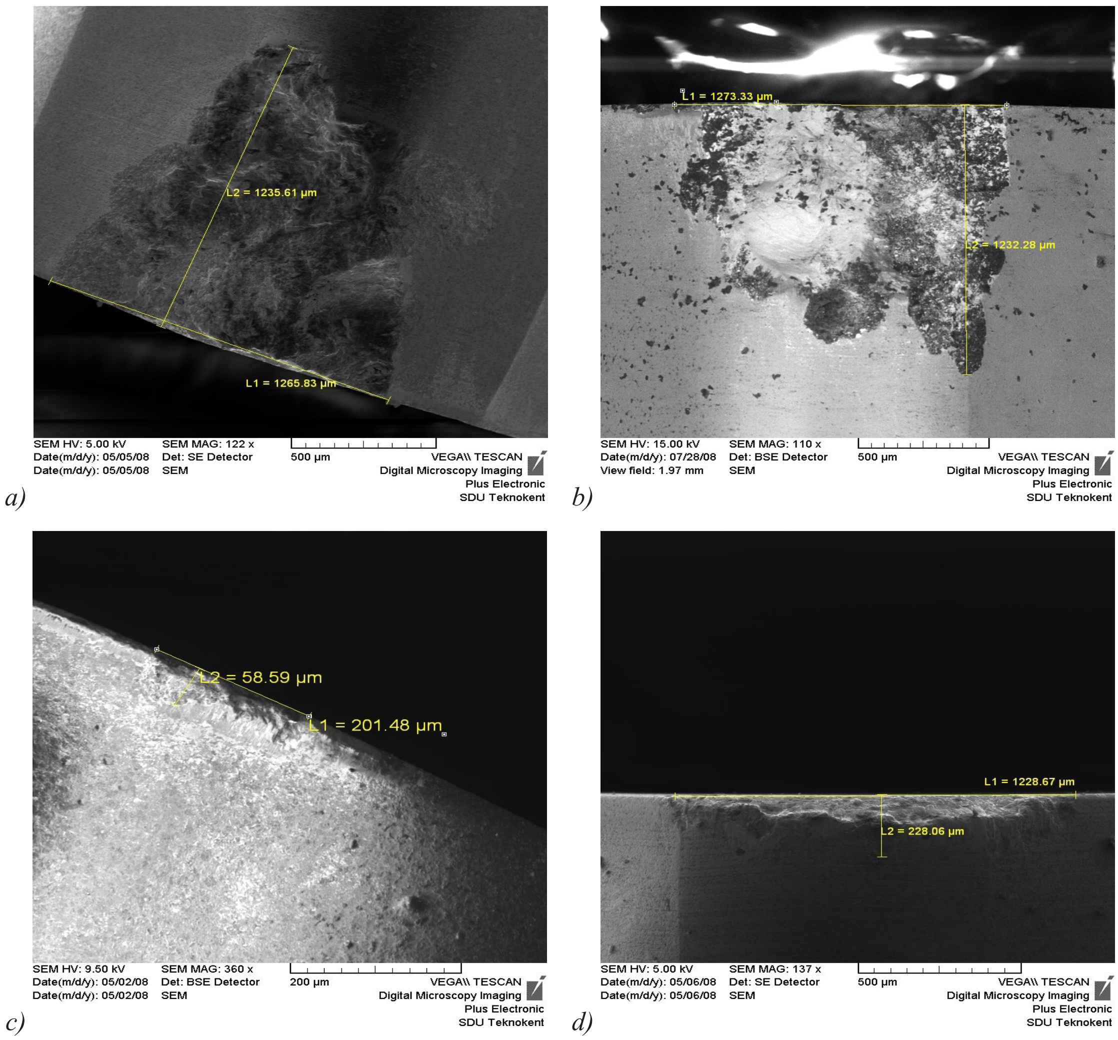


Fig. 6. *Tool wear SEM photo images; a) Maximum tool wear for six insert CBN tools (v_c = 154.4 m/min, f = 0.15 mm/teeth), b) Maximum tool wear for six insert Coated Ti(C,N) + (Ti, Al) N + TiN CBN tools (v_c = 154.4 m/min, f = 0.1 mm/teeth), c) Minimum tool wear for six insert CBN tools (v_c = 524.5 m/min, f = 0.05 mm/teeth), d) Minimum tool wear for six insert Coated Ti(C,N) + (Ti, Al) N + TiN CBN tools (v_c = 524.5 m/min, f = 0.05 mm/teeth)*

tools grade CBN in the machining of 90MnCrV8 cold work tool steel at various depths of feed and cutting speeds. The change in the chipping wear depth with various feed and cutting speeds for coated Ti(C, N) + (Ti, Al) N + TiN can be seen in Fig. 5b. It was found that at low cutting speed and high feed rate, the chipping wear increased significantly and at high cutting speed and low feed rate tool wear is decreased. As seen in Fig. 3 CBN grade is more stable depth and length tools wear rates than TiN Composite Coated CBN due to more breakage of TiN Composite Coated CBN.

The chipping wear decreased significantly when the cutting speed was increased from 300 to 525 m/min in both tool types. SEM images of maximum tool wear rate for each inserts are given Fig. 6. Maximum tool wear is obtained at low cutting speed which is 154.4 m/min. For both cutting tool grade minimum tool wear is obtained at 524.5 cutting speed and 0.05 mm/teeth feed rate. Maximum tool wears and minimum tool wear SEM photographs are illustrated in Fig. 6.

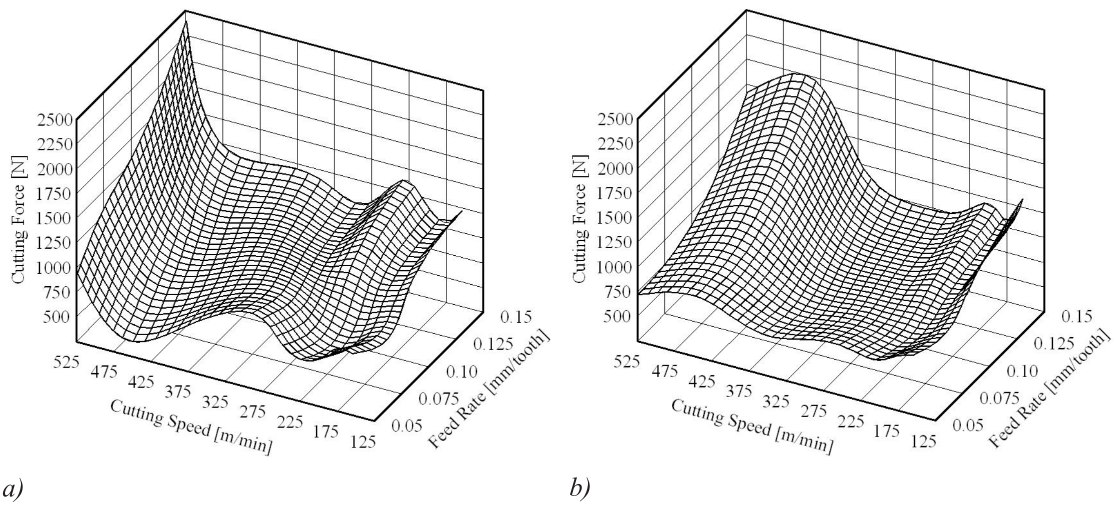


Fig. 7. *Average feed cutting forces (Fx), a) with different cutting speed and feed rate for test conditions CBN tool, b) coated Ti(C,N) + (Ti, Al) N + TiN CBN tool*

2.2 Cutting Forces

The average cutting forces (feed forces F_x) obtained with tool grades CBN and coated Ti(C,N) + (Ti, Al) N + TiN CBN are compared in Figs. 7a and b. It was found that when the chipping was increased (due to an increase feed rate or a reduction in the cutting speed), it also coincided with an increase in the cutting forces.

3 CONCLUSIONS

The following results can be extracted from the hard face milling of 90MnCrV8 tool steel by CBN and PCBN insert tools.

The face milling of 90MnCrV8 tool steel in the hardened state (61 HRC) were shown tool life values of <260 mm length of cut. Little difference was found in tool wear between the CBN insert tools and coated Ti(C,N) + (Ti, Al) N + TiN CBN insert.

An analysis of flank wear patterns indicated that macro chipping, governing mechanisms were responsible for tool wear. PCBN tools failed by fracture of the cutting edge.

In CBN cutting tools wear test 6.25% tool breakage is investigated. However, coated Ti(C,N) + (Ti, Al) N + TiN CBN cutting tools wear test 28.13% tool breakage was investigated.

Optimum cutting speed and feed rate were found for both cutting tool grades between 450 to 550 m/min (means high speed) and 0.05 to 0.1 mm/teeth (means low feed rate).

Cutting forces were significantly increased with high speed and high feed rate.

In this study white layer effects and chip formations of hard milling operation is not considered.

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