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Obraba orodij pri odrezovanju z velikimi hitrostmi

Cutting-Tool Wear during High-Speed Cutting

Janez Kopač

Obdelava z odrezovanjem je močno povezana z obrabo na rezalnem robu. Vrsta izbranega rezalnega materiala, vrsta obdelovanega materiala in parametri odrezovanja neposredno vplivajo na velikost obrabe in s tem na obstojnost orodja. Odrezovanje z veliki hitrostmi poteka pri večjih rezalnih hitrostih, zato je tudi potek obrabe spremenjen. Ne poteka več po značilni obliki S, ampak je znatno manj predvidljiv.
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(Ključne besede: odrezovanje z velikimi hitrostmi, oridja rezilna, obraba orodij, materiali za orodja)

Machining by cutting is strongly connected with wear on the tool's edge. The cutting-tool materials, the machined material, and the machining parameters have a direct influence on the tool's wear grade and, of course, on the tool life. High speed machining (HSM) involves high cutting speeds, so that the classical, well-known principle S of tool-wear growth does not exist as before. There are some unpredictable matters.
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(Keywords: high speed cutting, cutting tools, tool wear, cutting tool materials)

0 UVOD

Obraba rezalnih orodij še vedno pomeni izziv tako za proizvajalce kakor tudi uporabnike. Star rek navaja, da se stroške vrednoti prek konice rezalnega orodja. Kljub temu, da je razvoj rezalnih materialov dosegel neslutene razsežnosti, pa se razvijajo tudi obdelovani materiali, tako po značilnostih trdote kakor tudi žilavosti. Obdelava kaljenih jekel v orodjarstvu zahteva odrezovanje trdov (do 63 HRC), specifične pa so tudi zlitine Ni in Ti, ki niso tako trde, so pa žilave in se zato težko obdelujejo.

Obraba je najpomembnejši kriterij, ki torej popisuje obdelovalnost izbranega materiala. Med kriterije spadajo še velikost rezalnih sil, oblikovanje odrezkov in hrapavost obdelane površine. Prav hrapavost je neposredno povezana z obrabo orodja. Z naraščajočo obrabo izgubljamo kakovostni razred, ali pa moramo uvajati dodatne natančne obdelave, kar povzroči nekonkurenčnost tako z vidika časa kakor tudi stroškov obdelave. Rezalne sile predstavljajo bolj ekološki učinek, saj v zmnožku z rezalno hitrostjo pomenijo porabo moči obdelovalnega stroja. Razlika med novim in obrabljenim rezalnim robom glede na velikost rezalnih sil je lahko tudi 100-odstotna, to pa je še dodaten vpliv na strošek obdelave.

0 INTRODUCTION

Tool wear still represents a challenge for the producers and for the end-users of cutting tools. The well-known saying is that "the cost of machining is evaluated at the cutting edge". Despite enormous improvements in cutting-tool materials, there is an ever-increasing number of new machining materials with enhanced levels of hardness and toughness. The machining of hardened steel materials in tool-manufacturing involves hard cutting up to 63 HRC. Other specific hard-to-machine materials, although not as hard, are special Ni and Ti alloys.

Tool wear is the most important criterion for determining a specific material's machinability. However, it is also important to consider cutting forces, chip shapes and machined surface roughness. Surface roughness is directly related to tool wear. Increased wear reduces quality yield and leads to additional finishing operations, which in turn cause s reduced competitiveness from the machining-time and costs points of view. Cutting forces represent an ecological factor because their product with the cutting speeds equals the process power and the energy consumption of the machine-tool. The difference between the unpaired and the worn cutting edges, according to the cutting forces, can be 100 %, which can cause additional machining costs.

In ker je Evropa dejansko vedno bolj usmerjena v ekološki smeri (ISO 14001), k temu lahko pripomoremo tudi z načinom obdelave. To je suho odrezovanje ali minimalno hlajeno. Ob tem v celoti odstranimo hladilno mazalno tekočino (HMT) ali jo v največji meri zmanjšamo. To pa omogočijo sodobna rezalna orodja s posebnimi prevlekami (mehke), ki delujejo samomazalno in s tem zmanjšajo trenje in obrabo, zmanjšajo rezalne sile in izboljšajo hrapavost obdelane površine.

Europe is oriented more and more towards ecological demands (ISO 14001), with the selection of appropriate machining procedures. These refer to dry or near-dry machining. In this way cutting fluids are eliminated or minimised. However, this is only possible with modern cutting tools that have special soft coatings, which possess a lubricating effect and thus reduce friction and wear, cutting forces and enhance the surface finish.

1 OBRABA IN OBSTOJNOST ORODJA PRI OBIČAJNEM IN ODREZAVANJU Z VELIKIMI HITROSTMI

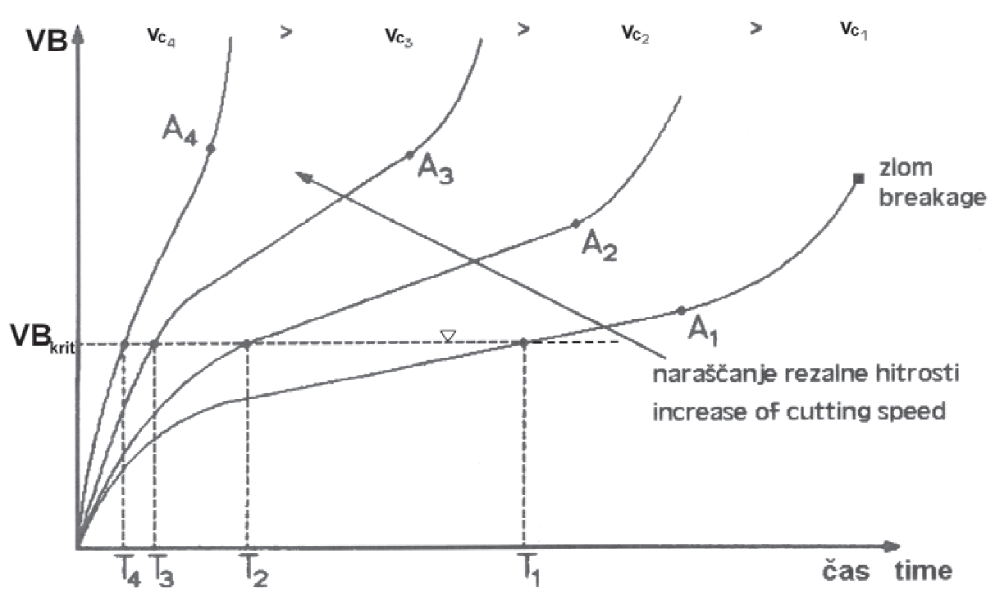
Obrabo na prosti ploskvi običajno zasledujemo z opazovanjem spremembe širine obrabne ploskve (*VB*) po času (*t*).

Slika 1 prikazuje skupino krivulj povečanja širine obrabe proste ploskve (*VB*) po času (*t*) za različne vrednosti rezalnih hitrosti (v_c). Te krivulje so na splošno podobne krivulji naraščanja obrabe koničnega drsnika pri drsenju po vrtečem disku. Obseg področja majhne hitrosti obrabljanja se zmanjšuje s povečanjem rezalne hitrosti. Hitrost obrabe se skokovito zveča, ko temperatura na rezalnem robu obrabne površine doseže točko toplotnega omehčanja obdelovanega materiala. Razmerje A_R/A se hitro poveča s časom in s hitrostjo obrabljanja. Obstojnost orodja *T* /min/ za dano rezalno hitrost ali čas rezanja do meje področja majhne hitrosti obrabljanja (čas, ki ustreza točkam A_i) - značilno za orodja iz hitroreznega jekla, ali pa čas do doseganja določene vrednosti obrabe na prosti ploskvi (VB_{krit}) (čas ustreza točkam pri T_i), ki je tipična za orodja iz karbidnih trdin. Običajna mejna vrednost za obrabo

1 TOOL WEAR AND WEAR RESISTANCE DURING CLASSICAL AND HIGH-SPEED CUTTING

Flank wear is usually monitored by observing the wear width (*VB*) variation as a function of time (*t*).

Figure 1 shows a cluster of curve lines that corresponds to an increase in the flank-wear width (*VB*) with time (*t*) at various cutting speeds (v_c). These curves are generally similar to curves of increasing wear of a conical guide aduring sliding on a rotating disc. The range of small wear propagation decreases with an increase in the cutting speed. However, wear propagation drastically increases when the temperature on the cutting edge corresponds to the workpiece material's softening temperature. The A_R/A ratio rapidly increases with time and with the rate of wear propagation. The tool life *T* /min/ for a specific cutting speed is defined as the cutting time to a small wear propagation threshold (a time that corresponds to A_i) – characteristic for high-speed steels or as the time until specific flank-wear values (VB_{krit}) (a time that corresponds to T_i), which is characteristic for carbide tools. The usual flank-wear threshold for carbide tools for



Sl. 1. *Potek obrabe orodij pri običajnem odrezovanju*
Fig. 1. *Tool-wear increase during a classical cutting process*

na prosti ploskvi za orodja iz karbidnih trdin pri obdelavi mehkih jekel je 0,4 mm. Bolj ko je material obdelovanca težaven za obdelavo, bolj temperaturno obstojne orodne materiale uporabljamo (so bolj krhki), ali pa zmanjšamo debelino odrezka. Poleg tega je priporočljivo uporabljati manjše dopustne vrednosti za obrabo na prosti ploskvi orodja.

Kadar obstojnost orodja *T*, ki sloni ali na popolnem uničenju (točka A) ali na omejeni vrednosti obrabe površine (točka T), narišemo v logaritemskem diagramu, dobimo rezultat, ki ga prikazuje slika 2.

Za praktično uporabno območje rezalnih hitrosti je ta krivulja premočrtna in ustreza enačbi:

the machining of soft steels is 0.4 mm. As workpiece materials become hard-to-machine, demands for temperature-resistant tool materials increase (they become more brittle) or the chip thickness is decreased. In addition, it is recommended that lower flank-wear thresholds be employed.

When tool life T, which corresponds to either the tool breakage (point A) or to the limited wear threshold (point T), is plotted on a logarithmic scale the results can be seen in Figure 2.

For practical cutting-speed applications the curve can be linearized and corresponds to the following equation:

$$v_c T^n = C \quad (1),$$

kjer sta n in C konstanti za preizkušan obdelovani in rezalni material ter za obdelovalne razmere, razen za rezalno hitrost. Ta enačba se imenuje tudi Taylorjeva enačba obstojnosti orodja. Ker je običajno določena v minutah, pomeni C rezalno hitrost, pri kateri je obstojnost orodja ena minuta. Vrednost eksponenta n se veča z večanjem temperaturne obstojnosti rezalnega materiala, in sicer za:

- hitrorezna jekla (HSS) - n = 0,1
- karbidne trdine (WC) - n = 0,2
- keramiko (Al_2O_3) - n = 0,3.

Taylorjevo enačbo lahko preuredimo in razširimo v obliko, ki upošteva tudi druge parametre rezanja. Tako imenovana razširjena Taylorjeva enačba se glasi:

The parameters n and C are constant for the investigated workpiece, the tool material and the machining parameters, except for the cutting speed. This equation is known as the Taylor tool-life equation. Tool life is usually expressed in minutes, hence the constant C refers to the cutting speed at which the tool life is reduced to one minute. The value of the exponent n increases with the temperature resistance of the cutting materials:

- high-speed steels (HSS) - n = 0.1
- cemented carbide tools (WC) - n = 0.2
- ceramic tools (Al_2O_3) - n = 0.3

The Taylor equation can be configured and expanded to a form that also considers other cutting parameters. The so-called expanded Taylor equation is expressed as:

$$T\, v_c^{1/n} f^{1/m} a_p^{1/l} = C \quad (2),$$

kjer sta: *f* - podajanje in a_p globina rezanja.

S preizkusi so ugotovili, da je obstojnost orodja močno odvisna od spremembe rezalne hitrosti in manj občutljiva na spremembe globine rezanja. Tako velja:

The factor f corresponds to the feed-rate, and a_p to the depth of the cut.

Experiments proved that tool life is significantly dependent on the cutting-speed alteration and less dependent on variations in the depth of the cut. Hence:

$$n < m < l$$

Prostornina zaradi obrabe odnesenenega rezalnega materiala na prosti ploskvi (B_r) je za določeno obrabno površino (VB), globino rezanja (a_p) in prosti kot α (pri $\gamma = 0°$):

The flank-surface tool-wear volume (B_r) for specific wear (VB), depth of cut (a_p) and clearance angle α (pri $\gamma = 0°$) can be calculated:

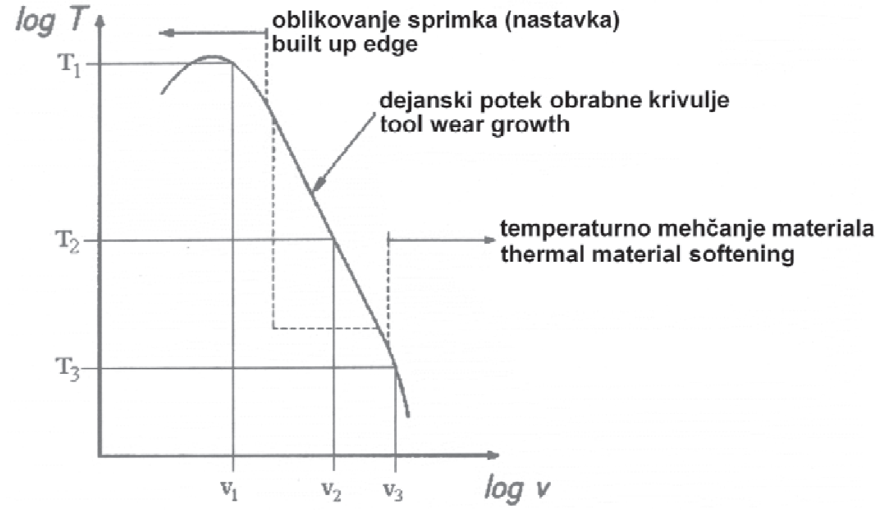
$$B_r = \frac{a_p VB^2 \tan\alpha}{2} \quad (3)$$

Za določeno obrabo površine (obstojnost orodja) vidimo, da se obrabna prostornina povečuje, če se veča kot α. Potemtakem je z vidika obrabne prostornine primernejši velik prosti kot α v modelu procesa rezanja.

Trdota rezalnega robu, zmožnost absorbiranja toplotne energije in zmožnost ohranjanja dimenzijske natančnosti se pa z večanjem prostega kota manjša, zato je optimalen prosti kot nekako v območju od 5 do 10° (α) [1].

For a specific surface wear (tool life) the wear volume increases with flank angle. Therefore, from the wear-volume point of view, a large clearance angle α is more appropriate for cutting-process modelling.

The cutting-edge hardness, the capability to absorb thermal energy and the stability of the dimensional accuracy decrease with increasing clearance angle, thus the optimal clearance angle α lies in the range from 5 to 10° (α) [1].



Sl. 2. *Potek obstojnosti orodja pri običajnem odrezovanju*
Fig. 2. *Tool-life as a function of cutting speed*

Za merjenje obrabe rezalnega robu orodja je priporočljivo, da jo merimo z orodjarskim mikroskopom pri 15 do 20-kratni povečavi in možnostjo odčitavanja natančnosti 0,01 mm. Pri meritvi upoštevamo srednjo polovico obrabne ploskve b/2, kakor je razvidno s slike 3a). Obrabo na prosti ploskvi merimo vedno glede na nepoškodovani rezalni rob orodja.

Pogosto velja za obrabni kriterij tudi največja obraba na prosti ploskvi VB_{max}. Pri tem velja omeniti, da je največja obraba v glavnem vzporedni kriterij za ocenjevanje obrabe.

Pri frezanju širina obrabe proste ploskve ni vedno enaka po celotni dolžini rezalnega robu, ampak se znatno spreminja v območju zaokrožitve rezila in na koncu obrabnega pasu (sl. 3b). Obrabo proste ploskve merimo glede na začetni neobrabljeni rezalni rob (del rezalnega robu, ki ni v dotiku z obdelovancem), in sicer na glavnem rezalnem robu, na posnetem ali zaokroženem oglu orodja ali na stranskem rezalnem robu. Posamezne vrste obrabe na glavnem rezalnem robu so [2]:

- dolžina zareze na glavni prosti ploskvi pri največji globini rezanja je VB_{max},
- širina obrabnega pasu na prosti ploskvi pri največji globini rezalnega robu je VB, največja širina obrabe proste ploskve v tem področju pa VB_{max}.

Dodatne vrste obrabe orodja so:

- povprečna širina obrabe na posnetem ali zaokroženem rezalnem robu je označena z VC (največja vrednost z VC)
- širina poprečne obrabe na stranskem rezalnem robu je označena z VS.

Pri vrtanju se obraba proste ploskve svedra zvečuje s povečano rezalno hitrostjo od prečnega rezalnega robu do zunanjega dela glavnega rezalnega robu. V odvisnosti povečanja obrabe proste ploskve in zaokrožitve rezalnega robu se pojavi odmik rezalnih robov v smeri proti vodilnemu robu svedra (sl. 3c). Izhodiščna črta za merjenje obrabe proste ploskve

It is recommended that the wear of the tool's cutting edge is measured with a workshop microscope at 15 to 20 magnification and an accuracy of 0.01 mm. The measurement takes into consideration the mean half of the surface wear b/2, which is evident in Figure 3a. Flank wear is always measured with respect to the unimpaired tool cutting edge.

Often, maximum flank wear VB_{max} is also employed as a wear criterion. In this way it should be stressed that the maximum flank-wear is generally used as a simultaneous wear-estimation criterion.

In milling, flank wear width is not always uniform over the entire length of the cutting edge; it varies significantly, especially in the range of the corner radius and at the ends of the wear zone (Figure 3b). Flank wear is therefore measured with regard to the unimpaired cutting edge (a part of the cutting edge that is not in contact with the workpiece), namely on the major cutting edge, the chamfered or rounded corner radii or on the minor cutting edge. Particular major cutting-edge wear types refer to [2]:

- the length of the incision on the major flank surface at the maximum depth of cut is $VB_{max,}$
- the width of the flank-wear zone at maximum depth of cut is VB, the maximum width of the flank wear in this area is VB_{max}

Other types of tool wear refer to:

- the mean wear width on the chamfered or rounded cutting edge is denoted by VC (maximum value)
- the width of the mean wear on the minor cutting edge is denoted by VS

During drilling the flank wear of the drill increases with the cutting speed from the transverse to the external major cutting edge. Depending on the flank-wear increase and the cutting-edge rounding, a shifting of the cutting edges towards the major drill cutting edge appears (Figure 3c). The starting line for the drill flank-wear measurement refers svedra je nepoškodovan glavni rezalni rob, ki ga na obrabljenem rezilu ni moč uporabljati za merjenje. Zato naredimo v območju prehoda proste ploskve v stransko prosto ploskev za vodilnim robom razo z diamantno iglo. Pri ostrem orodju nato izmerimo razdaljo od raze do črte glavnega rezalnega robu. Pri obrabljanju orodja lahko z zaporednimi meritvami od raze do črte obrabe v območju premera (3/4) do (4/4)d in povratnim računanjem določimo posamezne obrabe proste ploskve svedra. Obrabo moramo meriti na obeh rezilih in določiti srednjo obrabno vrednost:

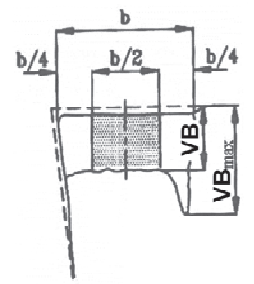
to the unimpaired major cutting edge, which cannot be used as a measuring reference in the case of a worn drill. Therefore, the scratch interfacing flank and the side plane are made with a diamond pin. The distance between the scratch and the line of the major cutting edge is then measured on the sharp tool. During tool-wear progress, the distance between the scratch and the wear line in the diameter range of (3/4) to (4/4)d is successively measured, and individual drill flank wear is appointed. Wear is measured on both cutting edges and the mean wear value is determined as:

$$VB = \frac{VB_1 + VB_2}{2} \quad (4).$$

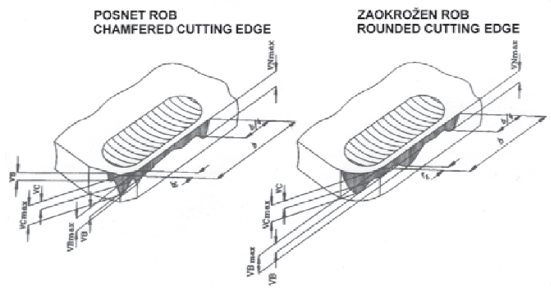
Podatke o obrabnih preizkusih je treba zbirati zelo pozorno in sistematično. Pri obrabnih preizkusih ne zadošča samo zapis o globini rezanja, podajanju, rezalni hitrosti in času rezanja. Brez podatkov o vseh obrabnih pojavih je izkoriščanje rezultatov premajhno, njihova nadaljnja uporaba pri podobnih obdelovalnih primerih pa nemogoča. Popolni podatki so ustrezna osnova za graditev dobre banke tehnoloških podatkov.

Wear-test data must be gathered exactly and very systematically. Wear-test recordings do not only contain parameters related to depth of cut, feed-rate, cutting speed and cutting time. Without all the wear phenomenon data the exploitation of results is irrelavent and their further use by similar machining procedures impossible. Complete data form a suitable base for adequate data-bank elaboration.

a) struženje
a) turning

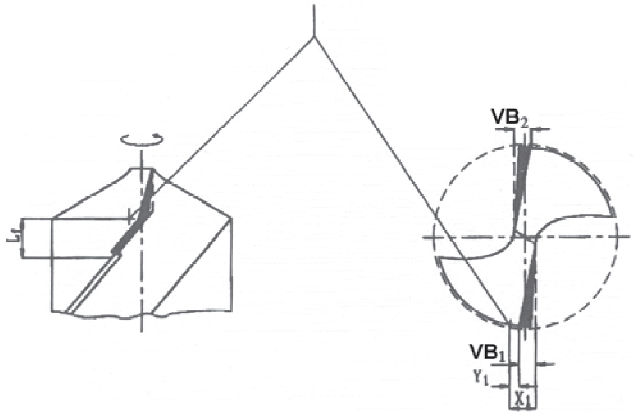


b) frezanje
b) milling

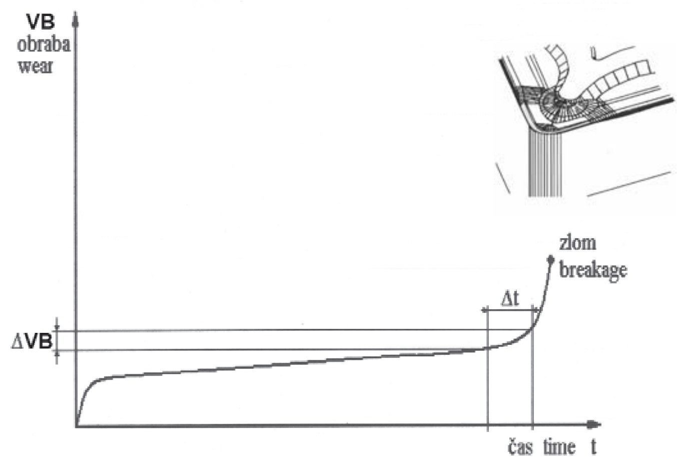


c) vrtanje
c) drilling

raza na prehodu proste ploskve na obod svedra za vodilnim robom
scratch interfacing flank plane and major edge drill circumference



Sl. 3. *Značilne oblike obrab pri tazličnih postopkih odrezovanja*
Fig.3. *Characteristic type of wear by different cutting processes*



Sl.4. *Potek obrabe pri obdelavi z velikimi hitrostmi [3]*
Fig. 4. *Tool wear during HSC [3]*

Te zakonitosti niso več zanesljivo definirane pri odrezavanju z velikimi hitrostmi. Ker želimo rezalne materiale izboljšati, še posebej na površini, jih prevlečemo. Zato je potek obrabe do preboja plasti prevleke zelo počasen, ko pa pride do preboja (plast je debela 2 do 8 μm) se prične obraba intenzivno večati [3].

The described relationships are not reliably defined for high-speed cutting HSC. Improvements to cutting-tool materials are achieved by surface layer coating. Therefore, wear propagation until coating breakthrough is very slow. At the point of coating (thickness of 2 to 8 μm) breakthrough the wear increases significantly [3].

2 MODERNI MATERIALI ZA REZALNA ORODJA IN PREVLEKE

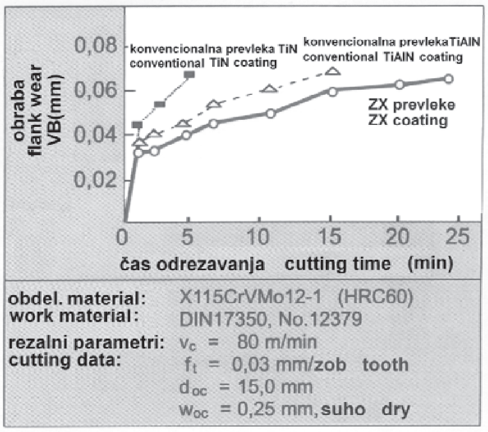
Kot osnovno orodje za obdelavo z velikimi hitrostmi komaj še najdemo hitrorezno jeklo, razen, če je namenjeno serijski obdelavi mehkih materialov v avtomobilski industriji. Vsekakor pa je HSS (hitrorezno jeklo) v takem primeru prevlečeno z več sloji oziroma plastmi. Znatno boljša osnova je karbidna trdina, ki s svojo trdoto že zagotavlja, da ne pride do popuščanja osnove pri večjih obremenitvah, še posebej temperaturnih. Za obdelavo z velikimi hitrostmi so tudi ta orodja prevlečena, in sicer s TiN, AlN, TiAlN, TiCN. Način oziroma postopek nanosa mnogoplastne prevleke TiN/AlN je ionsko platiniranje (Zx prevlečeno) [4].

Prevleka se uvršča v najvišji razred trdote, to je 4000 HV, kar je primerljivo s kubičnim borovim

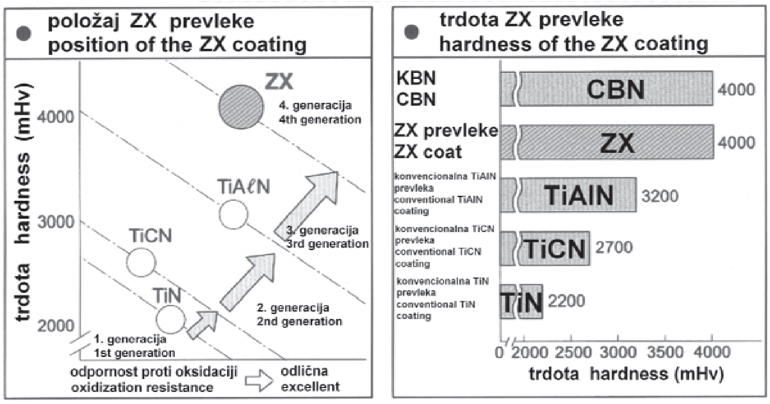
2 CONTEMPORARY CUTTING-TOOL MATERIALS AND COATINGS

HSS is rarely used in HSC, except in the large-volume machining of soft materials in the automotive industry. In any case HSS (high-speed steel) is in this way coated with a multi-layer coating. Cemented carbide is a considerably better base, and its hardness ensures against the base yielding under increased loads, especially thermal loads. HSC cemented carbide tools are also coated with TiN, AlN, TiAlN, TiCN. Multi-layer TiN/AlN (Zx) coating is achieved with the transmission arc-ion plating method [4].

These coatings first-class hardness of 4000 HV is comparable with CBN (cubic boron nitride). Figure 5 shows the very low flank wear



Sl. 5. *Primerjalni diagram obrabe za različne prevleke*
Fig. 5. *Wear comparison for different coatings*



Sl. 6. *Značilnosti prevlek*
Fig. 6. *Coatings characteristics*

nitridom (KBN). Na sliki 5 je razvidna izredno majhna obraba proste ploskve orodja. Ob tem je tehnološki čas rezanja primerjalno največji.

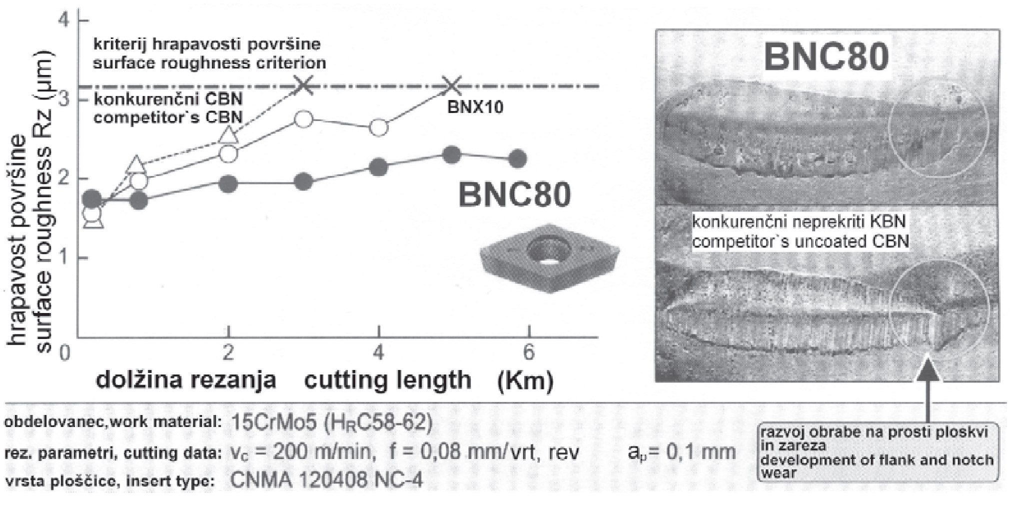
Nanos plasti poteka izmenično: AlN; TiN debeline 2,5 nm; takih plasti je okoli 2000. Zato dosežemo karakteristike, kakor jih kaže slika 6, torej izredno trdoto plasti tako imenovane 4. generacije prevlek ob odpornosti proti oksidaciji. To pomeni možno uporabo orodja tudi tam, kjer pričakujemo visoke temperature na cepilni ploskvi orodja.

Med trenutno najboljše rezalne materiale uvrščamo KBN, ki pa mu še dodatno izboljšamo značilnosti s prevleko iz TiN. S tem dobimo obstojnost orodij, ki se meri v poti obdelave, dolgi več kilometrov. Zato za kriterij uporabimo hrapavost obdelane površine. To pa zato, ker se pretežno uporabljajo taka orodja za fino obdelavo kaljenih jekel – slika 7 [5]. Torej lahko tudi obrabno izredno odporen KBN s prevleko TiN izboljšamo, in sicer tako, da preprečimo zarezno obrabo na prosti ploskvi zunanjega oprijema rezalne ploščice z obdelovancem. Ta je sicer povezana z oksidacijskim odgorevanjem rezalne ploščice ob pristopu zraka na vroč rezalni rob.

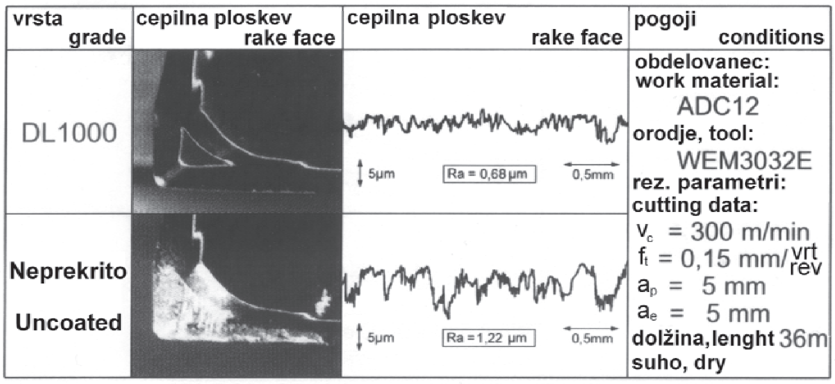
of a tool during the longest technological cutting time.

The layer deposition alternates: AlN; TiN with 2000 layers of micro-thickness 2.5 nm. Therefore, the following characteristics are achieved (Figure 6), i.e., the extraordinary layer hardness of the so-called 4th generation coatings, which are resistant to oxidation. This means that such a tool is appropriate for machining, where high tool-rake surface temperatures are expected.

TiN coatings improve the CBN cutting material's characteristics, which are currently the best available. In this way we achieve a tool life that can be measured in terms of a machining path length of several kilometres. The evaluation criterion, therefore, rather refers to the machined surface roughness, because these types of tools are mainly used for the finish machining of hardened steels (Figure 7). In this way the inherent CBN wear resistance can be further improved by TiN coating, which prevents scratch flank wear between the outer cutting insert contact and the workpiece. The latter is otherwise related to cutting insert oxidation burnout when the hot cutting edge comes in contact with an atmosphere.



Sl. 7. *Primerjava orodja iz KBN in KBN+TiN*
Fig.7. *Comparison between CBN tool and CBN coated with TiN*



Sl. 8. *Učinkovitost prevlek iz DO*
Fig. 8. *Efficiency of DLC coating*

Nadaljnja izboljšanja rezalnega materiala na osnovi KBN so bila dosežena s tako imenovano strukturo PcBN (trdno) s posebno vezivno fazo. S tem dosežemo veliko zlomno žilavost in toplotno prevodnost. PcBN se uporablja za zelo učinkovito obdelavo litega železa, pri katerem zagotavlja počasen potek obrabe orodja, možnost obdelave brez hlajenja in poleg grobe tudi fino obdelavo z enakim orodjem.

Za doseganje majhne hrapavosti pri fini končni obdelavi Al-zlitin in drugih neželeznih materialov je izredno uspešna prevleka daimantovskega ogljika (DO - DLC). Omogoča obdelavo na suho (sl. 8), kar je okolju bolj prijazen postopek.

The next improvement of cutting materials based on CBN is PcBN – grade (Solid) made with the help of a special binder phase. The special binder phase provides a high fracture toughness and a high thermal conductivity. This is useful for the high-efficiency machining of cast iron. The high wear resistance and the high edge stability provide wet and dry machining for roughing either at a high depth of cut or for finishing.

To achieve an excellent surface finish for the machining of Al–alloys and non–ferrous metals, DLC (Diamond Like Carbon) coatings can be used for dry cutting, which is also an environmentally friendly process (Figure 8).

3 RAZISKAVA IN ANALIZA OBRABE RAZLIČNIH ORODIJ RAZLIČNIH PROIZVAJALCEV

Kakor je že opisano, so za obdelavo z velikimi hitrostmi uporabljena orodja iz različnih materialov. Vsi proizvajalci navajajo zelo kakovostne podlage in prevleke. Ker naj bi bil predstavljeni prispevek znanstvenega značaja, ne pa s tržnim predznakom, smo v raziskavo vključili orodja štirih različnih proizvajalcev z oznakami A, B, C, D. Ob tem smo izbrali orodja enakih izmer – stebelno frezalo premera 10 mm in krogelno obliko. Parametri obdelave so razvidni iz preglednice 1.

Posnetki rezalnih robov preizkušenih orodij so razvidni iz preglednice 2. V prvi vrsti so posnetki rezalnih robov po 60 min čiste tehnološke uporabe. Tu se že pokažejo prve razlike med raziskovanimi orodji – širina obrabnega pasu je različna. Časovni intervali tehnološkega časa rezanja se večajo, po 60 min in po času 240 min že

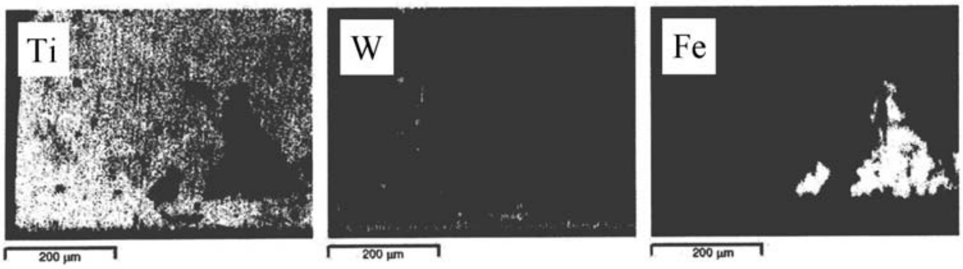
3 RESEARCH RESULTS AND ANALYSES OF WORN CUTTING TOOLS

As already mentioned, high-speed cutting tools consist of different cutting materials. Tool manufacturers are all claim high-quality substrates and coatings. For the scientific investigation of this paper we obtained four commercial tools named A, B, C, and D. The tools had the same dimensional characteristics, i.e., a pencil milling tool of 10 mm diameter with a ball nose end. The cutting parameters are presented in Table 1.

The photographs of the analysed tools' cutting edges are shown in Table 2. First, the upper row shows a little wear on the cutting edges after 60 minutes of cutting. At this point the first differences in tool wear started to be observable. The technological cutting time sequence is 60 minutes. We analysed the tools after every 60 minutes. After 240 minutes one of the tools achieved the first critical tool wear (VB_{cr}). This tool was

Preglednica 1. *Parametri obdelave*
Table 1. *Cutting parameters*

Material obdelovanca Workpiece material	Rezalna hitrost Cutting speed v_c [m/min]	Podajalna hitrost Feed-rate f [mm/vrt]	Globina rezanja Depth of cut a_p [mm]
Utop Mo 6 (52HRC)	350	0,1	0,5

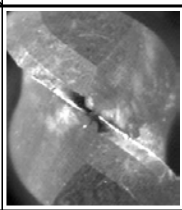
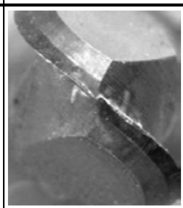
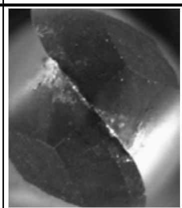
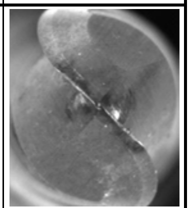
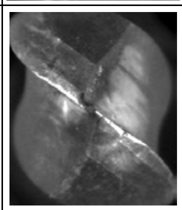
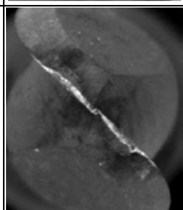
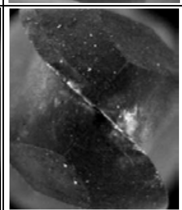
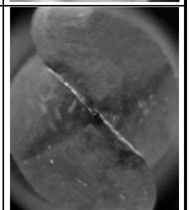
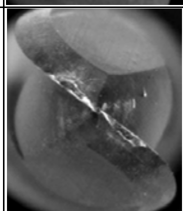
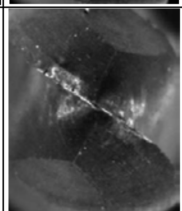
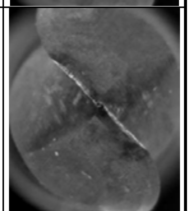
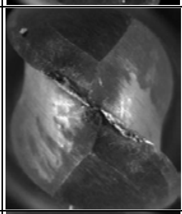
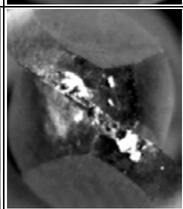
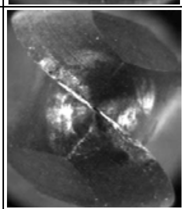
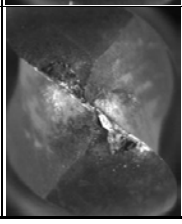
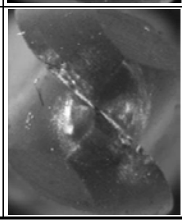
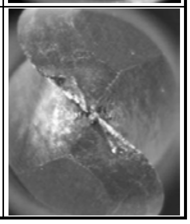


Sl. 9. *Mikro analiza elementov na rezalnem robu*
Fig. 9. *Microanalysis of elements on the cutting edge*

pridemo do izločilnega kriterija pri orodju B. Pri spremljanju izmer obrabe VB – kakor to teoretično pojasnjuje slika 4, smo v polju vprašljivega delovanja in uporabe. Zato je glede na izločilni kriterij treba orodje zamenjati, da ne pride do zloma in s tem dodatnih napak in okvar v celotnem sistemu (orodje – obdelovanec – stroj).

the one designated B. Tool-wear monitoring confirmed theoretical approach, shown in Figure 4, where we reached the uncertain operating and usage range. When the tool wear reach threshold value, the tool had to be exchanged in order to prevent its breaking and consequent failures and malfunctions of the whole system (cutting tool – workpiece – machine tool).

Preglednica 2. *Posnetki obrabljenih rezalnih robov preizkušanih orodij*
Table 2. *Micrographs of tested tools worn cutting edges*

Orodje Tool / Čas Time [min]	**A**	**B**	**C**	**D**
60				
120				
180				
240				
300				

Analiza močno obrabljenih orodij pokaže hkratnost več pojavov: adhezije, abrazije, difuzije, oksidacije, mehanskih okvar (zlomov v obliki okrušitev). Iz raziskav adhezijskih pojavov – (sl. 9), ki temeljijo na mikro analizi površine orodja, je mogoče sklepati, da se pri manjših rezalnih hitrostih pojavlja sprimek na rezalnem robu (SRR - BUE). Po enačbi $v_c = \pi \cdot d_{or} \cdot n$ je razvidno, da se proti osi frezala rezalna hitost manjša. V kombinaciji s povečano hrapavostjo rezalnega robu, kot posledici abrazivne obrabe in majhno rezalno hitrostjo, je izpolnjen pogoj za sprijemanje materiala. Sprimek izredno poslabša in spremeni odrezovalni postopek, tako z vidika spremembe rezalnih sil in momenta kakor tudi z vidika hrapavosti obdelane površine.

An analysis of the heavily worn tools shows simultaneousness of more effects: adhesion, abrasion, diffusion, and mechanical failures (cleaving breakages). We analysed the adhesion on the cutting edge with microanalysis of tool surface, see Figure 9 [5]. It shows BUE (Built Up Edge) presence on the inner part of the cutting edges, especially at lower cutting speeds. According to the equation $v = \pi \cdot d_{or} \cdot n$, the cutting speed decreases in the direction towards the cutter's central line. Low cutting speeds and an increase in the cutting edge's surface roughness (due to abrasion wear) are a prerequisite for BUE formation. The disadvantages of BUE are the changed and deteriorated process cutting characteristics, which cause an increase in the cutting forces and torque along with an increase in the machined surface roughness.

4 SKLEP

Obraba orodja očitno vpliva na tehnološki potek odrezovanja. Je izhodišče za določitev obstojnosti orodja in obdelovalnosti materiala. Opazna je značilna razlika med potekom obrabe pri običajnem in odrezovanju z veliki hitrostmi. Obstojnost pri obdelavi z velikimi hitrostmi ni tako natančno določljiva in zanesljiva. Moderni rezalni materiali zagotavljajo možnost obdelave izredno trdih obdelovanih materialov in v svoji obstojnosti zagotavljajo rezervo, ki zagotavlja zanesljiv postopek odrezovanja. Trde podlage, kot osnova dobrih rezalnih orodij (karbidna trdina, KBN), še pridobijo obstojnost, če jih ustrezno prevlečemo s trdimi plastmi. Mehke prevleke pa zmanjšajo rezalne sile, izboljšajo hrapavost in imajo ekološki učinek v smislu manjše uporabe hladilno mazalnih sredstev (suho odrezovanje, odrezovanje z najmanjšo uporabo hladilno mazalnih sredstev). Pomembna gospodarska panoga, kakršna je orodjarstvo, je značilno povezana z učinkovito in varčno obdelavo prostorskih (3D) gravur. Neposredna obdelava v trdo z odrezovanjem zmanjša termične poškodbe na površini obdelave gravure. Rezultati raziskav so pokazali, da številni proizvajalci rezalnih orodij ponujajo široko paleto orodij, ki pa se po učinkovitosti med seboj razlikujejo tudi do 60 %. Zato še vedno velja, da ustrezna banka tehnoloških podatkov ponuja stvarno sliko o kakovosti orodij.

4 CONCLUSION

Tool wear has a significant influence on the technological characteristics of the cutting process. It is the starting point for a determination of tool life and material machinability. Wear propagation during classical and HSC differs significantly. The tool-life prediction for HSC is not exactly accurate and reliable. Modern cutting materials enable hard machining due to their extended tool life, which in turn ensure a reliable cutting process. The hard substrate basis of enhanced cutting tools (cemented carbide and CBN) mean a longer tool life when they are applied with hard coatings. Soft coatings decrease the cutting forces, lower the machined surface roughness and provide ecological benefits in term of less cutting fluid (dry cutting, near-dry cutting). Demands for die and mould tools manufacturing relate to effective and economical machining of 3D shapes. Direct hard machining minimises thermal damage on machined surfaces. The research work and the comparison of the results proved that these are still large differences between various cutting-tool producers. The efficiency distinction between five different tool producers is as big as 60 % for approximately the same price. For this reason it is evident that an adequate technological data bank is required to provide realistic information about tool quality.

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