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Rezalne sile in njihov vpliv na gospodarnost obdelave

Cutting Forces and Their Influence on the Economics of Machining

Janez Kopač

Rezalne in posebej specifične rezalne sile imajo značilen vpliv na stroške obdelave. Znanje in poznavanje prave tehnologije o obdelavi sta teoretična podlaga za prihranek energije v proizvodnji. Poznamo teoretične modele rezalnih in specifičnih rezalnih sil pri struženju, frezanju in vrtanju. Podane so kot vpliv obdelovanega materiala, postopka obdelave in tehnoloških parametrov.

(Ključne besede: obdelave z odrezavanjem, sile rezanja, prihranki energije, učinki ekonomski)

Cutting forces, and especially specific cutting forces, have a significant influence on machining costs. Having the right knowledge and the right machining technology is a way of saving energy in the production process. There are theoretical models of cutting forces that specify the cutting forces during turning, milling, and drilling. In this paper we give an explanation of the influences of machining material, machining processes and technological parameters on cutting forces and economical machining.

(Keywords: mechanical cutting, cutting forces, energy savings, economic effect)

0 UVOD

Za obdelovalnost materiala so rezalne sile pri postopku pomemben kriterij. Zagotovljene informacije o pričakovanih komponentah rezalnih sil so pomembne zaradi spodaj naštetih razlogov.

Od načrtovanih rezalnih sil med postopkom odrezovanja je odvisna potrebna moč stroja.

Vrednost komponente rezalne sile povzroča, da se med postopkom odrezovanja deformirajo deli stroja, kar ima za posledico natančnost obdelave.

Za razvoj sprotnega nadzora rezalnega postopka je pomembno poznavanje velikosti rezalnih sil v odvisnosti od materiala obdelovanca. Poleg tega pa rezalne sile določajo tudi meje pri optimiranju.

Prava izbira rezalnega postopka in optimalnih tehnoloških parametrov znatno prihrani energijo pri obdelavi, kar neposredno vpliva na stroške.

Vplivni dejavniki na velikost komponent rezalnih sil si sledijo po pomembnosti:

a) način odrezovanja:
   neprekinjen oziroma prekinjen rez
b) rezalni parametri:

0 PREFACE

When it comes to the machinability of a material, the cutting forces used in the process are important criteria. Guaranteed information about the expected cutting-force components is, moreover, particularly significant for the following reasons.

The forces occurring in the metal-cutting process provide information about the power requirements of the machine and are therefore fundamental in the designing of the machine tool drive.

Data on the cutting-force components are required when designing the machine parts as the forces occurring during a cutting operation result in the deformation of certain machine elements, thus imparing the working accuracy of the machine.

For developments in the field of adaptive control of the cutting process, knowledge of the material-dependent cutting force is also of major importance in defining the performance limit confining the range of optimization.

Choosing the right cutting process and the optimum technological parameters results in significant savings of energy during machining.

Of the factors influencing the cutting-force components, the following are very important:

a) in the cutting methods: constant or varying cross-sectional area of the cut chip friction
b) in the cutting conditions:

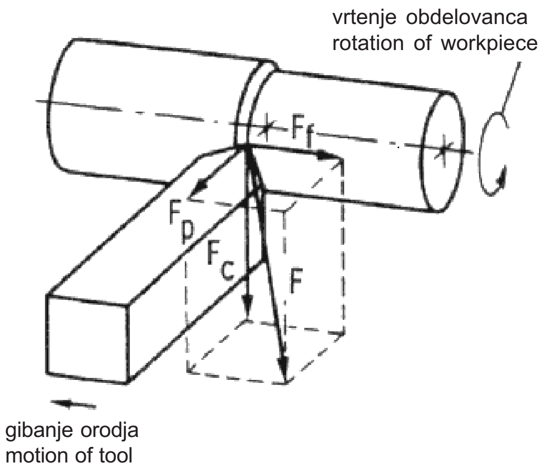
podajanje (f)
globina rezanja (a_p)
geometrijska oblika rezalnega roba
rezalna hitrost (v_c)
hladilna tekočina

c) material:
kemijska sestava
toplotna obdelava

d) orodje:
material orodja
lomilec odrezkov
prevleka
obraba orodja

1 VPLIV REZALNIH PARAMETROV PRI IZRAČUNU KOMPONENT STATIČNIH REZALNIH SIL

Rezultanta rezalnih sil sila F se pojavi med postopkom odrezovanja in je odvisna od smeri gibanja orodja in obdelovanca. Rezultanto rezalnih sil sestavljajo rezalna sila F_c, podajalna sila F_f in odrivna sila F_p (sl. 1). Obremenitev orodja pri struženju prikazuje slika 2.



Sl. 1. *Rezalne sile pri struženju*
Fig. 1. *Cutting force components during turning*

Rezalna sila F_c

Potek rezalne sile lahko delimo z širino odrezka b in ga prikažemo v odvisnosti od debeline odrezka h v dvojnem logaritemskem diagramu. Dobimo linearno odvisnost:

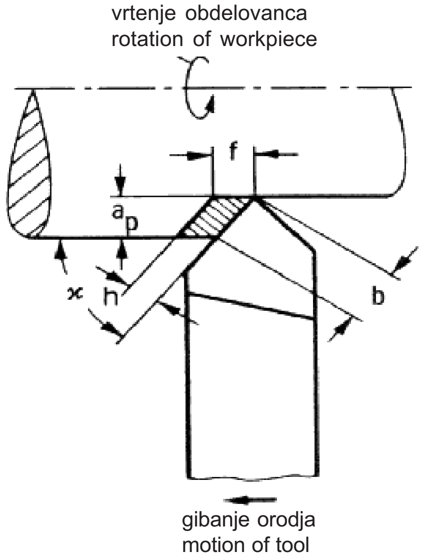
feed (f)
back engagement (a_p)
cutting-edge geometry
cutting speed (v_c)
cutting fluid

c) the material:
chemical composition
heat treatment

d) in the tool:
tool material
chip breaker
coating
tool wear

1 RELATIONSHIPS FOR THE CALCULATION OF THE STATIC CUTTING-FORCE COMPONENTS

The cutting force F acting on the tool during the machining operation can be divided in terms of the directions of motion of the tool and the workpiece into the cutting force F_c, the feed force F_f and the passive force F_p (Figure 1). The conditions of the tool's engagement are described in Figure 2 for the turning process. [1]



Sl. 2. *Razmere pri struženju*
Fig. 2. *Conditions of engagement during turning*

Cutting force F_c

The course of the cutting force F_c related to the width of the cut b is a function of the thickness of the cut h in the system of log-log coordinates as a straight line that is described by the equation:

$$F_c = b \cdot k_{c1.1} \cdot h^{1-m_c} \quad (1)$$

$$b = \frac{a_p}{\sin \chi} \quad (2)$$

$$h = f \cdot \sin \chi \quad (3).$$

Zgornjo enačbo je izkustveno razvil Kienzle in popisuje odvisnost rezalne sile F_c od prereza odrezka, kar prikazuje slika 3. Standardna specifična rezalna sila je odvisna od širne odrezka b in debeline odrezka h, kjer je $b \times h$=1mm², ter vplivnega koeficienta rezalne sile 1-m_c, kar je razvidno iz enačbe.

Standardna specifična rezalna sila $k_{c1.1}$ je v veliki meri odvisna od materiala, rezalnih parametrov, orodja in vpliva tehnološkega postopka.

Povečanje rezalne sile je odvisno od vplivnega koeficienta rezalne sile 1-$m_{c,}$ karakteristik materiala obdelovanca in materiala orodja ter različne globine rezanja.

Predstavitev izkustvene vrednosti rezalne sile F_c je odvisna od prereza odrezka b*h oziroma globine rezanja a_p kot funkcija debeline odrezka h. Rezultat je premica v dvojnem logaritemskem diagramu, ki je podana z enčbo:

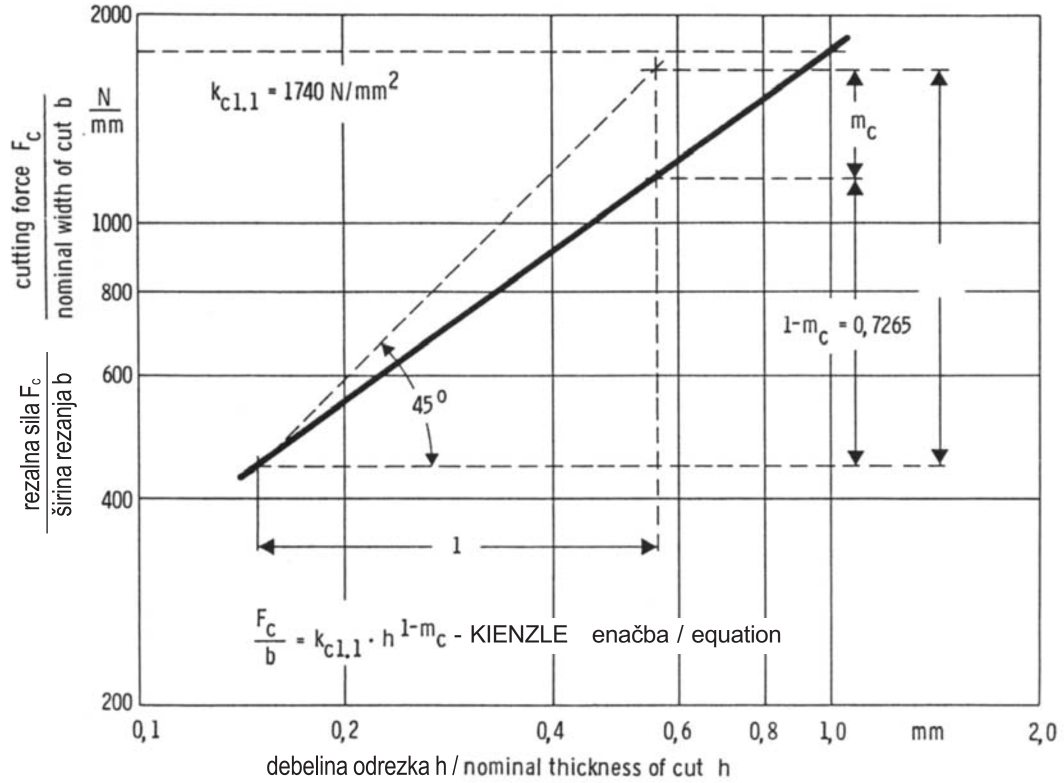
This equation was established by Kienzle according to the empirically determined dependence of the cutting force F_c on the cross-sectional area of the cut $a_p \times$ f or $b \times h$, subject to the turning data shown in Figure 3. The specific cutting force $k_{c1.1}$ related to the cross-sectional area of the cut $b \times h = 1$ mm² and the rise in the cutting force related to the nominal width of the cut 1-m_c are entered into the equation as characteristic data.[2]

The specific cutting force $k_{c1.1}$ is, in this case, largely dependent on the material, the cutting conditions, the tool and the procedural influences.

The increase in the cutting force related to the nominal width of the cut 1-m_c characterises the cutting-force behaviour of a workpiece-material–tool-material combination for different thicknesses of cut.

The representation of the experimentally determined cutting-force values F_c related to the cross-sectional area of the cut b * h or $a_{p*}f$ as a function of the thickness of the cut h also results, under log-log coordinates, in a straight line, which can be described by the equation:

$$k_c = k_{c1.1} \cdot h^{1-m_c} = \frac{F_c}{b \cdot h} \qquad (4).$$



Sl. 3. *Grafična predstavitev poteka rezalne sile in specifične rezalne sile*
Fig. 3. *Graphic determination of the cutting force and the specific cutting force*

V tej zvezi je specifična rezalna sila k_c podana kot funkcija debeline odrezka h. Te povezave nas pripeljejo do enačbe za rezalno silo F_c:

Through this relation, the specific cutting forces k_c are given as a function of the thickness of the cut h. These connections lead to a further equation for the calculation of the cutting force F_c:

$$F_c = b \cdot h \cdot k_c \qquad (5).$$

Podajalna sila F_f

Za izračun podajalne sile F_f, vpeljemo enako zvezo kakor pri rezalni sili F_c, ta je definirana kot linearna funkcija podajalne sile, ki je funkcija širine odrezka *b* kot funkcija debeline odrezka *h*, kar je predstavljeno v dvojnem logaritemskem diagramu:

Feed force F_f

For the calculation of the feed force F_f, a relationship can be established that is similar to that used for the cutting force F_c, which is based on the linear behaviour of the feed forces related to the width of cut *b* as a function of the thickness of cut *h* as shown under log-log coordinates:

$$F_f = b \cdot k_{f1.1} \cdot h^{1-m_f} \qquad (6).$$

Značilen podatek: standardna specifična rezalna sila je odvisna od prereza odrezka, ki je $b \times h = 1\,\text{mm}^2$. Povečanje podajalne sile je odvisno od vplivnega parametra podajalne sile, kar je upoštevano v enačbi.

Nasprotno kakor pri enačbi rezalne sile, moramo v enačbi za izračun podajalne sile upoštevati, da je raztros pri podajalni sili $F_f/b=f(\text{h})$ večji kakor pri rezalni sili.

Odrivna sila F_p

V skladu s pravili za izračun podajalne sile F_f, lahko odrivno silo F_p izrazimo z enačbo:

As characteristic data, the specific feed force $k_{f1.1}$ related to a cross-sectional area of cut of $b \times h = 1$ mm^2 and the increase in the feed force related to the nominal width of the cut $1 - m_f$ are included in the equation.

Unlike to the cutting-force equation, this equation to calculate the feed force must be regarded as an approximate solution as the scatter of the test values in the representation $F_f / b = f(h)$ is larger than with the cutting force [3].

Passive force F_p

In accordance with the rules of calculating the feed force F_f, the passive force *Fp* can be expressed as:

$$F_p = b \cdot k_{p1.1} \cdot h^{1-m_p} \qquad (7).$$

V preglednici 1 so zbrane vse enačbe za izračun rezalnih sil in torzijskih momentov za nekaj najbolj pogosto zastopanih postopkov obdelave.

2 REZALNI PARAMETRI

Podatki o obdelavi, kot sta globina rezanja a_p in podajanje *f,* so namenjeni izračunu povprečnega prereza odrezka $a_p \times f = b \times h$ in nakazujejo prek znanih enačb na velikost rezalne sile.

Rezalna geometrija

Rezalna geometrija ima precejšen vpliv na velikost komponent rezalnih sil. Po eni strani deformacija v strižni coni vpliva na geometrijsko obliko odrezka, po drugi strani pa je geometrijska oblika odrezka definirana z geometrijsko obliko orodja. Na velikost komponent rezalnih sil tako vplivajo razmere v strižni coni in geometrijska oblika orodja.

Če se spremeni cepilni kot γ (zmanjša ali poveča), se spremenijo omenjene sile (povečajo ali pomanjšajo) za naslednje vrednosti:

rezalna sila	F_c	za približno 1,5 %
podajalna sila	F_f	za približno 5,0 %
odrivna sila	F_p	za približno 4,0 %

za vsako stopinjo (1°) spremembe cepilnega kota.

Če je velikost prostega kota α 3° = α = 12°, ta nima značilnega vpliva na komponente rezalnih sil.

Table 1 shows some of the equations for computing the cutting forces and torques that occur during machining, such as turning, drilling, milling, etc.

2 CUTTING CONDITIONS

The machining parameters as data back engagement a_p and feed *f* pass over by way of the cross-sectional area of cut $a_p \times f = b \times h$ immediately into the cutting-force equations indicated.

Cutting-edge geometry

The cutting-edge geometry has a major influence on the quantity of the cutting-force components. On the one hand, the deformation processes in the zone of shear are affected by it and, as a result, so is the geometry of the chip formation, on the other hand, the tool angles determine, for geometrical reasons, the relative quantities of the various force components.

As the rake angle γ decreases (increases), there is an increase (decrease) of the:

cutting force	F_c	by about 1.5 %
feed force	F_f	by about 5.0 %.
passive force	F_p	by about 4.0 %

for every degree of rake angle change compared to the test value.

Within the usual range of clearance angles α 3° = α = 12° no influence can be determined on the cutting-force components.

Preglednica 1. *Enačbe rezalne sile in torzijskega momenta*
Table 1. *Cutting-force and torque equations*

	Enačbe za izračun Equation for the determination of	
Obdelovalni postopek Machining process	Rezalna sila F_c Cutting force F_c	Torzijski moment Md Torque Md
Struženje Turning	$F_c = b \cdot h \cdot k_c$ $F_c = b \cdot k_{c1.1} \cdot h^{1-m_c}$ $h = f \cdot \sin \chi$ $b = \frac{a_p}{\sin \chi}$; $a = \frac{D-d}{2}$	$Md = b \cdot h \cdot k_c \cdot \frac{D+d}{4}$ $Md = b \cdot k_{c1.1} \cdot h^{1-m_c} \frac{D+d}{4}$
Skobljanje Planing	Podobno kakor struženje Like turning	
Vrtanje Drilling	Posamezen rezalni rob: Each cutting edge: $F_c = b \cdot h \cdot k_c$ $F_c = b \cdot k_{c1.1} \cdot h^{1-m_c}$ $b = \frac{D}{2 \sin \chi}$; $\chi = \frac{\sigma}{2}$ $h = \frac{f}{2} \sin \chi$	$Md = 2b \cdot h \cdot k_c \cdot \frac{D}{4}$ $Md = 2b \cdot k_{c1.1} \cdot h^{1-m_c} \frac{D}{4}$ $Md = f \cdot k_c \cdot \frac{D^2}{8}$
Povrtavanje Boring	Posamezen rezalni rob: Each cutting edge: $F_c = b \cdot h \cdot k_c$ $F_c = b \cdot k_{c1.1} \cdot h^{1-m_c}$ $b = \frac{D}{2 \sin \chi}$; $\chi = \frac{\sigma}{2}$ $h = \frac{f}{2} \sin \chi$	$Md = 2b \cdot h \cdot k_c \cdot \frac{D+d}{4}$ $Md = 2b \cdot k_{c1.1} \cdot h^{1-m_c} \frac{D+d}{4}$ $Md = f \cdot k_c \cdot \frac{D^2 - d^2}{8}$
Frezanje Milling	Posamezen rezalni rob: Each cutting edge: $F_c = b \cdot h \cdot k_c$ $F_c = b \cdot k_{c1.1} \cdot h^{1-m_c}$ $h = f_z \sin \varphi_s \sin \chi$ $b = \frac{a_p}{\sin \chi}$	$Md = b \cdot h \cdot k_c \cdot \frac{D}{2}$ $Md = b \cdot k_{c1.1} \cdot h^{1-m_c} \frac{D}{2}$

Če se spremeni strmina λ (zmanjša ali poveča), se spremenijo tudi sile (povečajo ali pomanjšajo):

rezalna sila	F_c	za približno 1,5 %
podajalna sila	F_f	za približno 1,5 %
odrivna sila	F_p	za približno 10,0 %

za vsako spremembo strmine λ za 1°.

Vpliv nastavnega kota χ je zajet v enačbi (3) in (5) za izračun rezalne sile F_c in odrivne sile F_p pri znani širini b in debelini h odrezka. Medtem ko se rezalna sila F_c in odrivna sila F_p zmanjšata z nastavnim kotom χ, se podajalna sila F_f poveča.

Odvisnost podajalne sile F_f od nastavnega kota χ ni popolnoma popisana v enačbi (4), torej čisto matematično bi bila popisana z nastavnim kotom χ, širino odrezka b in debelino odrezka h, torej z enačbo (4) dobimo nepopoln rezultat. Za

As the cutting-edge inclination λ decreases (increases), there is an increase (decrease) of the:

cutting force	F_c	by about 1.5 %
feed force	F_f	by about 1.5 %
passive force	F_p	by about 10.0 %

for every degree of changing the angle of inclination as compared to the test value.

The influence of the cutting-edge angle χ is contained in the equations (3) and (5) for the calculation of the cutting force F_c and the passive force F_p by the indication of the width of cut b and the thickness of cut h. While the cutting force Fc and the passive force F_p increase as the cutting edge angle reduces the feed force F_f decreases.

The dependence of the feed force on the cutting-edge angle is, however, not described by the indicated equation, as a result, a purely mathematical consideration of the cutting-edge angle within the range width-of-cut b and thickness-of-cut h will lead to the nastavne kote χ manjše od normalnih, lahko podajalno silo izračunamo z matematično enačbo, vrednost podajalne sile pa je manjša od dvakratne velikosti te pri normalnih nastavnih kotih ($F_f = 2F_{f\,(\chi=70°)} - F_{f\,(\chi<70°)}$).

Velikost radija konice ima znaten vpliv na velikost komponent rezalnih sil, pri čemer mora biti najmanjša globina rezanja $a_p = 2$ r.

Rezalna hitrost

Rezalna hitrost vpliva na komponente rezalnih sil, njen vpliv je različen glede na material obdelovanca in orodja ter vrsto obdelave.

Hitrorezno jeklo se uporablja za rezalne hitrosti do 25 m/min, to pa je tudi hitrost $v_c = 25$m/min, pri kateri se določi standardno specifično rezalno silo.

Da preprečimo nastajanje nalepka pri rezalnih hitrostih $v_c < 30$m/min, uporabimo orodje iz karbidne trdine. Upoštevati pa moramo, da se pri odrezovanju pojavljajo tudi rezalne hitrosti do $v_c > 1000$m/min, kar vpliva na velikost rezalne sile.

Hladilna tekočina

Vpliv hladilne tekočine je bistvenega pomena pri velikih rezalnih hitrostih. Pri majhnih rezalnih hitrostih, se rezalne sile zmanjšajo zaradi prodora hladilno-mazalne tekočine v dotikalno območje, kar povzroči zmanjšanje trenja med odrezkom in orodjem. Pri večjih rezalnih hitrostih ima hladilno-mazalna tekočina v strižni coni samo hladilni učinek. Pri sodobnih rezalnih materialih ni nujno potrebna uporaba hladilno-mazalne tekočine, ker imajo nove prevleke rezalnih orodij dobre značilnosti.

Sodobne in naravi prijazne metode obdelave s hladilno-mazalno tekočino so metode minimalnega hlajenja, pri tem za mazanje uporabljajo sistem razprševanja naravnega olja s stisnjenim zrakom.

3 OBDELOVANI MATERIAL

Kemična sestava

Če poznamo kemično sestavo obdelovalnega materiala, lahko le ocenimo velikost rezalne sile pri obdelavi. Vendar pri tem ni pravila in so zato potrebne meritve sil.

wrong results. For cutting-edge angles smaller than those on which the test value is based, the feed force can be determined by calculation in such a way that the mathematical value of the feed force for the smaller cutting-edge angle is subtracted from the double test result ($F_f = 2F_{f\,(\chi=70°)} - F_{f\,(\chi<70°)}$).

Within the range of the usual values for the corner radius, no appreciable influence on the cutting-force components can be determined as long as the term 2 r = a_p is fulfilled.

Cutting speed

The influence of the cutting speed on the cutting-force components must be differently assessed for the various workpiece materials and the tool materials with their specific ranges of application.

The application range for high-speed-steel tools is, in general, for cutting speeds of about 25 m/min; so that for this material the cutting behaviour is described with sufficient accuracy by the indication of the specific cutting-force value at $v_c = 25$ m/min.

To prevent built-up-edge formation, no cutting speeds of $v_c < 30$ m/min are normally used for carbide cutting tools . As regards the cutting-speed-dependent behaviour of the cutting forces in turning operations in the range of $v_c < 1000$ m/min, fundamental examinations are available.

Cutting fluid

The influence of cutting fluids varies depending on the cutting speed. At low cutting speeds, the cutting forces are reduced owing to the penetration of the lubricant into the contact zones and the diminished friction between chip and tool. At higher cutting speeds within the range of the formation of continuous chips, the cutting fluid only has a cooling effect.

Modern and ecological methods use near-dry cutting with a minimum amount of natural oil dispersed with pressurised air.

3 WORKPIECE MATERIAL

Chemical composition

According to the present state of knowledge, the chemical composition of the workpiece materials is only suggestive of the size of cutting-force components in exceptional cases, because definite laws relating to this influence are quite rare.

Toplotna obdelava

Raziskava vpliva toplotne obdelave na rezalne sile je pokazala, da vpliv toplotne obdelave ni natančno definiran glede na rezalne sile. Pri običajnih rezalnih orodjih, kakor sta hitrorezno jeklo in karbidna trdina, je treba vpliv toplotne obdelave na podatek $k_{c1.1}$ in 1-m_c izmeriti za vsak primer posebej.

Pri preskusih odrezovanja toplotno obdelanih materialov s hitroreznimi jekli so izmerjene rezalne sile manjše kakor pri mehko žarjenih obdelovancih. Ta ugotovitev velja tudi za potek rezalne sile v povezavi z 1-m_c. Meritve rezalnih sil pri odrezovanju z orodji iz karbidne trdine so pokazale, da primerjava toplotno obdelanih proti mehko žarjenim vzorcem kaže večje vrednosti za $k_{c1.1}$ in1-m_c. Medtem ko primerjava med normalizacijo in žarjenjem na mehko ni pokazala značilnih sprememb rezalnih sil.

Odvisnost specifične rezalne sile $k_{c1.1}$ in povečanj rezalne sile glede na širino odrezka preko vplivnega eksponenta 1-m_c je povezana z napetostmi in deformacijskimi karakteristikami obdelovanega materiala. Zato ni natančno definirana povezava in lahko pričakujemo večje raztrose rezultatov.

4 ORODJE

Dogodki v rezalni coni, kjer potekata strig in nastanek lamel odrezka, prvinsko vplivajo na podajalno in odrivno silo. Tudi tu je značilen raztros glede na zvezo sila / debelina odrezka. Linearni popis komponent rezalne sile, kot funkcije debeline odrezka je izveden kot približna rešitev.

Materiali za rezalna orodja

Če uporabimo rezalno keramiko (Al_2O_3), so rezalne sile proti karbidni trdini za okoli 10% manjše. Vzrok so boljše torne razmere pri drsenju odrezka po cepilni ploskvi rezalne ploščice. Lomilnik odrezkov, ki je v moderni obliki že integriran na rezalni ploščici je dimenzioniran tako, da je polmer za iztek odrezka čim večji. S tem lomilnik nima bistvenega vpliva na rezalne sile; zmanjšana pa je tudi obraba segmenta lomilnika. Na splošno se priporoča, da je odmik lomilnika od rezalnega robu v vrednosti okoli 10 × f (torej desetkratnega pomika orodja).

Obraba orodja

Obraba orodja je zanesljivo v povezavi z velikostjo rezalnih sil. Deli se na dve značilni, in sicer na obrabo proste ploskve, ki jo povzroča

Heat treatment

Investigations aimed at defining the influence of heat treatment on the cutting forces have led to the result that there is no definite dependence of the main cutting force on heat treatment. However, as regards high-speed-steel tools and carbide cutting tools, the qualitative effects of heat treatment on the data $k_{c1.1}$ and 1-m_c can be determined separately.

Under the experimental conditions, heat-treated materials for the high-speed-steel tool material generally show much lower cutting-force values than for soft-annealed steels. This statement also applies to the increase in the cutting force related to the nominal width of the cut 1 –m_c. The cutting-force measurements conducted with carbide cutting tools showed that heat-treated materials, as compared to soft-annealed materials, frequently reveal higher values for $k_{c1.1}$ and 1-m_c. A comparison of the cutting forces for normalised and soft-annealed materials, however, does not result in any appreciable differences.

While the dependence of the specific cutting force $k_{c1.1}$ and of the increase in the cutting force related to the nominal width of the cut 1-m_c on the strength and deformation characteristics within the entire range of materials examined may be shown, no definite relationship can be attributed to this influence owing to the wide range of scatter.

4 TOOL

The deformation conditions in the shear zone of the tool – some of which varied for different thicknesses of the cut and made themselves felt in the position and size of the shearing plane and in the amount of chip crowding – had an effect on the feed forces and the passive forces. In view of the range of scatter of the various test results, a linear description of these force components as a function of the thickness of the cut must therefore be regarded as an approximate solution.

Tool material

When aluminium-oxide tools (cutting ceramics) are employed as a tool material, the resulting cutting forces are about 10 % lower than with carbide metal because with a ceramic cutting material there are more favourable frictional conditions on the true rake or chip face. The size of the chipbreaker b_{sp} should be dimensioned so that the radius of chip curvature is as large as possible. This is to ensure that on the one hand the size of the chip breaker will not have any major influence on the cutting-force components, and on the other hand, the wear action on the true rake is as low as possible. The rule-of-thumb value ‘chip former = 10 times the feed’ can generally be regarded as favourable.

Tool wear

Numerous results are available concerning the influence of tool wear on the cutting-force components. As a consequence of the increasing friction areas between the drsenje rezila po že obdelani površini obdelovanca, in na obrabo cepilne ploskve orodja, prek katere drsi odrezek. Značilen vpliv na večanje obrabe pa ima seveda čas uporabe orodja. Tudi tu ocene povečanja obrabe niso mogoče v zadostni natančnosti, zato so potrebne meritve. Le približne ocene povedo, kakšna sta vpliv in povezava med obrabo orodja in povečanjem rezalne sile:

rezalna sila F_c se poveča za 10% za vsak 0,1 mm obrabe W
podajalna sila F_f se poveča za 25% za vsak 0,1 mm obrabe W
odrivna sila F_p se poveča za 30% za vsak 0,1 mm obrabe W

Kot definicija kriterija izločilne obrabe rezalnega orodja pa seveda ne more biti pravkar omenjena povezava med rezalno silo in obrabo proste ploskve orodja W.

5 DINAMIČNA REZALNA SILA

Temeljita raziskava dinamičnih rezalnih sil pri struženju je pokazala, da ima poleg statične komponente rezalne sile tudi nastanek odrezka velik vpliv na komponente rezalnih sil.

V strižni coni in v področju nastanka nalepka na rezalnem robu, se lahko dinamična komponenta rezalne sile F_c poveča za 20%, podajalna sila F_f in odrivna sila F_p pa se lahko povečata za 50%. V področju zveznega nastanka odrezka se lahko dinamična komponenta rezalne sile zmanjša za 5 do 10 odstotkov (sl. 4).

Znaten vpliv na dinamično rezalno silo ima tudi lega lomilne stopničke b_{sp}, ki je lahko odvisna že od oblike sintrane ploščice. Majhna oddaljenost lomilne stopničke poveča gostoto odrezkov v taki meri, da je dinamična sila v strižni coni v smeri podajalne in odrivne sile lahko večja za 100 odstotkov od statične.

cut surface and the flank of the tool or between the chip and the chip face, on the one hand and the changing conditions of engagement of the tool on the other, a substantial increase in the cutting-force components with increasing cutting time is registered. In view of the number of factors, a quantitative statement on the increasing force in relation to the increasing tool wear can only be an approximation. Numerous experimental results have shown that for an increase of the cutting-force components as the tool wear increases the following corrective values should be introduced:

cutting force F_c: increase of about 10% per 0.1-mm width of land wear W
feed force F_f: increase of about 25% per 0.1-mm width of land wear W
passive force F_p: increase of about 30% per 0.1-mm width of land wear W

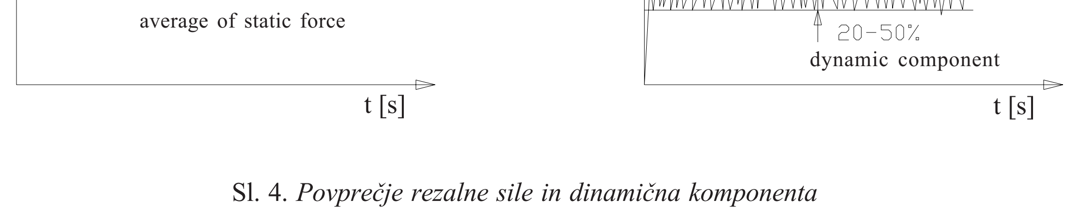
As a definition of the total wear is impossible, the increase in the cutting force was related to the width of the land wear W.

5 DYNAMIC CUTTING FORCE

Fundamental examinations of the dynamics of cutting forces during turning have shown that in addition to the factors influencing the static cutting-force components the chip formation has a major influence on the cutting-force components.

In the range of shear-chip formation, built-up-edge formation and the rigidity of the process, a high dynamic cutting-force component occurs in machining, which may acount for a cutting force F_c of up to 20%, and for the feed force F_f and the passive force F_p up to 50% of the static components. In the range of continuous chip formation, the dynamic cutting forces drop to 5–10 % of the static share, see Figure 4.

A considerable influence on the dynamic cutting forces is exercised by the chip-breaker distance b_{sp}, which can be made directly by shape-sintering of the cutting insert. With a short distance and thus heavy crowding of the chip flow, the share of the dynamic force in the direction of the feed force and the passive force can amount to as much as 100 % of the static share.



Sl. 4. *Povprečje rezalne sile in dinamična komponenta*
Fig. 4. *Average cutting force and dynamic part of the cutting force*

6 PRAKTIČNA PREDSTAVITEV

Praktična uporaba eksperimentalno dobljenih rezultatov je prikazana na sliki 5. Specifična rezalna sila vpliva na energijo, potrebno za obdelavo. Za prihranek energije in stroškov je ekonomična izbira največjega možnega podajanja.

Največje tehnološko mogoče podajanje je izbrano glede na postopek in zahtevano hrapavost (Ra). Kratka primerjava pokaže, kako lahko s pravilnim načrtovanjem tehnoloških parametrov dosežemo 2-kratni prihranek energije in časa obdelave ter tako zmanjšamo stroške.

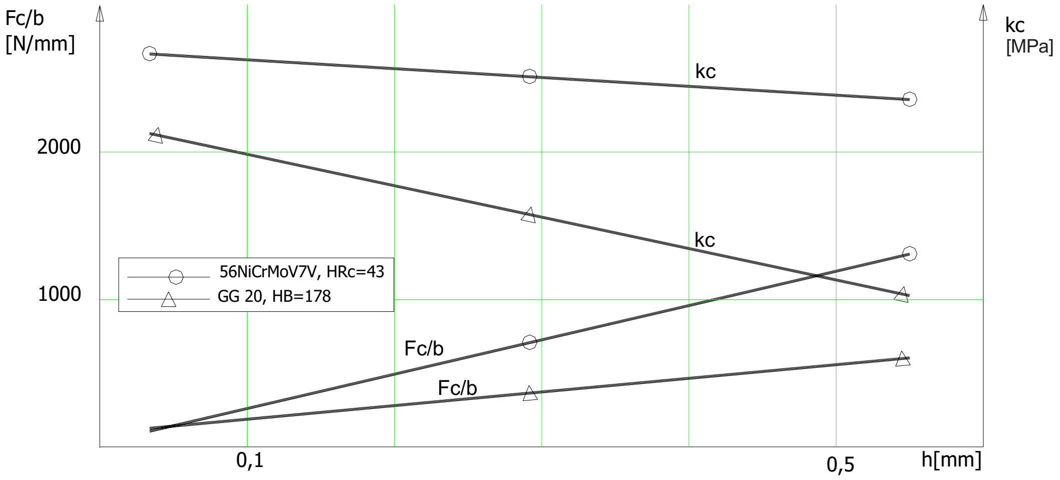
Iz primerjave finega struženja in postopka brušenja vidimo, da je specifična rezalna sila pri struženju 2-krat manjša (prej omenjeni prihranek).

6 PRACTICAL DEMONSTRATION

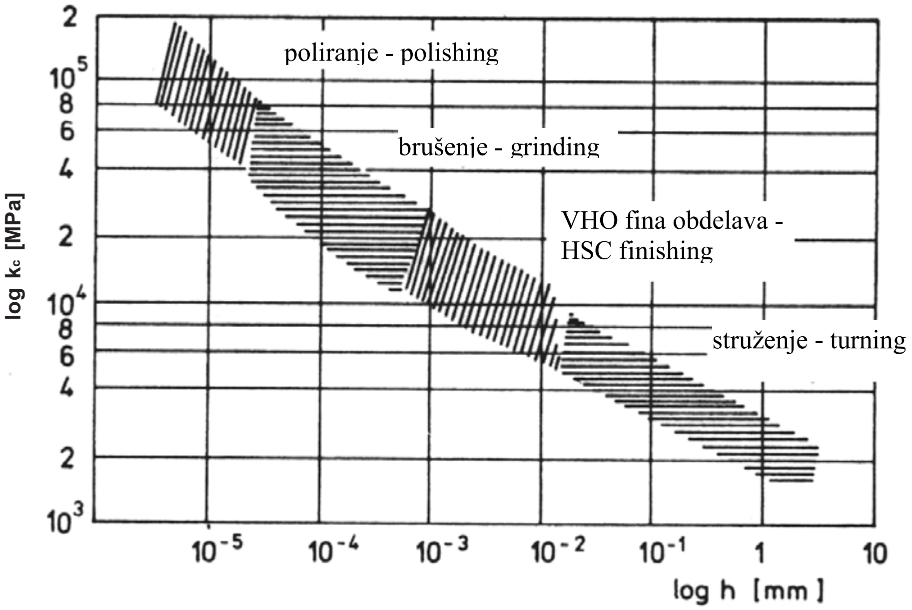
The practical use of the experimental results is shown in Fig. 5. The specific cutting force has an influence on the energy needed for machining. With regard to saving energy and costs it is best to choose the maximum possible feed rate.

The maximum technologically justifiable feed rate is chosen based on the limits of the process or the specimen roughness (Ra). The short comparision shows that using the right technological parameters can save more than 2x the equivalent of energy: shortening the machining time and reducing the costs.

Fine turning of the final surface of the workpiece in comparision with grinding bring about the mentioned 200% lower specific cutting forces. Some of the



Sl. 5. *Eksperimentalni rezultati rezalnih in specifičnih rezalnih sil*
Fig. 5. *Experimental results of cutting and specific cutting forces*



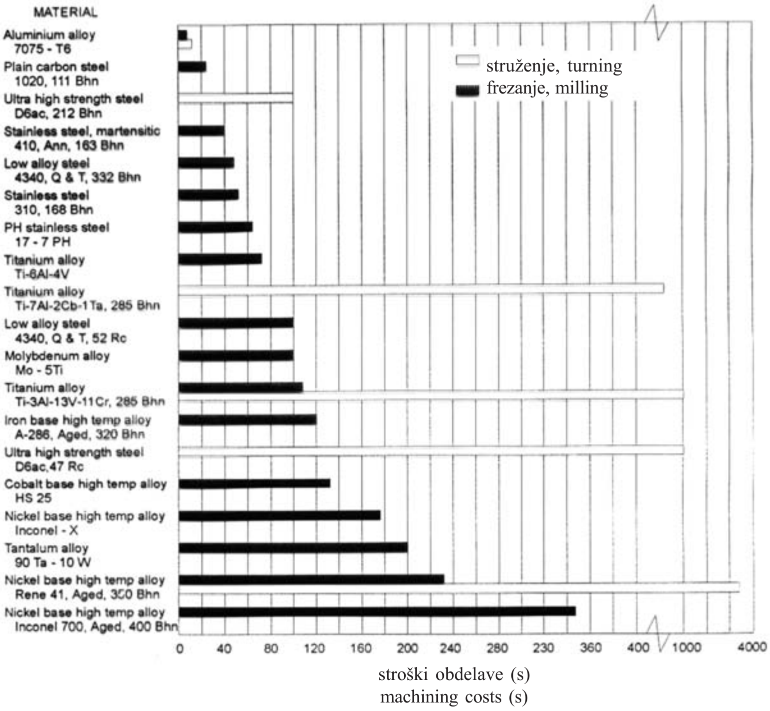
Sl. 6. *Specifične rezalne sile, odvisne od postopka obdelave*
Fig. 6. *Specific cutting forces during the process*

Podatki, zbrani v diagramu na sliki 6, kažejo razliko med postopki obdelave v odvisnosti od debeline odrezka *h*. Nasproten postopek pokaže, kako je specifična rezalna sila manjša pri večjem podajanju [4].

Da predstavimo in primerjamo teoretične rezultate s praktičnimi vplivi, je treba pogledati sliko 7. Razvidna sta vpliv obdelovalnega materiala in vrsta obdelave na stroške obdelave. Če primerjamo obdelavo mehkega materiala, npr. aluminij ali jeklo, s trdimi materiali, na primer nikljeve zlitine, opazimo, da je razlika v stroških obdelave kar 4-kratna. Pri tem je seveda opazen tudi vpliv rezalne sile, ki v povezavi s hitrostjo narekuje moč stroja, kar pa je tudi eden od stroškov.Razvidna je tudi razlika glede na vrsto postopka; struženje povzroča znatno večje stroške kakor frezanje, če gledamo glede na odvzem enake prostornine materiala.

results collected in the diagram in Fig.6 show diferences between processes, such as turning, HSC, grinding soft material and hard steels, depend on *h* (thickness). The reverse observation shows how the specific cutting force is lower with a higher feed rate [4].

Comparing the theoretical and measured results with the practical effect shows, in Fig. 7, how great is the influence of the type of machined materials, reflected in the cutting forces and the machining costs. The product of the cutting force and the cutting speed provides the power needed for the process: this is the energy costs. As first, the relative costs between soft (Al, steel) material and hard (nikel-based alloys) materials are a factor of four different for machining. Another influence is the chosen type of machining: the turning process is much more expensive than milling, which means the technologist has to be very careful when preparing the offer for the customer.



Sl. 7. *Relativni stroški obdelave mehkih in trdih materialov*
Fig. 7. *Relative costs of machining soft and hard materials*

7 VHO – OBDELAVA Z VELIKIMI HITROSTMI

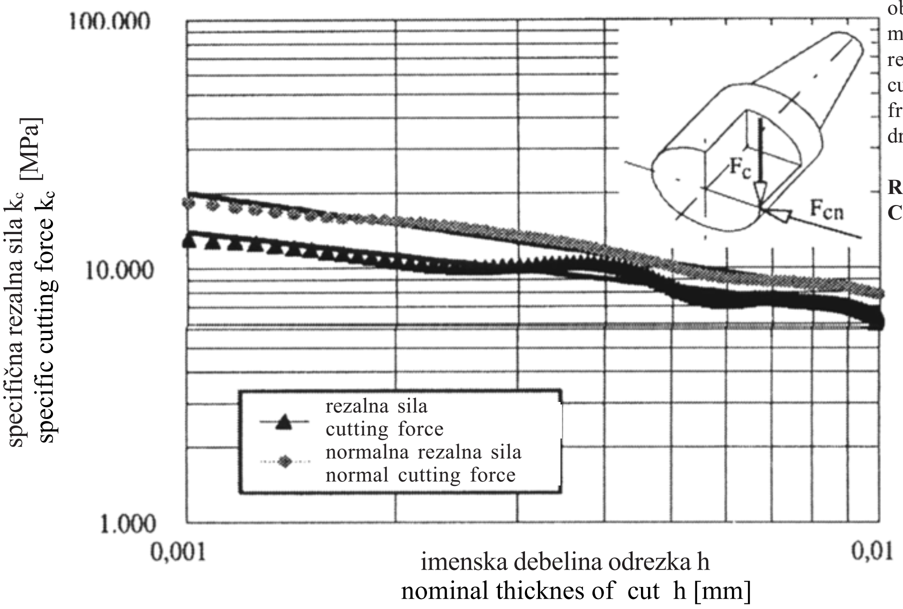
Uporabno območje debeline odrezka (*h*) pri obdelavi z velikimi hitrostmi je omejeno. Za primerjavo rezultatov (poglavje 6 – običajna obdelava) z rezultati sodobne obdelave v trdo je mogoče videti, da je odvisnost enaka. To pomeni, da sta rezalni postopek in rezalna geometrija ($\alpha, \beta, \gamma, r, \chi$) teoretično še vedno enaki. Klasična in sodobna obdelava VHO imata skupno to, da je njun izid odrezek in da se za oba postopka uporablja isti matematični model.

S slike je razvidno, da je pogosto odrivna sila pri odrezovanju v trdo celo večja od glavne rezalne

7 HSC – MACHINING CONDITION

The usable (*h*) thickness by HSC machining is explicitly limited in this process. By comparing the result shown before (section 6: classical machining) with the results of modern HM (hard machining) we can see that the relationship is the same. It means that cutting processes with an exact cutting geometry ($\alpha, \beta, \gamma, r, \chi$) are still in the same theoretical area. The classical cutting and modern HSC machining both have as a “product”, therefore the same models and equations are used for both processes.

Figure 8 shows that the passive force can be larger than the cutting force. In prac-



obdelovani material: machining material: **100CR6**
rezalno orodje: cutting tool: **PKB**
frezanje
dry up milling

Rezalni pogoji:
Cutting conditions:
a_p = 5 mm
a_e = 0,1 mm
f_z = 0,1 mm
v_c = 50 m/min

d = 40 mm, z = 1
α = 10°
γ = 0°
r_ε = 1,2 mm

Sl. 8. *Sile pri frezanju v trdo [5]*
Fig. 8.*Hard machining (HM) and forces [5]*

sile. To v praksi pomeni odmik orodja od načrtovanega obrisa obdelovanca in s tem napake na izdelku. Zato v praksi zmanjšamo debelino odrezka.

8 SKLEP

Nepoznavanje področja rezalnih sil ima lahko za posledico slabo obdelavo, lome orodja, in večje obdelovalne stroške. Običajni obdelovalni postopki še vedno ponujajo banko tehnoloških podatkov, v kateri so podatki o rezalnih silah glede na obdelovalni material, postopek, rezalno orodje itn. S tehnološko pripravo lahko inženir izbere in določi najboljši postopek in s tem debelino odrezka (h). Le ta mora biti vedno največja po vsem obrisu obdelovanca, glede na zahtevano hrapavost površine. To je prvi korak, ko lahko tehnolog prihrani energijo in zmanjša izdelovalne stroške.

Sodoben način napovedi velikosti rezalnih sil je model analitičnega simuliranja. Program je pomoč, ki omogoča napovedati potek dogodkov med obdelavo na osnovi nastavitev tehnoloških parametrov, orodja, obdelovanca in stroja.

Sodobni obdelovalni stroji imajo močno računalniško podporo s programom za “visoko podajanje”, kar omogoča obdelavo s konstantno rezalno silo in nespremenljiv prostorninski odvzem [6]. V tem primeru so dinamični učinki manjši, odrezovalni postopek pa je stabilnejši.

Če upoštevamo vse povzetke o rezalnih silah, so rezultati naslednji: manjša obraba rezalnega robu, boljša hrapavost obdelane površine, večja natančnost in gospodarnejša proizvodnja.

tice, it causes failure on a dimension of the product, as a result, we have to reduce the feed rate.

8 CONCLUSION

With a little knowledge of the cutting forces we can expect worse machining with tool breakages and higher production costs. Conventional machining is stil based on a technological data bank, where cutting forces are provided for various machining materials, machining proceses, cutting tools, etc. By tehnological preparation the enginer has to choose and find the best process with regards to the thickness of the cut (h). H has to be a maximum value with regard to the all-over contour of the workpiece to the required surface roughness. In this way we make the first step in reducing the energy and the machining costs.

The modern concept is a model of analytical simulation for the prediction of the cutting forces[6]. The program is an aid enabling us to forecast the course of events during the machining process with given initial conditions such as the technological parameters, the tool, the workpiece and the machine.

Modern machine tools (HSM) with strong software and programs such as “high feed” are working on a concept of constant cutting forces regarding the constant machining volume rate [6]. In this case the dynamic effect is lower and the cutting process much more stable.

To consider all the summarized effects on the cutting forces the results are: reduced wear on the cutting edge, better workpiece-surface roughness, greater accuracy and economic productivity.

9 SIMBOLI
9 SYMBOLS

globina rezanja	a_p	mm	back engagement
širina odrezka	b	mm	nominal width of cut
lega lomilne stopnične	b_{sp}	mm	chip breaker distance
notranji premer rezanja	d	mm	inner diameter of cut
zunanje premer rezanja	D	mm	outer diameter of cut
rezultanta rezalnih sil	F	N	resultant cutting force
rezalna sila	F_c	N	cutting force
podajalna sila	F_f	N	feed force
odrivna sila	F_p	N	passive force
debelina odrezka	h	mm	nominal thickness of cut
specifična rezalna sila	k_c	MPa	specific cutting force
standardna specifična rezalna sila	$k_{c1.1}$	MPa	specific cutting force unit
standardna specifična podajalna sila	$k_{f1.1}$	MPa	specific feed force unit
standardna specifična odrivna sila	$k_{p1.1}$	MPa	specific passive force unit
vplivni eksponent rezalne sile	$1\text{-}m_c$		coeficient of cutting force
vplivni eksponent podajalne sile	$1\text{-}m_f$		coeficient of feed force
vplivni eksponent odrivne sile	$1\text{-}m_p$		coeficient of passive force
torzijski moment	Md	Nm	torque
polmer ploščice	r	mm	corner radius
podajanje	f	mm	feed
podajanje na zob	f_z	mm	feed per tooth
rezalna hitrost	v_c	m/min	cutting speed
prosti kot	α	°	clearance angle
strmina	λ	°	cutting-edge inclination
cepilni kot	γ	°	rake angle
nastavni kot	χ	°	tool cutting-edge angle
kot konice	ε	°	tool included angle
kot oprijema (frezanje)	φ_s	°	cutting motion angle (milling)
natezna trdnost	R_m	MPa	tensile strength
meja elastičnosti	R_e	MPa	yield point
podaljševanje	A_5	%	elongation
redukcija površine	Z	%	reduction of area
trdota po Vickersu (število)	HV10		Vickers hardness (number)

10 LITERATURA
10 REFERENCES

[1] König, W., K. Essel, L. Witte: Specific cutting force data for metal – cutting, *Verlag Stahleisen MBH*, Düseldorf.

[2] Dolinšek, S., J. Kopač (1992) Odrezavanje, dopolnitveno gradivo za predavanja in vaje, Fakulteta za strojništvo, Ljubljana.

[3] Milfener, M., F. Čuš (2001) Analitical model of cutting forces simulation in end milling. ICIT 2001, Slovenija.

[4] Muren, H. (1976) Odrezavanje, *Tehniška založba Slovenije*.

[5] Schultz, H. (1996) Hochgeschwindigkeitsbearbeitung, *Carl Hanser Verlag*.

[6] Kopač, J., G. .Peterlin (2001) Novi pristopi pri visokohitrostnih obdelavah na osnovi CAM, Orodjarstvo 2001.

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