

## Analiza suhega rezanja pri postopku čelnega frezanja

### Analysis of Dry Cutting in the Process of Face Milling

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*Postopek frezanja spada po standardu DIN 8580 v tretjo glavno skupino, po nadrobnejši vrstni delitvi pa v podskupino odrezovanje z orodji, katerih rezala so določene geometrične oblike. Rezilo opisuje cikloido, rez je prekinjan, debelina odrezka pa je odvisna od kota rezanja.*

*Za prakso je obvladovanje procesa odrezovanja zelo pomembno. Z uvajanjem zahtevnih obdelovalnih sistemov se je povečala zahteva po zanesljivih tehnoloških informacijah [1]. To terja seveda zanesljivo analizo razmer v coni rezanja (sistem rezilo - obdelovanec - odrezek). V tem območju se pojavljajo napetosti, trenje, temperature in deformacije. Ker je potek mehanike reza v tem področju zelo zapleten, to pomeni, da prihaja do nenehnega prepletanja različnih zakonitosti, in ni mogoče podati nobenih natančnih trditev o njihovih medsebojnih vplivih. Uporaba hladiv in maziv pri odrezovanju se mora zmanjšati zaradi ekonomskih in ekoloških vzrokov. Tudi iz tehnoloških razlogov je zaželena odpoved uporabe hladiv in maziv, ker pri prekinjanem rezu prihaja do učinkov topotnega udara in s tem nastanka mikrorazpok.*

Ključne besede: procesi odrezovanja, frezanje čelno, obdelave suhe, analize rezanja

*According to standard DIN 8580 the milling process is classified into the third main group and, according to more detailed classification, into the subgroup "cutting-off with tools" whose cutters have a certain geometrical shape. The cutter describes a cycloid, the cut is interrupted and the thickness of cutting depends on the cutting angle.*

*Control by the cutting-off process is very important for practice. With the introduction of demanding machining systems the requirement for reliable technological information [1] has been increased. This requires reliable analysis of conditions in the cutting zone (system of cutter - workpiece - chip). In this zone stresses, friction, high temperatures and deformations occur. Since the mechanics of the cut in this area are very complicated, this results in continuous intermingling of various technical laws, and so it is not possible to make any precise assumptions about their mutual influences. The use of coolants agents and lubricants during the cutting-off must be reduced for economical and ecological reasons. Also for technological reasons the abandoning of the use of coolants and lubricants is desirable, because in the case of interrupted cut, there is thermal shock and, as a result, microcracks occur.*

Keywords: cutting process, face milling, dry cutting, analysis of cutting

#### 1 VPLIV HLADIVA IN MAZIVA

Teorija obstojnosti orodja je izredno zapletena, saj je potrebno poznvanje številnih znanstvenih panog. Po standardu DIN 50320 je obraba rezila definirana kot prisilno odnašanje rezalnega materiala, ki je posledica stika rezila z odrezkom in relativnega gibanja orodja proti obdelovancu.

Hladiva in maziva naj bi:

1. zmanjševala temperaturo rezila in podaljševala čas obstojnosti,
2. preprečevala neposredni stik med rezalnim in obdelovalnim materialom, zaradi česar se pojavlja manjše topotne obremenitve.

Pri orodjih iz karbidnih trdin bo prva točka uspešna le, če bo rezilo zaščiteno pred topotnim udarom. Druga točka prinese uspeh, če pride mazivo v dotikalno cono rezila in odrezka.

Nastanek oljnega filma je pri velikih hitrostih vprašljiv, saj so vplivni časi zelo kratki.

#### 1 INFLUENCE OF COOLANT AND LUBRICANT

The theory of tool resistance to wear is very complicated, since knowledge of various scientific disciplines is necessary. The DIN 50320 standard defines the cutter wear as forced abrasion of the cutter material resulting from contact between cutter and cutting and the relative motion of the tool towards the workpiece.

Coolants and lubricants are expected:

1. to reduce heating of cutter and increase the life time,
2. to prevent direct contact between the cutter and workpiece material; in this way the thermal loadings are reduced.

In the case of tools made of metallic carbide material, point 1 is successful only if the cutter is protected against the thermal shock. Point 2 is successful, if the lubricant comes into the contact zone of cutter and cutting. The formation of oil film at high speeds is unlikely, since the reaction times are very short.

Sodobni rezalni materiali, kakršne so prevečene karbidne trdine, kermet ali rezalna keramika, dosegajo zelo dobre rezultate obdelave brez uporabe hladiva in maziva. Treba pa je prilagoditi razmere pri rezanju, tako da se zmanjša čas dotika orodja in obdelovanca. To pomeni v praksi povečanje minutne prostornine odrezkov  $Q'$ :

$$Q' = a_p f v_c \quad (1)$$

kjer pomenijo:  $a_p$  = globina rezanja v mm,  $f$  = podajalna hitrosti v mm/vrt. in  $v_c$  = rezalna hitrosti v m/min.

Za preprečitev ogrevanja stroja in obdelovanca je nujno potrebno z mesta obdelave odstraniti nastale odrezke. To se naredi z zrakom in posebnimi napravami za odstranjevanje.

## 2 POMANJKLJIVOSTI UPORABE HLADIV IN MAZIV

Uporaba hladiv in maziv pri odrezovanju se mora zmanjšati zaradi ekonomskih in ekoloških vzrokov po ustreznih predpisih. V avtomobilski industriji je npr. delež stroškov tehnike hladiv in maziv od 7,5 do 17 odstotkov stroškov obdelovanca in s tem daleč večji od deleža stroškov orodja.

Stroški odstranitve porabljenih maziv in hladiv naraščajo progresivno in postajajo vedno pomembnejši dejavnik. Trenutno so stroški nabave hladilnega olja 3 000 DEM/m<sup>3</sup> in emulzij 270 DEM/m<sup>3</sup>. Stroški odstranitve hladilnih olj so 110 DEM/m<sup>3</sup> in emulzij 280 DEM/m<sup>3</sup>. Stroški odstranitve emulzije so torej že danes večji od stroškov nabave [2].

Hladiva in maziva vplivajo v okolju na zemljo, vodo in zrak. Javnost v ZDA, Japonski, Avstraliji in Nemčiji je že vplivala na pospešeno sprejetje ustrezne zaščitne zakonodaje. V sami proizvodnji prihaja do zdravstvenih težav osebja. Predvsem z neposrednim stikom s kožo, vdihavanjem ali mikroorganizmi. V skrajnih primerih prizadevajo pljuča, kožo ali povzročajo različne oblike raka.

Tudi iz tehničkih razlogov je zaželena odpoved uporabi hladiv in maziv, predvsem pri frezanju, ker pri prekinjanem rezu prihaja do učinkov toplotnega udara in s tem nastanka mikrorazpok.

## 3 IZHODIŠČA RAZISKAV SUHEGA REZANJA

Pri suhi obdelavi se morajo funkcije hladiva in maziva, torej hlajenje, mazanje, odstranjevanje odrezkov in čiščenje, izvesti na popolnoma drugačen način [6].

Modern cutting materials such as coated metallic carbide material, cermet or cutter ceramic assure very good machining results without the use of coolant and lubricant. However, it is necessary to adapt the cutting conditions so that the time of contact between the tool and workpiece is reduced. In practice, this involves an increase in the minute volume of cuttings  $Q'$ .

where:  $a_p$  = depth of cutting in mm,  $f$  = feeding speed in mm/rev. and  $v_c$  = cutting speed in m/min.

In order to prevent heating of the machine and workpiece it is necessary to remove cuttings from the point of machining. This can be done by air-jets or by special removal devices.

## 2 DISADVANTAGES OF USE OF COOLANTS AND LUBRICANTS

The use of coolants and lubricants must be reduced for economical and ecological reasons on the basis of relevant rules and regulations. For example, in the car industry the portion of costs of the cooling agents and lubricants amounts to 7.5 to 17 percent of costs of the workpiece and is thus far higher than the portion of costs of tools.

The costs of removal of lubricants and coolants are progressively increasing and are becoming a more and more important factor. At present, the purchase price of cooling oil is 3000 DEM/m<sup>3</sup>, and the purchase price of emulsions is 270 DEM/m<sup>3</sup>. The costs of removal of cooling oil are 110 DEM/m<sup>3</sup> and 280 DEM/m<sup>3</sup> for emulsions. The costs of removal of the emulsion are today even higher than their purchase price [2].

Ecologically, the cooling agents and lubricants affect the ground, water and air. The public in the U.S.A., Japan, Australia and Germany has already influenced accelerated adoption of the relevant protective legislation. The production process itself is dangerous to the personnel's health. The particular, direct contact with skin, inhalation and microorganisms are dangerous. In extreme cases the affected persons develop lung and skin diseases or various types of cancer.

Also for technological reasons the abandoning of the use of cooling agents and lubricants is desirable, particularly in milling, because in the case of interrupted cut there is thermal shock and, as a result, microcracks occur.

## 3 ASSUMPTIONS FOR RESEARCH INTO DRY CUTTING

For dry machining the functions of cooling agents and lubricants i. e. cooling, lubrication, removal of cuttings and cleaning must be effected in a completely different way.

Zaradi pomanjkanja hlajenja prihaja do povisja temperature rezanja, notranjih napetosti v obdelovancu, merskih pogreškov in oblikovnih napak, mehčanju odrezka, lepljenju odrezka na rezilo itn. Te toplotne obremenitve lahko zmanjšamo z različnimi ukrepi: večja globina rezanja in večje podajanje na zob povzročajo manjšo toplotno zaradi trenja in s tem odvaja odrezek več toplotne. Večje rezalne hitrosti pa preprečujejo prestop toplotne na obdelovanec. Z optimalno geometrično obliko rezila se rezalna sila in s tem nastala toplotna zmanjšata [3].

S tehnologijo približane oblike se zmanjšata prostornina rezanja in nastala temperatura. Z uporabo visoko temperaturno odpornih prevlek rezil se zmanjša vpliv temperature na orodje. Pri čelnem frezanju je zaradi izjemno velikih mehanskih in toplotnih obremenitev zelo pomembno poznavanje dotikalnih razmer pri vteku in izteku rezalne ploščice.

Odločilen je prvi dotik rezila z obdelovanim materialom in s tem povezane udarne obremenitve, ki so primarno odvisne od geometrične oblike rezila in lege osi frezala glede na vstopno ravnino.

#### 4 MODEL IZRAČUNA REZALNIH SIL

Pri procesu odrezovanja vdira rezilo zaradi relativnega gibanja med obdelovancem in orodjem v material. Komponente odrezovalne sile so merjene na merilni plošči v koordinatnem sistemu ( $x, y, z$ ), prijeteno po DIN 6584.

Za praktično uporabo rezultatov je primerno iz izmerkov posameznih komponent  $F_x(\Phi)$ ,  $F_y(\Phi)$ ,  $F_z(\Phi)$  izračunati tangencialne komponente, tj. rezalno silo  $F_c(\Phi)$ , podajalno silo  $F_f(\Phi)$  in odrivno silo v smeri osi vretena  $F_p(\Phi)$ , če vzamemo, da je  $\Phi_c = \Phi$ .

Vrednosti preizkusov za katero obdelovani material so dobijene s preizkusi (S1C.4321) in izbrane vstopne  $F_f(\Phi) = F_x(\Phi) \sin \Phi - F_y(\Phi) \cos \Phi$  (3),  $F_p(\Phi) = -F_z(\Phi)$  (4).

Odrezovalna sila je tako:

$$F(\Phi) = \sqrt{F_c(\Phi)^2 + F_f(\Phi)^2 + F_p(\Phi)^2} \quad (5).$$

Natančen izračun komponent odrezovalne sile je odvisen od kota rezanja. To je izredno pomembno za poznavanje dinamičnih obremenitev stroja in računske kontrole posameznih delov stroja in vpenjalnih naprav [4].

Prva naloga je določitev kota rezanja. Zato je bil izdelan poseben podprogram KOTRE. Ko je določen začetni kot rezanja  $\Phi_1$  za prvo rezilo, ki leži med  $\Phi_1$  in  $\Phi_2$ , je mogoče določiti lego drugih rezil v ubiranju.

Lack of cooling results in an increase in cutting temperature, internal workpiece stresses, dimensional and shape defects, softening of cuttings, gluing of cuttings to cutter etc. These temperature loadings can be reduced by the following measures: greater depth of cutting and greater feeding to tooth cause less heat due to friction and the cuttings to remove more heat. Higher cutting speeds prevent heat transmission to the workpiece. With optimum cutter geometry the cutting force and, consequently, the heat created are reduced [3].

The Near-net-shape technology reduces the volume of cutting and the resulting heat. The use of high temperature resistant coatings on the cutter reduces the effect of heat on the tool. Because of the very high mechanical and thermal loadings in face milling, it is most important to be familiarized with contact condition during the run-in and run-out of cutting plate.

The first contact of cutter with material being machined and the resulting impact loadings-depending primarily on the cutter geometrical shape and position of milling cutter axis with respect to the entry plane are decisive.

#### 4 CALCULATION MODEL OF CUTTING FORCES

During the cutting-off process the cutter penetrates into the material because of relative motion between the workpiece and tool. The cutting-off force components measured on the measuring plate form the coordinate system ( $x, y, z$ ), adapted according to DIN 6584.

For practical application of the results it is appropriate to calculate tangential components from measurement of particular components  $F_x(\Phi)$ ,  $F_y(\Phi)$ ,  $F_z(\Phi)$ , the cutting force  $F_c(\Phi)$ , the feeding force  $F_f(\Phi)$  and the pushing-off force in direction of the spindle axis  $F_p(\Phi)$ , by assuming that  $\Phi_c = \Phi$ .

$$F_c(\Phi) = F_x(\Phi) \cos \Phi + F_y(\Phi) \sin \Phi \quad (2),$$

$$F_f(\Phi) = F_x(\Phi) \sin \Phi - F_y(\Phi) \cos \Phi \quad (3),$$

$$F_p(\Phi) = -F_z(\Phi) \quad (4).$$

Hence, the cutting-off force is:

Precise calculation of the cutting-off force components depends on the cutting angle. This is very important for familiarization with the dynamic loadings of the machine and computational checking of the individual parts of the machine and clamping devices [4].

First, it is necessary to determine the cutting angle. To this end, a special subprogram KOTRE has been worked out. Once the initial cutting angle  $\Phi_1$  has been determined for the first cutter lying between  $\Phi_1$  and  $\Phi_2$ , it is possible to determine the position of the other cutters in engagement.

$$\Phi_1 \leq \Phi_j - m\Phi_z - (m-1)\Phi_z, \dots, \Phi_j - \Phi_z, \Phi_j + \Phi_z, \dots, \Phi_i + (n-1)\Phi_z, \Phi_j + n\Phi_z \leq \Phi_2 \quad (6)$$

pri čemer je:

$$\Phi_z = \frac{360^\circ}{z} \quad (7)$$

kjer je  $m$  število zob pred  $\Phi_j$ , in  $n$  število zob do izstopa  $\Phi_2$ :

$$n = \frac{\Phi_2 - \Phi_1}{\Phi_z} + 1 \quad (8)$$

Celotna odrezovalna sila je:

$$F_{i_{\text{cel}}} = \sum_{j=1}^n F_i(\Phi_j) = b \sum_{j=1}^n [h(\Phi_j) k_i(h(\Phi_j))] \quad (9)$$

ali

$$F_{i_{\text{cel}}} = \sum_{j=1}^n F_i(\Phi_j) = b k_{i,1x1,1} \sum_{j=1}^n h(\Phi_j)^{1-m_i} \quad (10)$$

pri čemer je  $i = c, f, p$ .

Postopek izračuna je naslednji:

- določitev začetnega kota rezanja  $\Phi_i$ ,
- izračun ustrezne debeline odrezka  $h(\Phi_i)$ ,
- izračun komponent odrezovalne sile  $F_i(\Phi_i)$ ,
- seštevanje komponent odrezovalne sile  $F_i(\Phi_i)$ ,
- simuliranje vrtenja orodja za  $\Delta\Phi$ .

Nato se postopek ponovi, vendar z novimi začetnimi pogoji:

$$\Phi_{j,n+1} = \Phi_{j,n} + \Delta\Phi \quad (11)$$

To se ponavlja toliko časa, dokler ni izpolnjen pogoj za frezala s sodim številom rezil:

$$\Phi_{j,n+1} \geq \frac{360^\circ}{z} \quad (12)$$

in lihim številom rezil:

This is repeated until the condition for milling cutters with an even number of cutters has been fulfilled:

$$\Phi_{j,n+1} \geq 360^\circ \quad (13)$$

and with an odd number of cutters:

## 5 REZULTATI MERITEV SUHEGA REZANJA

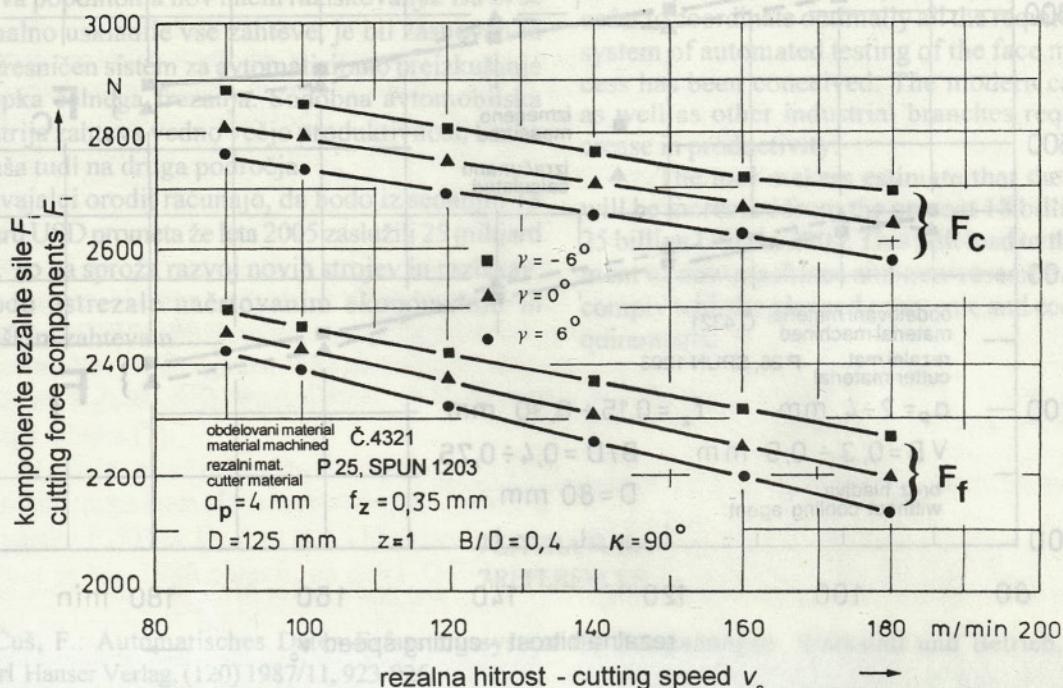
Vpliva spremenjanja rezalne hitrosti in cepilnega kota na komponente odrezovalne sile sta razvidna slike 1. Pri povečani rezalni hitrosti in povečanem cepilnem kotu se rezalni in podajalni sili zmanjšujeta. Povečanje cepilnega kota je odvisno od vrste obdelovanega materiala in postopka obdelave. Ker je frezanje postopek s prekinjanim rezom, so

## 5 RESULTS OF MEASUREMENT FOR DRY CUTTING

The influence of variation of the cutting speed and true rake angle on the cutting-off force components is shown in Figure 1. With increased cutting speed and increased true rake angle the cutting and feeding forces are decreased. The increase of the true rake angle depends on the type of the material machined and on the machining process. As milling is a process with interrupted cut, the cutter loadings

obremenitve rezila zelo velike. Pri grobi obdelavi se zaradi stabilnosti konice rezila najpogosteje reže z negativnim cepilnim kotom. Obdelovanec se bistveno ni bolj zagrel, obraba orodja je bila normalna.

are very great. In the case of rough machining cutting is most frequently effected by the negative true rake angle because it provides cutter tip stability. The workpiece was not considerably more heated, and tool wear was normal.



Sl.1. Vpliv rezalne hitrosti  $v_c$  in cepilnega kota  $\gamma$  na rezalno silo  $F_c$  in podajalno silo  $F_f$   
Fig. 1. Influence of cutting speed  $v_c$  and true rake angle  $\gamma$  on cutting force  $F_c$  and feeding force  $F_f$

V zadnjih dvajsetih letih ponujajo raziskovalci različne enačbe, v katerih skušajo zajeti čimveč posameznih vplivov. Doslej jim še ni uspelo postaviti splošne enačbe, ki bi pri posameznih postopkih odrezovanja zajela vse vplivne veličine. V naših raziskavah postopka čelnega frezanja smo se omejili na enačbo s petimi vplivnimi veličinami [5].

Vrednosti preizkusov za kombinacijo rezalni in obdelovani material so dobljene s preizkusi. Za material Č.4321 in izbrane vstopne veličine ima enačba obliko (14). S slike 2 so razvidni odstopki izračunanih vrednosti od izmerjenih komponent odrezovalne sile.

$$F_c = 1,4 \cdot 10^{13} \cdot v_c^{-5,7} \cdot f_z^{-2,6} \cdot VB^{-3,8} \cdot a_p^{-3,3} \cdot (B/D)^{-5,1} \quad (14)$$

kjer pomenijo:  $v_c$  - rezalna hitrost v m/min,  $f_z$  - podajanje na zob v mm/zob,  $VB$  - širina obrabe na prosti ploskvi v mm,  $a_p$  - globina rezanja v mm,  $B$  - širina ubiranja v mm,  $D$  - premer frezala v mm

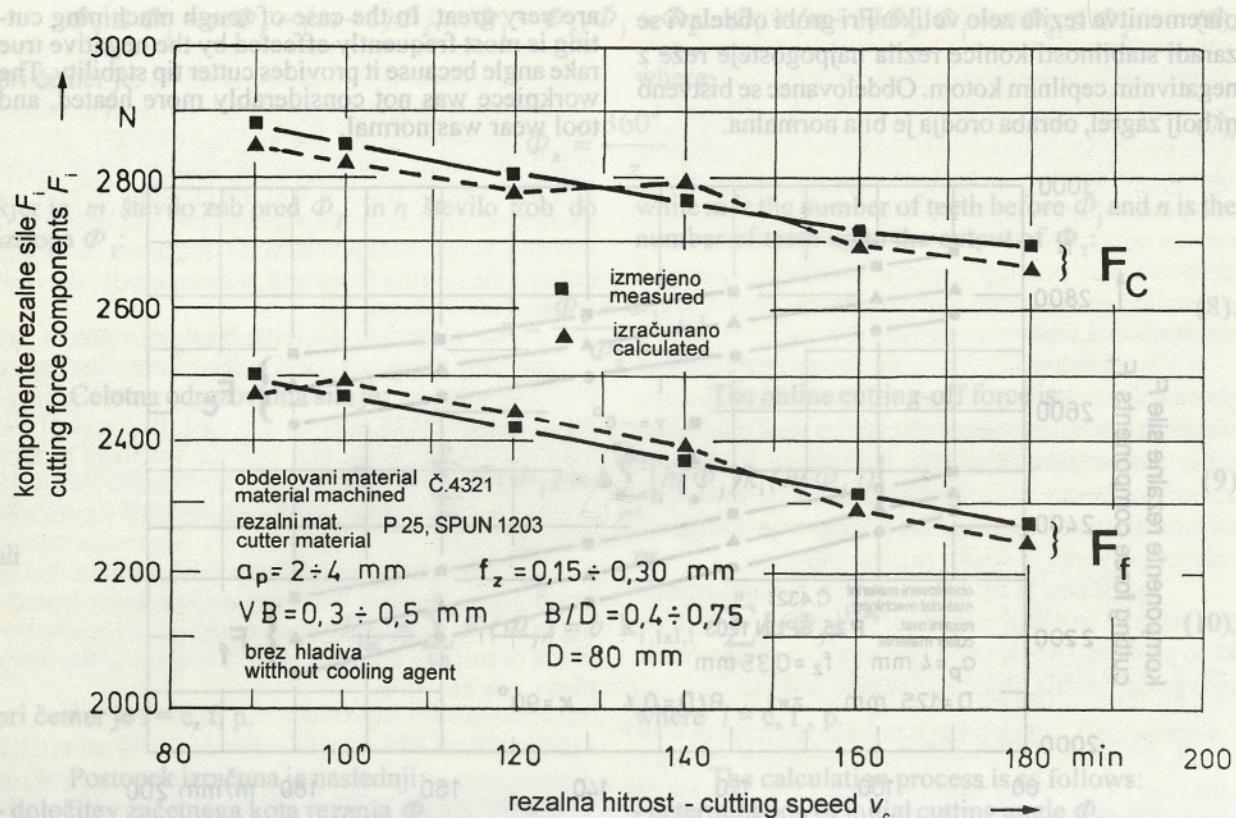
Vse vrednosti so izračunane z regresijsko analizo in veljajo za širše območje glavnih spremenljivk. Iz raziskav je mogoče ugotoviti, da so vrednosti specifičnih rezalnih sil pri manjši debelini odrezka za približno 25 do 30 odstotkov večje od vrednosti, dobljenih po enačbi. Pri debelini odrezka 1 mm je največji odstopek komaj 5 odstotkov.

In the past twenty years researchers have offered various equations in which they tried to include as many individual influences as possible. So far however, they have not managed to establish an universal equation which would include all influencing variables for individual cutting-off processes. In our research into the face milling process we limited ourselves to an equation with five influencing variables [5].

Experimental values for the combination of cutting and workpiece materials are obtained by tests. For material Č. 4321 and selected input variables the equation has the form (14). Figure 2 shows deviations of calculated values from measured components of the cutting force.

where:  $v_c$  - cutting speed in m/min,  $f_z$  - feeding into tooth in mm/tooth,  $VB$  - width of wear on free face in mm,  $a_p$  - depth of cutting in mm,  $B$  - width of engagement in mm,  $D$  - milling cutter diameter in mm.

All values are calculated by regression analysis, and apply for a wide range of main variables. From research it is possible to establish that in the case of cuttings of small thickness the values of the specific cutting forces are approximately 25 to 30 percent higher than the values obtained according to the equation. With cuttings, 1 mm thick, the greatest deviation is as low as 5 percent.



Sl. 2. Odstopanje izračunanih od izmerjenih komponent odrezovalne sile  
Fig. 2. Deviation of calculated cutting-off force components from measured ones

## 6 SKLEP

Povečanje produktivnosti terja poleg organizacijskih ukrepov še zavzetost vseh proizvodno-tehničnih kadrov za popolno aktiviranje razpoložljivih zalog izdelovalnih sredstev.

Na področju sodobne tehnike obdelave opažamo dve pomembni usmeritvi. Po eni strani se skuša doseči povečanje prožnosti v proizvodnji. To ima za posledico zelo produktivne, prilagodljive obdelovalne centre s skrajno velikimi rezalnimi hitrostmi. Po drugi strani se pospešeno uveljavljajo suho rezanje ali pa sistemi z minimalnim hlajenjem in mazanjem. Tem ciljem sledi sodobni razvoj rezalnih materialov. Predvsem se uveljavljajo tanki sloji umetnih diamantov, silicijevega nitrida ali silicijevega karbida, kubičnega borovega nitrida, kermeta itn.

Z uvajanjem vse zahtevnejših obdelovalnih sistemov in rezalnih materialov se je povečala tudi potreba po bolj zanesljivih tehnoških informacijah. To terja temeljito analizo razmer v coni rezanja (sistem rezilo - obdelovanec - odrezek). V tem območju se pojavljajo napetosti, trenje, toplota in deformacije.

## 6 CONCLUSION

In addition to organizational measures the increase of productivity requires also engagement of all production-technical staff for complete activation of available manufacturing facilities.

In the area of modern machining technology there are two trends. On the one hand, there is a tendency towards an increase of flexibility in production resulting in highly productive flexible machining centers with very high cutting speeds. On the other hand, dry cutting or systems with minimum cooling and lubrication are being introduced at an accelerated rate. These processes are accompanied by modern development of cutting materials. In particular, thin layers of synthetic diamonds, silicon nitride or silicon carbide, cubic boron nitride, cermet etc. are being introduced.

With the introduction of demanding machining systems and cutting materials the need for more reliable technological information has increased. This requires thorough analysis of conditions in the cutting zone (system of cutter-workpiece-cuttings). It is in this zone that the stresses, friction, heat and deformations occur.

Za izhodiščno veličino pri procesu suhega rezanja je definiran funkcionalno dober obdelovanec ob obvladovanju odrezovalne sile in obrabe v odvisnosti od vstopnih veličin in struktur sistema. To zahteva popolnoma nov način raziskovanja. Da bi se optimalno uskladile vse zahteve, je bil zasnovan in tudi uresničen sistem za avtomatizirano preizkušanje postopka čelnega frezanja. Sodobna avtomobilска industrija zahteva vedno večjo produktivnost, kar se prenaša tudi na druga področja.

Proizvajalci orodij računajo, da bodo iz sedanjih 18 milijard USD prometa že leta 2005 zaslužili 25 milijard USD. To pa sproža razvoj novih strojev in raziskav, ki bodo ustrezale načrtovanim ekonomskim in ekološkim zahtevam.

The starting variable in the dry cutting process is a well-defined functionally good workpiece, combined with the control of the cutting force and wear depending on input variables and system structures. This requires a completely new type of research. In order to coordinate optimally all the requirements, the system of automated testing of the face milling process has been conceived. The modern car industry as well as other industrial branches require an increase in productivity.

The tool makers estimate that their turnover will be increased from the present 18 billion USD to 25 billion USD in 2005. This will lead to the development of new machines and new research which will comply with the planned economic and ecological requirements.

vsakega učinka [7].

Mnenje o učinkovitosti delcev PTFE je razpršenih v mazahem olju, sta objavila tri raziskovalci: prvega PTFE-ja: DuPont in ICI Fluoropolymers, ki sta leta 1980 objavili, da gleci s tehnologijo, po

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