© Strojniški vestnik 47(2001)1,45-52
ISSN 0039-2480
UDK 621.9:621.9.025.7:536.5
Predhodna objava (1.03)

© Journal of Mechanical Engineering 47(2001)1,45-52
ISSN 0039-2480
UDC 621.9:621.9.025.7:536.5
Preliminary paper (1.03)

Analiza temperatur in toplotne energije pri odrezavanju

An Analysis of Temperatures and Thermal Energy during Cutting

Matjaž Milfelner - Franci Čuš

V predstavljenem prispevku je opisana analiza temperatur in energij, ki se pojavijo med postopkom odrezavanja. Vpliv temperature na rezalno ploskev in rob rezalne ploščice je zelo pomemben, ker povzroči obrabo cepilne ploskve in rezalnega roba orodja, s tem pa se zmanjša obstojnost orodja. V zadnjem delu prispevka je prikazan primer simuliranja porazdelitve temperature na rezalnem robu orodja pri spremembi rezalne hitrosti in geometrije orodja.

(Ključne besede: temperature, energije toplotne, ploskve strižne, ploskve cepilne)

This paper describes an analysis of the temperatures and energies which occur during the cutting process. The influence of the temperature on the cutting face and the cutting insert edge is very important since it causes wear of the tool face and of the tool cutting edge and thus the tool's resistance to wear is reduced. The final part of the paper shows an example of a simulation of the isothermal lines on the tool cutting edge for the case of a change of cutting speed and a change of the tool geometry.

(Keywords: temperature, thermal energy, shear plane, tool face)

0 UVOD

Pri obdelavi materiala z odrezavanjem je pomembnih več temperatur. Med te temperature prištevamo temperaturo v strižni ravnini θ_S, ki vpliva na potek napetosti v strižni ravnini in temperaturi na cepilni ploskvi θ_T in prosti ploskvi θ_R rezalne ploščice. Temperatura na cepilni ploskvi θ_T povzroča obrabo na cepilni ploskvi v obliki kotanje, temperatura na prosti ploskvi θ_R pa obrabo proste ploskve.

1 TOPLOTNE RAZMERE PRI ODREZAVANJU

Pri procesu odrezavanja oziroma tvorbi odrezka nastala mehanska energija se spreminja v toplotno energijo. Vir toplote pri odrezavanju z ostrim rezalnim robom rezalne ploščice razdelimo v dve področji: (slika 1a)

- prvo z virom v strižni ravnini (1) in
- drugo z virom na cepilni ploskvi (2).

Po prvih ugotovitvah o spremembah energije pri procesu odrezavanja lahko predpostavimo da: [1] (slika 1b)

0 INTRODUCTION

During machining several temperatures are important: the temperature in the shear plane θ_S, which influences the distribution of stresses in the shear plane; the temperature on the tool face θ_T; and the temperature on the free face θ_R of the cutting insert. The temperature on the tool face θ_T causes wear on the tool face in the form of a crater, whereas the temperature on the free face θ_R causes wear of the free face.

1 THERMAL CONDITIONS DURING CUTTING

The mechanical energy produced during the cutting process and/or chip formation is transformed into thermal energy. The heat source during cutting with the sharp cutting edge of a cutting insert comprises two areas: (Figure 1a)

- the area with the source in the shear plane (1);
- the area with the source on the tool face (2).

On the basis of the first findings about the transformation of energy during the cutting process it is possible to assume that: [1] (Figure 1b)

- se vsa energija, ki nastane v točki (1 – strižna ravnina) in (2 – cepilna ploskev) spremeni v toplotno energijo,
- energija iz točke 1 in 2 se usmeri na cepilno in prosto ploskev in
- energija je v točkah 1 in 2 enakomerno porazdeljena.

Tudi z uporabo teh predpostavk je določitev glavnih temperatur, to je temperature na cepilni in prosti ploskvi rezalne ploščice, zelo zahtevna. To je predvsem zato, ker se del energije iz točke 1 odvede v odrezek vzdolž cepilne ploskve, drugi del pa v proces. Prav tako se en del energije iz točke 2 odvede v odrezek, drugi del pa v orodje.

Zaradi tega določimo dva razdelitvena koeficienta R_1 in R_2:

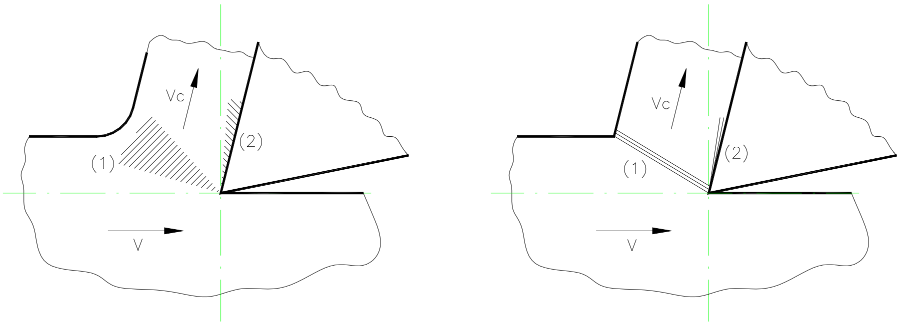
- koeficient R_1 je del energije iz strižne ravnine – točka 1, ki gre v odrezek,
- koeficient R_2 pa je del energije na cepilni ploskvi – točka 2, ki gre v odrezek.

- all energy occurring at points 1 (shear plane) and 2 (tool face) is transformed into thermal energy;
- the energy from points 1 and 2 is directed onto the tool face and the free face;
- the energy at points 1 and 2 is uniformly distributed.

Even with these assumptions the determination of the main temperatures, i. e. the temperatures on the tool face and on the free face of the cutting insert, is very demanding because some of the energy from point 1 moves to the chip along the tool face and the rest to the process. Also a part of the energy from (2) is conveyed to the chip and the other to the tool.

As a result, two partition coefficients, R_1 and R_2, need to be defined:

- coefficient R_1 is the fraction of the energy from the shear plane - point 1 - which goes to the chip;
- coefficient R_2 is the fraction of the energy on the tool face - point 2 - going to the chip.



(a) (b)

Sl. 1. *Toplotne razmere pri pravokotnem odrezavanju*
Fig. 1 *Thermal conditions during orthogonal cutting*

Četrta predpostavka pri analizi postopka odrezavanja je, da se toplotna energija, ki nastane pri nastanku odrezka, ne izgublja v okolico. To pomeni, da je energija na enoto prostornine, ki preide v odrezek v strižni ravnini (1) enaka:

The fourth assumption in the analysis of the cutting process is that the thermal energy generated during chip formation is not lost to the environment. This means that the energy per unit volume going to the chip in the shear plane (point 1) is equal to:

$$U_{C1} = R_1 \cdot u_S \tag{1}$$

in energija na enoto prostornine, ki preide v odrezek na cepilni ploskvi (2) enaka:

and that the energy per unit volume going to the chip on the tool face (point 2) is equal to:

$$U_{C2} = R_2 \cdot u_F \qquad (2),$$

pri čemer sta u_S in u_F specifični energiji pri strigu in trenju.

where u_S and u_F are specific energies in the shear and the friction.

2 ANALIZA TEMPERATUR IN TOPLOTE

Z uporabo dimenzijske analize lahko določimo temperature pri procesu odrezavanja za praktično uporabo. Prvi, ki je uporabil dimenzijsko analizo za rešitev problema temperature na cepilni

2 AN ANALYSIS OF TEMPERATURE AND HEAT

By means of dimensional analysis it is possible to determine the temperatures in the cutting process for a practical application. Kronenberg [2] was the first to apply dimensional analysis to solve ploskvi rezalne ploščice, je bil Kronenberg [2]. Na podlagi svojega širokega znanja in izkušenj je utemeljil, da velikost povprečne temperature na cepilni ploskvi rezalne ploščice θ_T lahko opišemo z enačbo, če vanjo vključimo spremenljivke, zapisane v preglednici 1.

the problem of the temperature on the tool face of the cutting insert. On the basis of his knowledge and experience he postulated that the mean temperature on the tool face of the cutting insert θ_T can be described by an equation which use the quantities listed in table 1.

Preglednica 1. *Kronenbergove veličine za dimenzijsko analizo*
Table 1. *Kronenberg's quantities for dimensional analysis*

Veličina Quantity	Simbol Symbol	Enota Unit
povprečna temperatura na cepilni ploskvi mean tool-face temperature	θ_T	K
rezalna hitrost cutting speed	V	m/min
nedeformirani prerez odrezka undeformed-chip area	A	mm^2
specifična rezalna sila specific cutting energy	k_c	MPa
toplotna prevodnost thermal conductivity	k	W/mK
specifična prostorninska toplota volume specific heat	ρC	$\mathrm{J/m^3K}$

V preglednici 1 imamo štiri dimenzijsko neodvisne veličine V, k_c, k in ρC. Te štiri dimenzijsko neodvisne veličine lahko povežemo v enačbo v kombinaciji z eno od preostalih dveh nedimenzijskih veličin θ_T in A. Ti dve veličini sta dobljeni na podlagi načela o dimenzijski homogenosti. Iz te dimenzijske enačbe dobimo enačbo za povprečno temperaturo na cepilni ploskvi orodja:

Table 1 lists four dimensionally independent quantities i. e. V, k_c, k and ρC. They can be combined in an equation with one of the other two non-dimensional quantities θ_T and A. These two quantities are obtained on the basis of the principle of dimensional homogeneity. From this dimensional equation the equation for the mean temperature on the tool face is obtained:

$$\frac{\theta_T\cdot(\rho\cdot C)}{k_c}=f\left(\frac{A\cdot V^2\cdot(\rho\cdot C)^2}{k^2}\right) \qquad (3).$$

Vrednosti za vse te veličine dobimo pri Gottwein-u [3]. Razmerje med obema stranema enačbe je prikazano v diagramu na sliki 2. Os X predstavlja desni del enačbe, os Y pa levi del enačbe. Če je dimenzijska analiza pravilna, potem je krivulja v diagramu premica. Enačbo (3) izboljšamo tako, da veličino $A=b\cdot t$ - nedeformiran prerez odrezka nadomestimo s t - nedeformirano debelino odrezka, ker ima b - nedeformirana širina odrezka zanemarljiv vpliv na θ_T, medtem ko ima t zelo velik vpliv.

Naslednja izboljšava je v tem, da upoštevamo količnik $k/\rho C$ kot eno spremenljivko namesto dveh posameznih spremenljivk k in ρC. Vse ostale Kronenbergove spremenljivke so bile dobro izbrane.

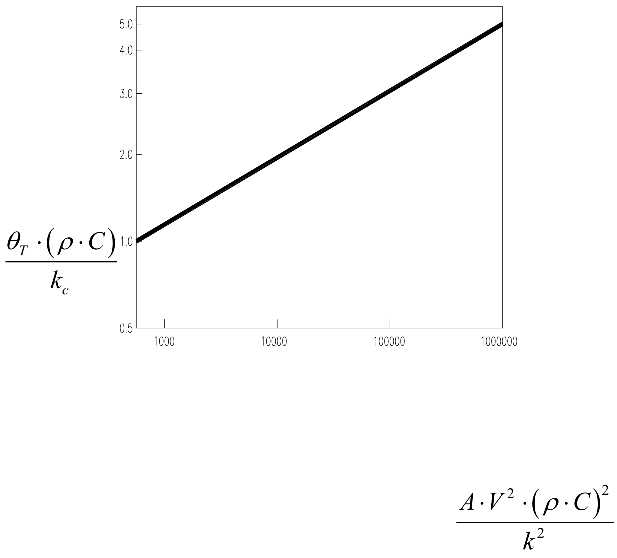
V preglednici 2 so prikazane izboljšane veličine, ki vodijo do enojne nedimenzijske veličine in iz tega izhaja, da je povprečna temperatura na cepilni ploskvi rezalne ploščice:

The data on all these quantities are available from Gottwein [3]. The relation between both sides of the equation is shown in the diagram in figure 2. The X-axis represents the right-hand side of the equation and the Y-axis represents the left-hand side of the equation. If the dimensional analysis is correct, the curve in the diagram is a straight line. Equation 3 is improved by replacing $A=b\cdot t$ of the undeformed chip area, by t, the undeformed chip thickness, because the undeformed chip width b has a negligible influence on θ_T, whereas t has an appreciable influence.

The situation is further improved by considering the quotient $k/\rho C$ rather than the individual quantities k and ρC. All the other Kronenberg variables were correctly selected.

Table 2 shows the improved quantities leading to a single non-dimensional quantity and using this we can calculate that the mean temperature on the tool face of the cutting insert:

$$\theta_T \approx u\cdot\left[\frac{V\cdot t}{k/\rho\cdot C}\right]^{\frac{1}{2}} \qquad (4).$$



Sl. 2. *Gottweinov diagram*
Fig. 2. *Gottwein's diagram*

Preglednica 2. *Izboljšane Kronenbergove veličine za dimenzijsko analizo*
Table 2. *Improved Kronenberg quantities for the dimensional analysis*

Veličina Quantity	Simbol Symbol	Enota Unit
povprečna temperatura na cepilni ploskvi mean tool-face temperature	θ_T	K
rezalna hitrost cutting speed	V	m/min
nedeformirana debelina odrezka undeformed chip area	t	mm
specifična rezalna hitrost specific cutting energy	u	J
temperaturna difuzivnost temperature diffusivity	$k/\rho C$	m^2/s

Na prvi pogled enačba (4) prikazuje, da sta V in t enako pomembna glede na θ_T. To lahko prikažemo z drugo enačbo, v kateri določimo temperaturo v odvisnosti od rezalne hitrosti V in nedeformirane debeline odrezka t iz eksperimentalnih vrednosti:

At first glance equation 4 suggests that V and t are equally important with respect to θ_T. However, θ_T can be represented by another equation in which the temperature is determined in terms of the cutting speed V and the undeformed chip thickness t from experimental values:

$$\theta_T \approx V^{0,5} \cdot t^{0,3} \qquad (5).$$

Povprečno temperaturo v strižni ravnini določimo na temelju privzetega modela, ki sloni na Piispanenovem modelu nastanka odrezka. Pri procesu nastanka odrezka se lastnosti v strižni ravnini spreminjajo, zato lahko strižno ravnino opišemo kot gibljivi toplotni vir. Povprečno temperaturo v strižni ravnini določimo z enačbo [4]:

The mean temperature in the shear plane is determined on the basis of the adopted model based on Piispanen's model of chip formation. During the process of chip formation the properties in the shear plane change, so the shear plane can be described as a mobile heat source. The mean temperature in the shear plane is determined by equation [4]:

$$\theta_S = 0,754 \cdot R_1 \cdot u_S \cdot \sqrt{\frac{V \cdot t/\gamma}{(k/\rho \cdot C)}} + \theta_0 \qquad (6),$$

pri čemer so: V - rezalna hitrost, t - nedeformirana debelina odrezka, γ - strižna deformacija, ρC -

where V is the cutting speed, t is the undeformed chip thickness, γ is the shear deformation, ρC is the specifična prostorninska toplota in k - toplotna prevodnost. Koeficient R_1 določimo iz enačbe:

specific volume heat and k is the heat conductivity. The coefficient R_1 is determined from the equation:

$$R_1 = \frac{1}{1+1,328\sqrt{\left[\frac{k_1 \cdot \gamma}{V \cdot t}\right]}} \tag{7}$$

Specifično strižno energijo u_S izračunamo po enačbi [5]:

The specific shear energy u_S is calculated according to equation [5]:

$$u_S = \frac{F_S \cdot V_S}{V \cdot t \cdot b \cdot \csc(\Phi) \cdot \sin(\Phi)} \tag{8}$$

V enačbi (8) je F_S - sila vzdolž strižne ravnine, V_S - strižna hitrost, b - nedeformirana širina odrezka in Φ - strižni kot.

Enačbo za povprečno temperaturo v strižni ravnini lahko zapišemo tudi v obliki:

where F_S is the force along the shear plane, V_S is the shear speed, b is the undeformed chip width and Φ is the shear angle.

The equation for the mean temperature in the shear plane can also be written as follows:

$$\theta_S \cong 0,754 \cdot u_S \cdot \sqrt{\frac{V_S \cdot l_S}{(k/\rho \cdot C)}} + \theta_0 \tag{9}$$

Dolžina strižne cone $l_S = t/\sin(\Phi)$.
Razlika temperature v strižni coni $\Delta\theta_S$ je:

The shear plane length $l_S = t/\sin(\Phi)$.
The difference in the temperature in the shear plane $\Delta\theta_S$ is:

$$\Delta\theta_S \cong u_S \cdot \sqrt{\frac{V_S \cdot l_S}{(k/\rho \cdot C)}} \tag{10}$$

Povprečno zvišanje temperature na površini odrezka zaradi trenja določimo po enačbi:

The mean temperature increase on the chip surface due to friction is determined according to the equation:

$$\Delta\theta_F \cong u_F \cdot \sqrt{\frac{V_C \cdot a}{(k/\rho \cdot C)}} \tag{11}$$

kjer je a dolžina stika med orodjem in odrezkom. Specifično energijo trenja u_F odrezka ob cepilno ploskev izračunamo po enačbi (6):

where a is the length of the contact between the tool and the chip. The specific energy of friction u_F of the chip against the tool face is calculated according to equation (6):

$$u_F = \frac{F_C \cdot V_C}{V \cdot t \cdot b} \tag{12}$$

pri čemer sta F_C - strižna sila in V_C - hitrost odrezka.

Povprečno zvišanje temperature na cepilni ploskvi je vsota temperature v strižni ravnini in temperature zaradi trenja:

Where F_C is the shear force and V_C is the chip speed.

The mean temperature increase on the tool face is the sum of temperature in the shear plane and the temperature due to friction:

$$\Delta\theta_T \cong \theta_S + \Delta\theta_F \tag{13}$$

Prav tako je specifična rezalna energija vsota specifične strižne energije in specifične energije trenja:

In addition, the specific cutting energy is the sum of the specific shear energy and specific energy of friction:

$$u \cong u_S + u_F \tag{14}$$

Na koncu lahko iz rezultata dimenzijske analize definiramo, da je povprečna temperatura na cepilni ploskvi:

In the end it is possible to define, on the basis of the result of the dimensional analysis, the mean temperature on the tool face to be:

$$\theta_T \cong u \cdot \sqrt{\left[\frac{V \cdot T}{k/\rho \cdot C}\right]} + \theta_0 \tag{15}$$

3 PRIKAZ TEMPERATURE NA REZALNEM ROBU

V prikazanem primeru je predstavljen potek temperature na konici rezalne ploščice [7]. Simuliranje je izvedeno na podlagi metode končnih elementov in prikazuje izotermo porazdelitev temperature na rezalnem robu, odrezku in obdelovancu.

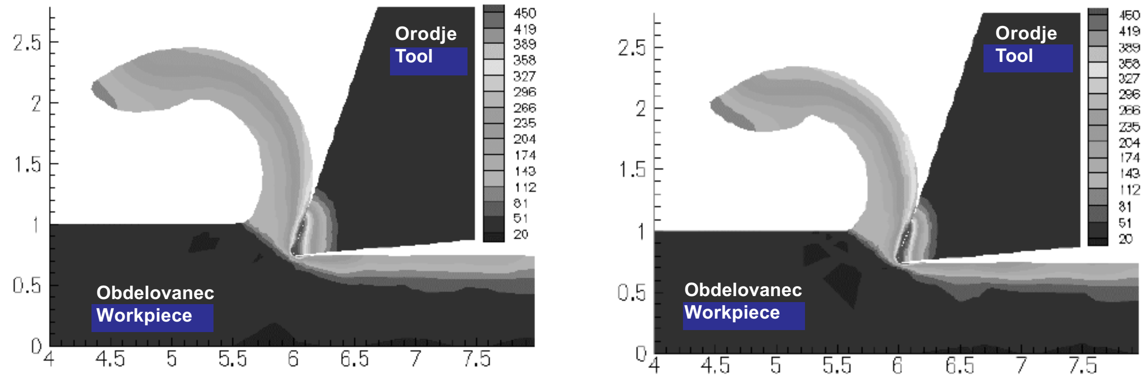
Prvi primer prikazuje porazdelitev temperature pri spremembi rezalne hitrosti. Parametri odrezavanja so prikazani v naslednji preglednici:

3 REPRESENTATION OF TEMPERATURE ON THE CUTTING EDGE

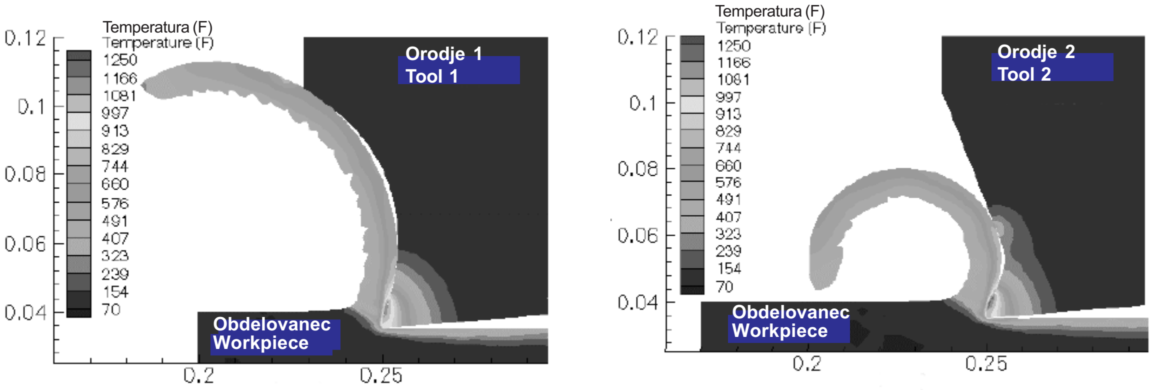
The example shows the areas of temperature on the cutting insert tip [7]. The simulation is made on the basis of the finite element method (FEM) and shows the isothermal lines of temperature on the cutting edge, chip and workpiece.

The first example shows the isothermal lines of temperature for the case of a change of cutting speed. The cutting parameters are shown in the following table:

rezalna hitrost cutting speed	914, 1220	m/min
rezalna sila cutting force	935, 956	N
podajanje feed	0,254	mm/vrt
globina reza depth of cut	6,35	mm
cepilni kot rake angle	20	°
radij rezalnega roba cutting-edge radius	0,025	mm
material orodja tool-insert material	karbidna trdina tungsten carbide	
material obdelovanca workpiece material	AL6061-T6	



Sl. 3. *Sprememba temperature pri različnih rezalnih hitrostih*
Fig. 3 *Change of temperature for the case of different cutting speeds*



Sl. 4. *Sprememba temperature pri različni obliki rezalnega roba*
Fig. 4. *Change of temperature for the case of a different cutting-edge shape*

V drugem primeru je prikazana porazdelitev temperature pri spremembi oblike rezalnega roba in cepilnega kota [8]. Parametri so:

The second example shows the isothermal lines of temperature for the case of a change of shape of the cutting edge and rake angle [8]. The parameters are:

rezalna hitrost cutting speed	144	m/min
podajanje feed	0,12	mm
globina reza depth of cut	2	mm/vrt
cepilni kot rake angle	15, 20	°
radij rezalnega roba cutting-edge radius	0,025	mm
material orodja tool-insert material	tungsten carbide	
material obdelovanca workpiece material	X5CrNiMo17122	

4 SKLEP

V današnjem času se je z uvajanjem novih obdelovalnih sistemov povečala potreba po vse boljšem rezalnem materialu in natančnih informacijah o postopkih obdelave in parametrih, ki vplivajo na proces odrezavanja [9]. Za določitev parametrov, ki vplivajo na proces pri odrezavanju, uporabimo programe za analizo in simuliranje. Glede na opravljeno simuliranje in raziskave smo ugotovili in priporočamo za obdelavo materiala AL6061-T6 orodje iz karbidne trdine in delo z naslednjimi tehnološkimi parametri: rezalna hitrost Vc = 1220 m/min, podajanje f = 0,254 mm/vrt in globina rezanja a_p = 6,35 mm. Razlika temperature je pri povečanju hitrosti od 914 do 1220 m/min približno 20°C. Za struženje jekla X5CrNiMo17122 pa priporočamo rezalno orodje iz karbidne trdine (M20-M30 GC2025) in geometrijo rezalne ploščice γ = 15° in r = 0,025 mm ter naslednje tehnološke parametre odrezavanja: rezalna hitrost Vc = 144 m/min, podajanje f = 0,12 mm/vrt in globina rezanja a_p = 2 mm. S takim prijemom bomo dosegli najboljše rezultate odrezavanja.

4 CONCLUSION

The introduction of new manufacturing systems means there is a need for better cutting materials as well as accurate information on the machining process and the parameters influencing the cutting process [9]. Programs for the analyses and for the simulation were used to determine of the parameters which influence the cutting process. The results of the simulation and experiments reported here support the following conclusions. For machining of the material AL6061-T6 we recommend a tungsten-carbide cutting insert with the following cutting conditions: cutting speed Vc = 1220 m/min, feed f = 0,254 mm/rev and depth of cut a_p = 6,35 mm. The example shows that in the case of an increase in speed from 914 to 1220 m/min the temperature increases by about 20°C. The recommended cutting conditions and geometry of the cutting insert for machining the material X5CrNiMo17122 with a tungsten-carbide cutting insert (M20-M30 GC2025) are: rake angle γ=15°, cutting-edge radius r = 0,025 mm, cutting speed Vc = 144 m/min, feed f = 0,12 mm/rev and depth of cut a_p = 2 mm. Using this approach the best cutting results can be obtained.

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5 REFERENCES

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Naslov avtorjev: Matjaž Milfelner
prof.dr. Franci Čuš
Inštitut za proizvodno strojništvo
Fakulteta za strojništvo
Univerza v Mariboru
Smetanova 17
2000 Maribor

Authors' Address: Matjaž Milfelner
Prof. Dr. Franci Čuš
Production Engineering Institute
Faculty of Mechanical Eng.
University of Maribor
Smetanova 17
2000 Maribor, Slovenia

Prejeto:
Received: 15.9.2000

Sprejeto:
Accepted: 12.4.2001