RESEARCH INTO HIGH SPEED, DRY AND HARD MILLING OPERATIONS

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Key words: HSC, HSM, High-Strength and Super-Hard Metal Materials, Cutting Forces, Chip Morphology, Optimization

1. Introduction

At present, high speed cutting (HSC) is already widely used especially in machining of low-melting-point materials e.g. aluminium, copper and their alloys. Its application in machining of materials with higher mechanical properties is still at the beginning because of many difficulties and complications (in terms of tools and their tool lives, optimization of cutting conditions, resultant accuracy, efficiency etc.). It is assumed that deeper understanding of rules and phenomena related to HSC will help to overcome the difficulties and expand this technology also within materials with higher mechanical properties. High-quality steels with higher mechanical properties are undoubtedly most commonly used materials in a dies and moulds production. The machining of high-strength and super-hard steels mostly appears in production of shape-sophisticated dies and moulds, where high-quality tool steels are applied. This production of sophisticated surfaces also calls for other high requirements e.g. time consumption, dimensional and shape accuracy, high standard tools etc. Consequently, they stand for huge expenses and lower productivity. Therefore, HSC appears to be very suitable for application in the production of dies and moulds, because it brings not only advantage of time-shortened machining, but also an increase in machining accuracy and quality of the workpiece surface. As a result, the research in this field is a very up-to-date issue and extended knowledge will enable progressive application into the production. According to the circumstances stated above, the least explored field of the HSC technology is the machining of high-strength and super-hard steels.

Advances in cutting tool materials, coating techniques, tool machines and the needs develop new processes and production techniques resulted in the spread of high speed milling (HSM) technology. The most significant of these is in the die and mould industry, where difficult-to-cut materials are mainly used as a workpiece. The benefits for the manufacture of generally hardened steel components are substantial in the terms of reduced machining cost and lead times, in comparison to the more traditional route which involves machining in annealed state, heat treatment, electrical discharge machining (EDM) and manual polishing. High speed milling is generally associated with end milling at high rotation speeds up to 100 000 rev./min., which could be misleading. There is a great influence of the workpiece material and its hardness (higher rotation speeds and feed rates are used for aluminium alloys then for steel alloys). Such high speeds are only used with the ball end cutters of small diameters (<10 mm), therefore the real cutting speeds are not so high and the real diameter is about few millimetres. In the recent years, HSM technologies were used not only when end milling, but semi-finishing and even roughing. The work presented here, investigate the possibility of HSM use as an advantage in machining hardened tool steels. Especially, deals with looking for the most suitable cutting conditions as are cutting speed, feed and axial-radial depth of cut to reach the best tool performance in dependence on tool and workpiece material.

2. Effect of Selected Process Parameters on Cutting Forces Magnitudes in HSM

The cutting speed together with the kind of material, in terms of process parameters, has the most important influence on component forces in HSM. In contrast to the conventional way, the effect of cutting speed on component forces has a principal and fundamental character. An increase of cutting speed causes thermal softening actions in the material being cut. These actions decrease the material cutting resistance and thus cause a massive fall of cutting force. In HSC, more then in the conventional way, the fall of cutting force due to the cutting speed depends upon the material to be cut. Let us think of two fundamental kinds of material: Shapeable (plastic, cohesive chip, e.g. steel, Al alloys) and brittle (tear type chip, e.g. cast iron). Only shapeable materials enable the drop of cutting force with an increasing cutting speed (thermal softening actions are possible), whereas the drop within brittle materials is slight because of an increase in the cutting resistance against reshaping (another drop of plasticity).

In 1974 Liemert published the following theory. When the cutting speed enormously raises, the magnitudes of component cutting forces drop and asymptotically approach a specific constant value. But an experimental measurement, carried out by Schulz [3], [4] (1990-2001), disproves such assumptions and illustrates, that the cutting force, after reaching its minimum, boosts gradually again up to the values obtained at conventional cutting speeds. The reasons for such a growth of cutting force can be described according to Fig. 1. A resultant cutting force F in HSC consists of a shear force F_s, needed to cut material off, and a dynamic force F_m (momentum force), needed to give a chip of specific weight an outgoing speed v_{CH} (equation 1). As the F_s-component slightly raises from a specific "conventional" value and on reaching the cutting speed $v_{\theta t}$ (the speed at which the temperature in the primary plastic deformation zone nears to the melting temperature of the workpiece material) rapidly falls due to the massive thermal softening and asymptotically reaches the zero value, the F_m-component grows in a nonlinear way from the zero value in accordance with the equation of momentum change [4]:

$$\frac{dH_{CH}}{dt} = F_m = \frac{m_{CH} \cdot v_{CH}}{t} \qquad [\mathrm{N}] \qquad (1)$$

where: H_{CH} … momentum of chip [kg.m.s^{-1}]
t … time [s]
m_{CH} …chip weight [kg]

As the cutting speed v_c increases, the v_{CH}-speed increases together with the mass (weight) of the chip that was cut off within a unit of time. This results in a nonlinear growth of the F_m-component. As shown in Fig.1, the F_s-component prevails up to the cutting speed $v_{\theta t}$, in the range between $v_{\theta t}$ a v_K the F_m-component begins to dominate and at cutting speeds exceeding v_K the resultant cutting force F is influenced only by the Fm-component. In practice it means, that cutting speeds should not (according to cutting forces) exceed v_K. At this speed the cutting force reaches a "conventional" magnitude and HSC would lose its advantage in reduction of cutting forces. Also the expenses (energy, special tools…) to achieve these high speeds would cause an economic loss.

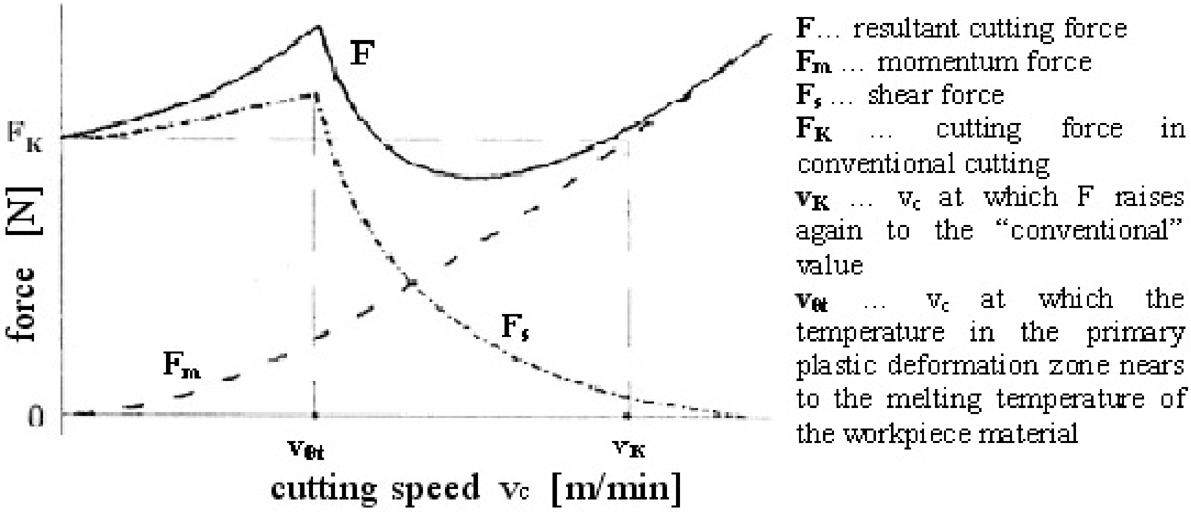

Figure 1. Theoretical behaviour of the resultant cutting force and its components v. cutting speed

3. Mechanism of Chip Formation in HS Milling

Based on a chip formation we distinguish two kinds of chip: a cohesive chip and a tear type chip. In accordance with distribution of plastic deformation, the cohesive chip can be either continuous or segmented. The continuous chip is produced from metals and their alloys with a body-centred or face-centred cubic lattice, high thermal conductivity and low hardness (e.g. aluminium alloys or low-carbon steels). On contrary, the segmented chip is obtained while machining metals with a hexagonal crystal lattice, low thermal conductivity and super hardness. Especially materials, such as titanium and nickel alloys, belong to this group [1]. The kind of chip for a specific workpiece material also depends on the cutting speed. Therefore, HSC produces a continuous chip, a segmented chip and also a tear type chip. For one and the same workpiece material the continuous chip can be formed at low cutting speeds and from a certain speed the segmented chip begins to be produced. With a further growth of the cutting speed the segmented chip changes into the tear type chip.

The mechanism of segmented chip formation in HSC of steels has been described [4] in four stages. Description of the chip formation is performed for orthogonal cutting with a negative rake angle and is shown in Fig.2.

In stage 1 a maximum compressive stress occurs in the region of cutting edge radius and decreases along the shear plane towards the workpiece surface. A low value of the surface compressive stress and a critical value of the shear stress initiate a crack. The crack originates at the surface point B’ and expands towards the cutting edge, where it stops because of the plastic stage (in Fig.2 the crack is limited within A’ and B’ points). The crack initiation is the beginning of formation of a new chip segment. The length of the crack is comparable to the undeformed width of the chip (lettered h_c).

In stage 2 as a result of the crack presence, the incoming chip segment is situated between the crack and the cutting face. Then, owing to the cutting edge movement, abscissa AA’ shortens and a part of the chip is deformed. The chip segment moves along the face and narrows, consequently a huge amount of heat is generated. The chip temperature reaches approx. Ac3. Under certain conditions, a martensite can be formed because of this temperature.

In stage 3 the distance AA’ is so short that high deformation occurs in the remaining part of the chip. The chip width is low at this stage and the cooling action runs extremely fast. Transformation proceeds in an adiabatic way in this part.

In stage 4 the chip is already formed and the compressive stress begins to grow. The chip formation cycle repeats.

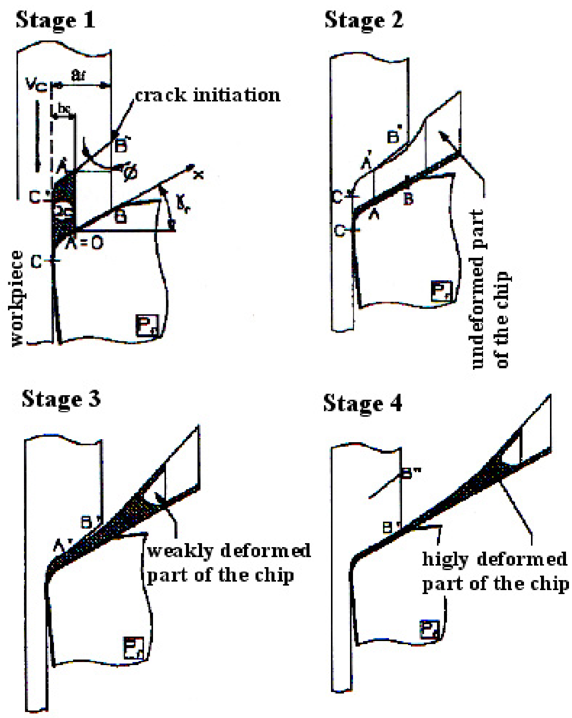

Figure 2. The different stages of segmented chip formation in HSC [4]

4. Experimental procedure

4.1. Workpiece material, tooling and equipment used

The workpiece material was a hot work high-alloyed tool steel ČSN 19552, heat-treated to 58HRC (equivalent to DIN 1.2343). The workpiece was prepared in the form of 300x160x80 mm block, directly clamped on the piezoelectric dynamometer, which was mounted on the machine table. The cutting tool was a 25mm diameter indexable insert toroidal cutter settled with only one insert to avoid the influence of tool run-out. According ISCAR the toolmaker, sintered carbide of a new generation IC908 was used for the purpose of HSM. The inserts were coated TiAlN (~ 4 μm thick) and screw-mounted in the cutter body. The assembly provided a rake angle of +8° and a primary relief angle of 19°. Chamfered edge 0,160 mm and corner radius 6,2 mm were used. The tool had <15μm radial run-out and the tool overhang was fixed at 45mm. Cutting experiments were performed on a MCV 750A, vertical 3-axis CNC machining center with maximum spindle speed 14 000 rev./min. Force measurement in three axes was undertaken using a KISTLER piezoelectric dynamometer (type 9255A) and charge amplifier (type 5007) connected to a PC with appropriate software for measuring and analysing such signals (LabView 6.1). Tool wear measurement was taken using a CCD video microscope system equipped with a 150x magnification lens.

4.2. Experimental design, operating parameters and test procedure

The face milling was performed as appropriate technology for process optimisation. The workpiece was machined for 8 – 64 passes, equivalent to a specific volume of the workpiece material removed. Down milling was employed with tests performed, cutting tool axis orientated normal to the workpiece surface. Selected tests were replicated. As far as possible, tests were carried out in accordance with ISO 8688-1,2 [10]. The cutting conditions involved, represent typical semi-finishing parameters [11], and see Tab.1. Two different types of metal removal rate per revolution were performed (Type I. and Type II.). Volume of the material removed in Type I. was kept constant at ~$5,3.10^{-2}$ mm^3 and Type II. at ~$9,6.10^{-2}$ mm^3. Each type was undertaken with variable cutting parameters (c.p.) as cutting speed, axial and radial (stepover) depth of cut and feed rate, see Fig.3. The most suitable proportion of cutting parameters in the terms of cutting forces, tool life, process reliability, material removal rate and total material removed were investigated.

Table 1. Cutting parameters tested and results

	c.p.	Test	V_c (m/min)	a_p (mm)	a_e (mm)	f (mm/tooth)	Tool life	Material removed (cm^3)
Type I.	1	A	100*	0,5	2	0,1	107 min	
		B	300	0,5	2	0,1	25 min	14,1
		C	350	0,5	2	0,1	12 min	7,5
		D	400	0,5	2	0,1	7 min	4,8
	2	E	250	0,2	4	0,1	18 min	7,2
		F	300	0,2	4	0,1	8 min	4,1
	3	G	200*	0,37	2	0,15	32 min	13,3
		H	300	0,37	2	0,15	7 min	4,4
	4	I	300	1	2	0,03	33 min	9,6
Type II.		J	200	1	2	0,1	22 min	14,4
		K	300	1	2	0,1	5 min	4,8

(* - unfinished test, c.p.- cutting parameters, v_c – cutting speed, a_p – axial depth of cut, a_e – radial depth of cut, f – feed rate)

c.p. **E**: a_p=0.2mm, a_e=4mm, f=0,1mm/tooth   c.p. **B**: a_p=0.5mm, a_e=2mm, f=0.1mm/tooth

Figure 3. Constant volume of the material removed per revolution with different cutting parameters set

5. Result and Discussion

5.1. Tool wear and tool life

In the majority of tests, tool wear was characterised by progressive flank wear growth and gross chipping of the coat. In semi-finishing and finishing machining of hardened steel, tool life is taken to be the time needed for the surface finish to deteriorate to a predetermined level. However, in finish machining of dies and moulds, it would be misleading to rely solely on the surface roughness to evaluate the tool life. A worn tool may cause a better surface finish than a new one [12]. Hence, the tool life in this study was ended when the level of maximum flank wear reaches 0,3 mm or coat chipping occurred. Two different modes of tool wear were observed. At the point where maximum cutting speed was achieved (depends on axial depth of cut) the flank wear reached its maximum magnitude. Generally, the flank wear developed uniformly up to its maximum with no signs of different tool wear. On the other hand, gross chipping turned up unexpectedly during uniform flank wear growth and ended tool life. Actually, it was gross chipping of the coat and appeared on the rake face only.
Because of the influence of temperature on the physical and mechanical properties of the tool material, it was expected that wear has been strongly influenced by temperature. Experimental investigation has shown that there is indeed a direct relation between tool life (represented as the workpiece material removed) and temperature generated during cutting (increasing cutting speed increases temperature), see Fig.4.

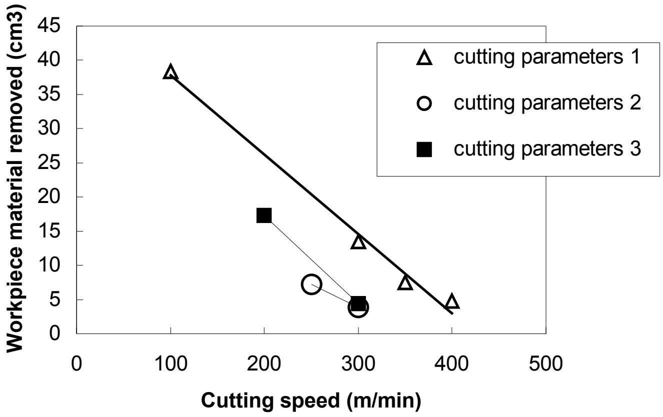

Figure 4. Workpiece material removed for cutting parameters No.1, 2 and 3 as a function of cutting speed

The lines obtained by linear regression show that increase in cutting speed for all variation of cutting parameters causes dramatic decrease in tool life expressed in workpiece material removed (cm^3). This expression is used by reason that time (min) or cut length (m) varies with change of cutting parameters, therefore are not comparable. It can be seen that the best performance was achieved with the cutting parameters No.1 at 100 m/min (test A), but such a low cutting speed would lead to poor productivity due to corresponding low feed rates. Therefore the optimum cutting speed in terms of material removed and productivity lies between 200 – 300 m/min. The tools tested at high cutting speeds predominantly failed by chipping. Chipping occurred at speeds over 300 m/min = higher temperature, thus thermal fatigue may be one of the causes. Although, cutting speed has been found to be the most significant process parameter in tool life, axial-radial depth of cut and feed rate are also important. Chipping also appeared at lower cutting speeds when machining type II. With bigger removal rate was performed, so mechanical shocks are other possible cause. Fig.5 shows an increase of the maximum flank wear with the workpiece material removed for selected tests. Test **J** finished with V_{Bmax} lower than predetermined level 0,3mm due to gross chipping. The rest of the tests achieved less than $5cm^3$ material removed and had similar progress as the test **F**.
There was an improper proportion between axial depth of cut a_p=0.2mm and radial depth of cut a_e=4mm, when c.p. **F** were used. Great sliding length between the tool and workpiece resulted in a high abrasive wear, so the volume of the workpiece material removed was lowest. Using lower feed rate (f)=0,03mm, c.p. **I**, resulted to extensive heat generation and badly influenced cutting process. Tool and even tool holder was extremely hot, because of greater heat transfer into the tool body, which was disadvantage. After ten passes the rake face was visibly damaged and tool wear increased very quickly. Increasing feed rate, c.p. **G** (f)=1,5mm/tooth, seems to be way how to achieve good tool performance, but needs to be used with lower cutting speeds up to 250 m/min. Maximum flank wear was 0,2mm when test was stopped, because the tool life should not exceed 35 min in term of its productivity. More tests at cutting speed about 250m/min and feed rate over 0,15mm/tooth need to be undertaken. The best performance was achieved when type I. with c.p. **B** and type II. with c.p. **J** were used. Both c.p. reached almost the same workpiece material removed but c.p. **J** in a shorter time T=22min. Different tool wear occurred, c.p. **B** reached predetermined maximum flank wear in contrast to c.p. **J** where tool failed by gross chipping. The tests were repeated with similar results.

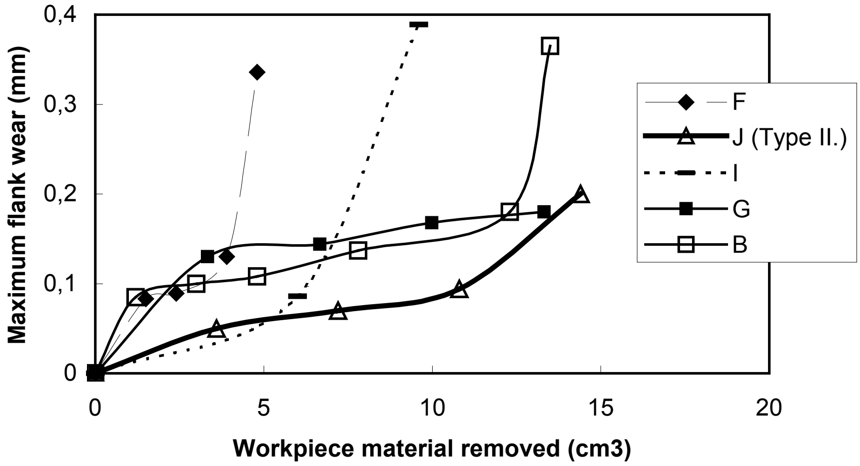

Figure 5. Maximum flank wear vs. tool life for different cutting parameters

5.2. Cutting forces

Force measurement in three axes was undertaken. In all cases the highest force component was the thrust (Z axis) force. Irrespective of the resolution of forces, force component in the Z axis is considerable higher than the others. This phenomenon can be related to the hard machining process where a pronounced increase in the thrust component is always observed when cutting at low feeds and depths of cut. Influence of increasing cutting speed on the cutting forces was investigated. Machining in the range of cutting speeds between 100 - 400 m/min showed, that there was no decrease of the thrust force component up to 400 m/min. On the other hand, cutting forces in X and Y axes started to decrease at cutting speed 350 - 400 m/min and were lowest at 400 m/min. A reduction of the cutting forces can be related to the chip thinning. Average resultant forces (Fr) versus number of passes for different cutting parameters and constant cutting speed set at 300 m/min were investigated. The average force (within one tooth period) was calculated as the square root of the sum of the squares for the three cutting force components in X, Y and Z directions. As can be seen in Fig.6, the cutting forces were highest when cutting conditions Type II. were used. It was expected, that increasing the axial depth of cut increases the average resultant forces as the chip width increases.

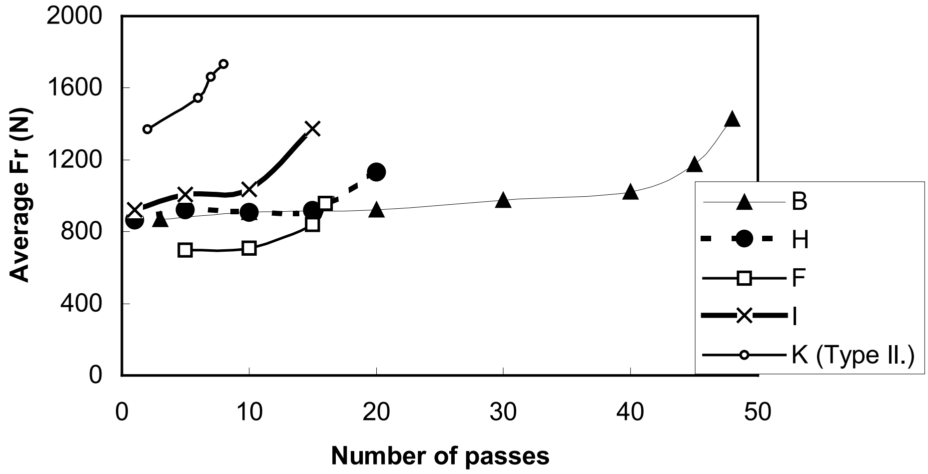

Figure 6. Effect of different cutting parameters on average milling force F_r

Cutting conditions Type I. have similar magnitudes of average resultant forces when unworn tool was employed (fresh insert). There were no great differences due to proportion of cutting parameters except c.p. **F**, where the average force was about 150N lower, than the others. The lower average forces were caused by decreasing axial depth of cut at the expense of the radial depth of cut, thus decrease in chip cross-section. The average forces slightly rise with increasing tool wear, until the specific limit. Finally the forces considerably increase about 300N just before tool failure.

5.3. Conclusion of experiment

- The semi-finishing of DIN 1.2343 tool steel in the hardened state (58 HRC) gave tool life values of < 15 cm^3 of workpiece material removed. Great differences were found in performance of the tests with variable cutting parameters and constant removal rate per revolution.
- An analysis of wear pattern indicated that tool wear was characterised by progressive flank wear growth and gross chipping of the coat on the rake face. Progressive flank wear occurred when lower cutting speeds up to 300m/min and smaller removal rates were used. On the contrary, gross chipping appeared when higher cutting speeds and bigger removal rates were employed.
- The best results in term of total material removed were achieved when cutting conditions **B** (v=300m/min, a_p=0.5mm, a_e=2mm, f=0.1mm/tooth) or **J** (v=200m/min, a_p=1mm, a_e=2mm, f=0.1mm/tooth) were employed. Increased feed rate, f=0.15mm/tooth with lower cutting speed v=200-250m/min also resulted in good performance.
- There was no decrease of the thrust force component up to 400 m/min. Cutting forces in X and Y axes started to decrease at cutting speed 350 - 400 m/min. A reduction of the cutting forces can be related to the chip thinning. The lowest cutting force was achieved with c.p. **F** (v=300m/min, a_p=0.2mm, a_e=4mm, f=0.1mm/tooth) due to decrease in chip cross-section.

6. Optimizing and the High Speed and Hard Cutting

Optimization of cutting conditions is closely attached to the economic, the quantity (quality) of the production and it influences the prize of each item even so the final prize of the product. Nowadays, the inveterate concept for the optimizing of cutting conditions is not right for some cutting procedures. This concept cannot be used for today's machines with higher level of automation. One of the most important reasons is the costs of machine time, which increase by the prize of modern machines, tools and accessories. From this aspect, there is a press to decrease the value of optimal durability. Lower values of optimal durability help increase the cutting speed (cutting conditions). If these fats are not respected in real production, cutting cost may grow many times. Optimization of cutting conditions may be described as the optimal value definition made by the optimizing criterion within limiting conditions. In this problematic there must be always compared two basic economical effects. Production time is decrease by the increasing the values of cutting conditions and at the same time there is fall of the cutting edge durability that cause rising of tool costs [Mádl 1998]. HSC milling of the heat threatened materials, especially by production of dyes and moulds, is innovation manufacturing method, which includes enormous rational potential. The full benefit from this technology will be achieved only if the whole process chain is build optimally, because stability of the system is determined by the weakest element. Very expensive cutting machines are useless without appropriate technology and optimal technology is unusable without proper machines. It depends on case to case what method of production is more effective. Application research should help with expansion of knowledge base about possibilities, principles and recommendation for the profitable application of HSC hard milling and it should become the base for complex economical computing integrated optimization that should allow real possibilities for introduction of this modern and innovation method for hard machinable materials with increasing of process reliability of the whole manufacturing chain [Skopeček 2003]. Importance of cutting condition optimization and cutting edge durability rises simultaneously with rising requirement on complex optimization of work conditions, especially on connection with geometry and material optimizing of cutting tool edge. These connections are very complicated and be successfully solved only on the computer by applying of the fitting optimizing algorithms which respect specifications of HSC technology.

6.1. Optimizing software "OPTIMAL"

Nowadays, authors are developing a computing optimizing software OPTIMAL, which is used for complex computing integrated optimizing of cutting conditions in 3-axes milling. It is ranged especially for production of dies and moulds by HSC milling. Concept of the software is based on remade costs equations by the computing integrated statistical- iterative software that uses extended Taylor's equations with experimentally established parameters. This suggestion is based on the communication with CAD/CAM systems, too. Software permits to keep the selected milling strategies which are specific for different stages of die and mould manufacturing (roughing, semi-finishing, finishing).Software supports specification of HSC technology. The selection of tools is adjusted for die and mould manufacturing. It means that user may choose any type of tool, but only with ball-shaped end that must be used by this technology.

Basement of software is composed by common cost equation for cutting with filled in complex Taylor's equation (established by the experimental research). In these equations (forced for individual period, strategy and tools) are all partial unknown (e.g. already adverted function of durability or machining time) expressed mathematically by the help of all cutting conditions (v_c, f_z, a_p, a_e) and other economically-organizational data are set by user (or counting from database). Speciality of this access consists also of that machining time is formalized like part of material volume for removing (see CAD/CAM) and material volume that is taking away by one tooth of milling cutter. That is of course function of cutting conditions. This equation (function of four unknowns - cutting conditions) is after that underwent the statistical iteration (gradual feeding) according to conditions given by user with the aim of matching the cost minimum of this function (with complying all of engaged restrictive conditions) These conditions are cutting conditions, at which the cost minimum is achieved. These cutting conditions can be called optimal from standpoint of cost for given operation and their instalment to the Taylor's equation is gained the value of optimal durability [Skopecek, 2004].

<u>Example of Cost Equation</u> for certain strategy and round replaceable cutting tips:

$$N_{OPER} = \underbrace{\frac{D_s}{60}\cdot t_s \cdot \left(1+\frac{t_{VN}}{k.v_c^{\,x}.a_e^y.a_p^z.f_z^c}+k_p\right)}_{\textit{Machine costs}} +$$

$$+\underbrace{\frac{t_s}{k.v_c^{\,x}.a_e^y.a_p^z.f_z^c}\cdot\left[z\cdot N_{VBD}\cdot\frac{\arccos\left(\frac{\frac{d}{2}-a_p}{\frac{d}{2}}\right)+\frac{\pi}{36}}{2\pi}\cdot 1{,}02+\frac{N_{SE\check{R}}\cdot t_{VN}}{60}\right]}_{\textit{Tool costs}} \qquad (2)$$

where:

N_{OPER}	... costs of operation
D_s	... machine hourly rate
k_p	... on-coming coefficient (blank tool cutting cycle (e.g. 0,2 => 20% of machine time)
t_s	... machine time, function of cutting conditions – equation 2)
V	... material volume to removing (add CAD/CAM)
V_{1z}	... material volume removed by one mill-tooth
n	... rotation speed
z	... number of tool-edges
T	complex Taylor's formula T = $k.v_c^{\,x}.a_e^y.a_p^z.f_z^c$; experimentally established for specific event (k, x, y, z, c – numerical values)
v_c	... effective cutting speed
t_{VN}	... tool change time
$N_{SEŘ}$	... tool setter hourly rate
N_{VBD}	... cost prize of replaceable cutting tip
1,02	... 2% = amortization of tool holder, tips liquidation

Matematical formulation of machine time as function of cutting conditions and removed material volume (for certain strategy and round replaceable cutting tips):

$$t_s = \frac{V}{n.z.V_{1z}} = \frac{V}{n \cdot z \cdot \left(f_z.\cos\left[\frac{\pi}{2} - \arccos\left\langle \frac{\frac{D_{ef}}{2} - \left(a_e - \sqrt{a_p(d-a_p)}\right)}{\frac{D_{ef}}{2}} \right\rangle \right] \right)} \cdot$$

$$\cdot \frac{1}{\left(\frac{D_{ef} \cdot \arccos\left\langle \frac{\frac{D_{ef}}{2} - \left(a_e - \sqrt{a_p(d-a_p)}\right)}{\frac{D_{ef}}{2}} \right\rangle}{2} \right) \cdot \left(\frac{d}{2} \arccos\left(\frac{d/2 - a_p}{d/2} \right) \right)} \tag{3}$$

Software OPTIMAL works under the operation system MS WINDOWS or it can be integrated into the CAD/CAM system. It is solved by modular method with informative desktop, where the most important data from separate modules. First module is called Materials Database, where user is able to enter experimentally established data as relation of durability, cutting forces and roughness towards cutting conditions, tool type selection, milling method, etc. In the second module Economical-organization Database user is able to enter economical data like machine hourly rate, tool cost, etc. and organizational-technical data like number of tool edges, tool diameter, removed material volume, etc. The third module is called Restrictive Conditions. User is able to enter the iteration steps a theirs ranges also the limitations of performances, torques, forces, quality, etc. By all these modules it is possible to load all data from database. The last is Compute Module, where user can set the priority of computing or its suspension. In this module there is displayed computing status and all results: optimal cutting conditions, optimal durability, values of minimal operation costs, operation time, force tension and hypothetical achieved surface roughness. User can print and save the results here, too.

6.2. Practical application of optimizing software

There were tested two different types of tools with different materials of tool edges and by ten different milling situations and strategies, so there can be imagine basic idea and database for application of optimizing algorithms. During many tests there were analysed relations between tool abrasion, durability, cutting forces, roughness and geometrical accuracy (it is supplied by the stadium of surface integrity, it means by the heat influence of surface and hardening). Varying cutting conditions were chose to include both transition region and HSC region for selected material.

Exp. work-piece:	Tool steel ČSN 19 556, hardened to 58 HRC
Tool 1:	Milling head SANDVIK Coromant for round replaceable cutting tips, (Fig. 7) round shape ø12 mm, SK: P10, PVD: TiNAl
Tool 2:	Monolith ball-shaped cutter RÜBIG, (Fig. 8) ø12 mm, SK: ultra-fine K10, PVD: TiAlN
Machine tool:	MCV 750 A – Kovosvit Sezimovo Ústí Accelerating spindle with max. 3 kW a 24 000 rpm
Milling strategy:	Down-feed dry milling, VB_{krit} = 0,3 mm
Starting conditions:	Cutting speed v_c [m/min] 150 ÷ 500
	Axial deep of cut a_p [mm] 0,5 ÷ 1
	Radial deep of cut a_e [mm] 2 ÷ 5
	Feed per tooth f_z [mm] 0,06 ÷ 0,36

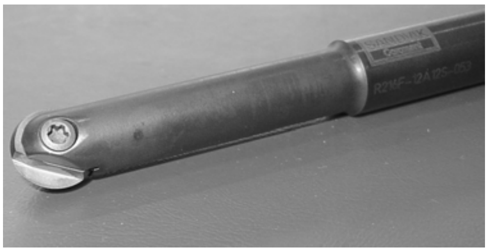

Figure 7. Tool 1, Sandvik Coromant

Figure 8. Tool 2, RÜBIG

Analysed relations between durability of tool edge and basic cutting conditions must be described by complex mathematical function. There was chosen an exponential function in form of extensive Taylor's formula.

Taylor's formula for tool 1 – Milling head SANDVIK with round replaceable cutting tips:

$$T_1 = 4395 \cdot v_c^{-0,96} \cdot f_z^{-1,59} \cdot a_p^{-0,05} \cdot a_e^{-2,92} \quad \text{[min]} \tag{3}$$

Taylor's formula for tool 2 – Monolith ball-shaped mill RÜBIG:

$$T_2 = 2786 \cdot v_c^{-0,47} \cdot f_z^{0,25} \cdot a_p^{-0,27} \cdot a_e^{-0,29} \quad \text{[min]} \tag{4}$$

Obtained values were subsequently completed by technical-economical-organizational information and fill into the optimizing software. As comparison "etalon" was chosen material volume to remove = 10 m^3 and as basic limiting condition was chose roughness = 1,6 μm. Optimal values from economical aspect for tool 1 were found these: v_c = 360 [m/min], f_z = 0,06 mm, a_p = 0,5 mm, a_e = 4 mm by durability of tool-edge T_1 = 24 min and operation time t_1 = 58,3 hours. For tool 2 – monolith-mill: v_c = 430 [m/min], f_z = 0,36 mm, a_p = 0,7 mm, a_e = 5 mm by durability of tool-edge T_2 = 87 min and operation time t_2 = 20,8 hours. By comparing of operation costs there was found out, that costs for first tool are for times higher then costs for tool 2. Finally there is not really important several absolute values so much as the fact that there is existing software tool for establishing optimal cutting conditions for individual tools, situations and phase of cutting, even so for comparing of different types and conceptions of cutting tools.

7. Conclusion

There are many approaches for economical optimizing of cutting conditions, but only computing integrated procedure based on statistical methods and experimental research brings high quality results. Its usage, of course, depends on production size, because there are higher costs by this technology. Same thing responds with presented software OPTIMAL. Functionality and accuracy of this software were tested by the real examples of shaped surfaces milling in HSC mod. As material there was used heat threatened tool steel (CSN 19556, 58HRC). There were tested roughing and finishing tools with sharp edges from sintered carbide and cutting ceramics. There were tested solid tools and tools with inserted cutting tips. By using this optimizing method were achieved surprising high economical savings. Software is useful even as the tool for judging of economical and time convenience and for comparing of separated variants.

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Footnote

The research was made in the field of HS milling (HSM) of high-strength and super-hard workpiece materials, where this technology application is at the very beginning of its evolution. The report is concentrated on finding a relation between forces ratio and chip morphology mainly. Effects of selected parameters of the machining process (particularly of cutting speed and kind of workpiece material) on cutting force magnitudes and chip morphology are characterised in this work. The results of experimental measurement are also included. The measurement, carried out during HS milling, was made in order to support and confirm theoretical assumptions. Synthesis of the results and their confrontation with theoretical hypothesis form conclusions are the topic of the report too. The most of investigation works in this paper was made in connection with the research grant project No. MSM 232100006 by Ministry of Education, Youth and Sports in Prag in years 1999 – 2004.