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# A calculating system of cutting conditions

*The physical model of the cutting process which contains new ideas for the cutting theory, such as: a cutting system efficiency, limiting work of the tool, a material index of plasticity. Its mathematical model allows not only to represent existing knowledge from the area of metal cutting, but to join the new ones. The desing program is compact, it does not demand big databases, it allows to calculate cutting process characteristics at turning without any preliminary joint tests of the tool and processed materials. Designing by the observed method is a selection of the optimal parametres of machining at turning on the virtual equipment.*

***Keywords**: the cutting force; the greatest work of the cutting system; the cutting system efficiency; the tool life; the cutting conditions; the roughness parameters; the model.*

*Материальная модель режущего процесса, который содержит новые идеи для режущей теории, как например: режущая системная эффективность, ограничивающая работу инструмента, материальный коэффициент пластичности. Ее математическая модель позволяет не только представлять существующее знание от площади металлической выемки, но и присоединяться к новым. Desing программа компактна, не требует больших баз данных, позволяет вычислять режущие характеристики процесса в повороте без любых предварительных объединенных критериев инструмента и обрабатываемого материала. Проектирование предлагаемым методом - выбор оптимальных параметров механической обработки во включении виртуального оборудования.*

***Ключевые слова**: режущая сила; максимальная работа режущей системы; режущая системная эффективность; срок службы инструмента; режущие условия; параметры грубости; модель.*

*Матеріальна модель різального процесу, який містить нові ідеї для різальної теорії, як наприклад: різальна системна ефективність, що обмежує роботу інструменту, матеріальний коефіцієнт пластичності. Її математична модель дозволяє не лише представляти існуюче знання від площі металевої виїмки, але і приєднуватися до нових. Desing програма компактна, не вимагає великих баз даних, дозволяє обчислювати різальні характеристики процесу в повороті без будь-яких попередніх об'єднаних критеріїв інструменту і оброблюваного матеріалу. Проектування пропонованим методом - вибір оптимальних параметрів механічної обробки у включенні віртуального устаткування.*

***Ключові слова**: різальна сила; максимальна робота різальної системи; різальна системна ефективність; термін служби інструменту; різальні умови; параметри грубості.*

## 1 INTRODUCTION

At designing of turning operation the following basic characteristics of the cutting process are important: cutting conditions – $V$, $f$, $t$; blade geometry – $\gamma_{ol}$, $\alpha_{ol}$, $\kappa_r$, $\kappa_{r1}$, $\lambda_{ol}$, $\beta_{ol}$, $r_k$, $r_l$; Tool life – $T$; a machine time – $\tau$; parametres of a roughness of the processed surface - $Rz$, $Ra$; cutting temperature – $\theta$; chip compression ratio – $\zeta$; a component force cutting - $F_x$, $F_y$, $F_z$; stress – $\sigma$; parametres of deterioration of a blade – $h$; the form and erosion for built up edge (BUE) – $B$; properties of processed and instrumental materials – $P_w$, $P_t$.

From this list the set $I = \{V, f, t, \gamma_{ol}, \alpha_{ol}, \kappa_r, \kappa_{r1}, \lambda_{ol}, \beta_{ol}, r_k, r_l, P_w, P_t\}$ is an initial data. And at transition optimisation only the properties of the processed material Pw stay invariable in case that the part is not exposed to preliminary physical affecting (such as high and low temperatures, a plastic straining etc.).

Other elements of the set $I$ are selected in such a way to provide necessary durability ($T$), parametres of a roughness of the processed surface ($Rz$, $Ra$), the maximum productivity ($\tau$) and the minimum cost of machining ($C$). By other words, the optimization of elements values of the set $Y = \{T, Rz, Ra, \tau, C\}$ is the purpose of the designing process.

Elements of the set $W = \{\theta, \zeta, F_x, F_y, F_z, \sigma, h, B\}$ are used for the control and the analysis of designing process, generalisation of practical observations and for explanation of scientific researches results.

The traditional technique forms the set $Y$ on the basis of empirical expressions which do not reflect physical models, are restricted by values of parametres of their creation and use of bulky databases demand.

The reason for this is the fact that cutting process is the most complicated combination of simple destroying and deforming processes. The material inhomogeneous deformation and the material reversal load are observed in a cutting zone. There are some zones in a plastic state, there are some in the elastic state. There is a destruction and in the same place, after a while, there is a adhesion (friction welding) in some areas. Therefore any known theory of deformations and destruction can not completely describe a concrete chip formation because each local area in a cutting zone is characterised by its inherent conditions only.

Obviously, the functioning of the cutting system as the most complicated system has the following coordinates: $Co = (I, Y, W)$. To link them among themselves by mathematical relationships it would mean a creation of mathematical model of a cutting process. In connection with not a sufficient level of study of the phenomena at chip formation, the authentic physical model of this process does not exist. Therefore it is impossible to develop adequate mathematical expressions. The quantity of unknown parametres, unfortunately, surpasses quantity of the equations reflecting the physical phenomena in a zone of cutting. In this connection one has gained a wide circulation the empirical expressions which are, per se, «a black box». Models created on their basis demand considerable empirical data and are suitable in the conditions of restricted to the conducted experiment.

Very often cutting conditions are installed by analogy, on the basis of practical experience. As a result there are no weighty demonstrations of what the accepted conditions of cutting are optimum as from the point of view of maintenance of durability of the tool and productivity of process, and from the point of view of creation of necessary parametres of quality of the processed surface. This article is devoted for upgrade of physical model of cutting system and working out to mathematical model matching to it.

## 2 LIMITING WORK OF THE TOOL

To adjust quantity of unknown parametres and quantity of the allowing equations in mathematical model of the cutting process it is necessary to improve its physical model. If on a modern level of a science development about cutting of metals it is not possible to merge achievement of thermodynamics and the statistical physics at mathematical modelling then it is necessary to change physical model. It is necessary to use such a complex factor which merges statistics and thermodynamics rules.

Work is such a complex parametr. It is possible to discriminate limiting possible work of the blade made from the material and the performed work by the cutting system at the present time.

Limiting (the maximum) work of the plates from the various materials can be discovered experimentally [1, 2, 3]. There is also other possibility - it is possible to calculate the limiting work.

At correctly chosen instrumental material deterioration of the tool mainly depends on the fatigue phenomena which develop under the influence of a cyclic loading of microroughnesses of its surface in volumes of a processed material. Thus, some work is carried out.

The elementary work executed at destruction of a layer of the instrumental material is equal

$$dA = \sigma_f \cdot u \cdot dW,$$

where $\sigma_f$ – compression strength of the instrumental material; $u$ – limiting, destroying value of cycles for the instrumental material; $d_W$ – the volume element destroyed as a result of deterioration.

From here it is possible to write down, that

$$A = \sigma_f u \int dW.$$

Choosing value of a tool orthogonal clearance αol, an apex angle , tool cutting minor cutting edge angle $\kappa_{r1}$, corner radius rl and value of deterioration on flank $h$ it is possible to calculate the outweared volume. For engineering calculations it is possible to take advantage of the formula [4].

$$\delta = 180 - (\kappa_r + \kappa_{r1}).$$

Thus, adopting a value wear on flank $h$, the limiting value of work of the cutting system is calculated as

$$A = 7,38 \cdot 10^5 \frac{t^{0,41} (r_l)^{0,35} h^{2,11}}{(\kappa_{r1})^{0,25} \alpha_{ol} \delta^{1,92}} \cdot \sigma_f \cdot u. \qquad (1)$$

In this formula a value of a factor u can be corrected towards a diminution if the wear mechanism differs from fatigue (the increased abrasive properties of the treated material, the increased temperature in a cutting zone).

## 3 WORK IN THE CUTTING SYSTEM

It is impossible to calculate an exact value of the work in the cutting system under various conditions of the process now. However it is possible to gain an approximate value, assuming for the initial value a specific work of destruction of the sample in the course of a standard testing and efficiency of the cutting system. A specific work at destruction of the sample in the course of a standard testing

$$A_0 = \int_0^{\varepsilon_f} \sigma(\varepsilon) d\varepsilon, \qquad (2)$$

where $\sigma(\varepsilon)$ – stress; $\varepsilon$ – strain; $\varepsilon_f$ – strain at fracture.

Because of complexity of the processes happening at the chip removal from the surface of the workpiece, a power demand is more than at simple rupture of the tested sample. The ration of the specific work at destruction of the sample in the course of the standard testing (2) to specific work in cutting system (which it is equal $A_1 = \frac{F_z}{f \cdot t}$) can be named by efficiency of the cutting system $\omega$. It is calculated by formula

$$\omega = \frac{f \cdot t}{F_z} \int_0^{\varepsilon_f} \sigma(\varepsilon) d\varepsilon. \qquad (3)$$

Numerical value of the cutting system efficiency is an index of the consumption power use efficiency.

However it is possible to find out the exact value of $F_z$ in the formula (3) for the concrete conditions of machining only experimentally, hence predicting ability of an observed technique is lost. In this connection, it is offered to calculate the cutting system efficiency by the formula:

$$\omega = 0,91 \frac{V^{0,14} S^{0,48} t^{0,15}}{k_f (1 - k_R)}, \qquad (4)$$

where $k_f$, $k_R$ – the factors considering influence of the treated material plastic properties on the cutting process.

As it will be shown further, due to cutting process specific the parameters calculation accuracy of the cutting regime always are not high. Therefore it is possible to consider as satisfactory the outcomes gained by use of the formula (4). Thus, the specific work of the concrete turning process implementation is calculated by treated material mechanical properties and by cutting system efficiency:

$$A_1 = \frac{A_0}{\omega}. \qquad (5)$$

It is possible to find out the relation $F_z = F_z(V, f, t)$ in case of accurately certain boundary coditions for the process applied multiply and to use the formula (3) for the cutting system efficiency calculation.

## 4 TAKING INTO ACCOUNT THE DERGEE OF A TREATED MATERIAL PLASTICITY

The dependences of a tangential cutting force, chip compression ratio, roughness parametre from the cutting speed are shown at turning of a ANSI 1045 steel on fig. 1. At increase og the cutting speed the tangential cutting force and chip compression ratio drop and having attained a minimum increase to some maximum and then again decrease. Since this cutting speed value the processed surface roughness parametre starts to decrease. Obviously, the decrease of cutting forces and of chip compression ratio, the maximum roughness of the processed surface at the cutting speeds less than 50 m/ min are connected with the increased plastic deformation in the cutting zone.

Besides, with increase of material plasticity the interval of the cutting speeds at which plastic deformations are especially developed and the area of the plastic deformation maximum moves towards high speeds.

Influence of cutting speed and of material properties on factors $k_S$ and $k_R$ are approximated by the following expressions:

$$k_f = 0{,}33\left(\frac{V+350}{580\eta^{0{,}24}}\right)e^{-\left(\frac{V+350}{580\eta^{0{,}24}}\right)^6};\ k_R = 1 - 2{,}5k_f,$$

where $\eta = \dfrac{\varepsilon_f}{\sigma_f}$ – index of plasticity of a processed material [2], GPa$^{-1}$ (σf – stress at fracture).

There are two major factors at cutting, related with the chip formation mechanism which influence to the roughness parametres of the processed surface. They are: the geometrical (set of geometrical elements and parametres of the blade move) and the plastic (plastic deformation development in a the cutting zone). It is obvious, that the roughness is influenced by crenation of the cutting edge form and vibration, but these factors are not a consequence of cutting process but they are defined by quality of the tool, the equipment and devices.

For the calculation of geometrically formed height of a roughness known formulas [5] are used

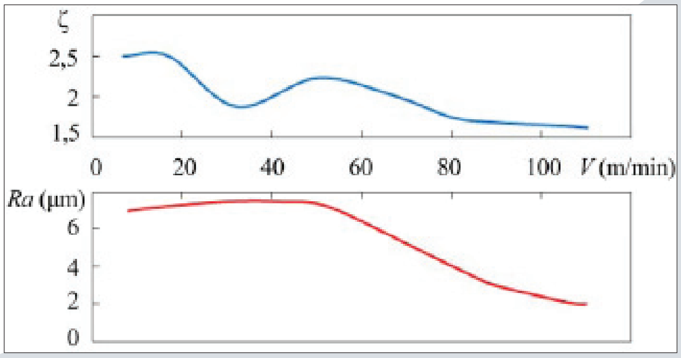


***Fig. 1. Influence of cutting speed on parameter of roughness Ra and chip compression ratio ζ.***
*Work material – ANSI 1045 steel, feed $f$ = 0,26 mm/ rev, a cutting depth $t$ = 0,5 mm*

$$Rz = f\cdot\frac{\tan\kappa_{r1}\cdot\tan\kappa_r}{\tan\kappa_{r1}+\tan\kappa_r} + \frac{r_l}{\tan\kappa_{r1}+\tan\kappa_r}\times$$

$$\times\left[\tan\kappa_{r1}\left(1-\frac{1}{\cos\kappa_r}\right)+\tan\kappa_r\left(1-\frac{1}{\cos\kappa_{r1}}\right)\right]. \quad (6)$$

$$Rz = r_l - \frac{\sqrt{4(r_1)^2 - f}}{2}. \quad (7)$$

$$Rz = r_l\left(1-\cos\kappa_r\right) + f\cdot\sin\kappa_r\cos\kappa_r -$$

$$-\sin\kappa_r\sqrt{f\cdot\sin\kappa_r\left(2r_1 - f\cdot\sin\kappa_r\right)}\ . \quad (8)$$

$$Rz = r_l\left(1-\cos\kappa_{r1}\right) + f\cdot\sin\kappa_{r1}\cos\kappa_{r1} -$$

$$-\sin\kappa_{r1}\sqrt{f\cdot\sin\kappa_{r1}\left(2r_1 - f\cdot\sin\kappa_{r1}\right)}\ . \quad (9)$$

If an axis $x$ can be matched with an average line of a surface contour the average arithmetical deviation of a profile is defined by formula

$$Ra = \frac{1}{l}\left(\int_0^{x_a}\left|y(x)\right|dx + \int_{x_a}^{x_b}\left|y(x)\right|dx + \ldots + \int_{x_n}^{l}\left|y(x)\right|dx\right), \quad (10)$$

where $l$ – length of a base line; $x_a$, $x_b$, ..., $x_n$ – parameters, which restrict y(x) function on the x axis.

The algorithm is developed for automatic choice of one of the the formula specified above [2].

Geometrically the roughness is formed at a combination of the blade geometry and the feed motion. However it not the final form of a microrelief as there is a distortion at the expense of the plastic deformation. At the high speeds of cutting when the plastic deformation is insignificant, the calculated values of the roughness parametre $Ra$ correspond well enough to the experimental ones.

With the plastic deformation degree increase in the cutting zone (at cutting speed reduction) the experimental values Ra deviate sharply from the calculated ones.

Taking into account conditions of the chip formation [2, 6, 7] the analysis of the microroughnesses forms allows to separate three principal causes of the plastic component creation. First, the shift of the next layers as a result of destruction with subsequent "curing" in the field of a plastic zone at a blade corner is possible. This zone can develop itself and move to the workpiece external surface. After blade pass it remains on the residual ridge in the form of outgrowth. Secondly, as a result of the plastic area presence ahead the blade corner, the radius of the sliding line curvature on which metal separates from the workpiece is less than blade corner radius. Thirdly, there is a plastic change of the residual ridge as a result of not breaking deformations act in the reference plane.

If at machining of the materials possessing some plastic properties, the plastic zone develop at the blade corner, its mobile part can be pushed to the processed surface changing its roughness parametres.

Thus, the ridge forms on the microroughness corner, its height is restricted by the tool minor cutting edge. The value of the metal plastic replacement is defined by factor $k_S$.

At turning of a ANSI 1045 steel with the cutting speed $V$ = 49 m/min and more the ridge was absent on the microroughness. However radiuses of the created microroughnesses dints curvature differed from the blade corner radius (fig. 2). The average value of the dint curvature radius was $R$ = 0,22 mm (the blade corner radius was $r$ = 0,8 mm). That is, the radius of the sliding line curvature on which the chip separates from the workpiece is a $k_R$ part of a blade corner radius $r_l$. Hence, in this case the roughness increases not at the expense of microroughness height but at the expense of dint depth increase.

It is possible to calculate Rz and Ra under condition of considerable plastic deformation in the cutting zone using the previously offered dependences (6 – 10), substituting instead of the feed value S the any other feed value

$$f_f = f\left(1 + k_f\right), \tag{11}$$

and instead of the blade corner radius any other radius

$$R_f = r_l k_R. \tag{12}$$

We can disregard the microroughness plastic change as it is rather small.

## 5 CALCULATION STAGES

The material mechanical properties and workpiece sizes are the initial data for calculation as well as material physicomechanical properties; the cutting tool geometry; flank limiting wear; the relative motion parametres; positioning of the tool and workpiece (fig. 3).

The value A0 is calculated using (2), the cutting system efficiency is calculated using (3) or (4).

Specific work of cutting is calculated by the formula (5). Then it is easy to calculate the cutting tangential force: $F_z = A_1 ft$. By means of the expression (1) the cutting system maximal work is defined as $A$, that allows to calculate the tool life $T = \dfrac{A}{F_z V}$. Under the formulas (6–10) taking into account the plastic deformation influence (11, 12), the parametres $R_z$, $R_a$ can be calculated.

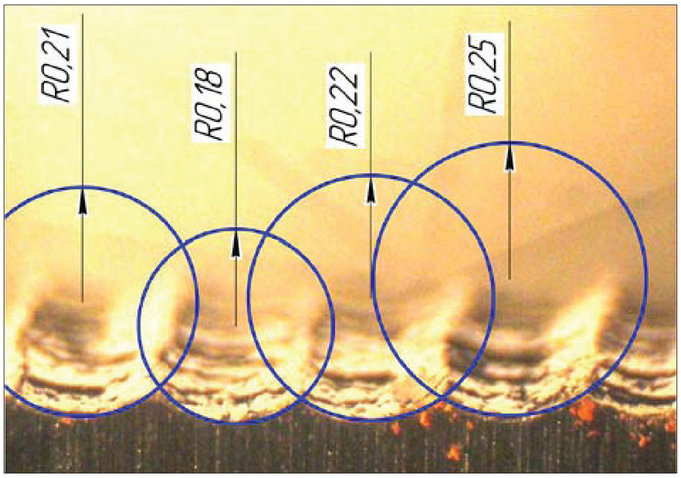
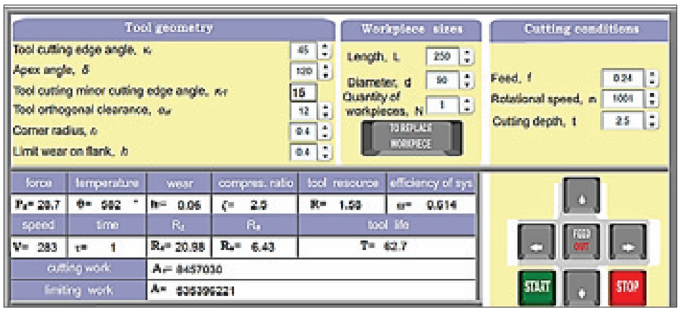


***Fig. 2. Microroughness profile. V = 49 m/min; f = 0,38 mm/rev; t = 0,3 mm; $r_l$ = 0,8 mm; κr = 93˚; $\kappa_{r1}$ = 27˚. Work material – ANSI 1045 steel, tool material – Carbide P20 (15% TiC, 6% Co)***



Tool cutting edge angle, $\kappa_r$ 45
Apex angle, $\delta$ 120
Tool cutting minor cutting edge angle, $\kappa_{r1}$ 15
Tool orthogonal clearance, $\alpha_o$ 12
Corner radius, $r_\varepsilon$ 0.4
Limit wear on flank, $h$ 0.4

Length, L 250
Diameter, d 90
Quantity of workpieces, N 1

Feed, f 0.24
Rotational speed, n 1001
Cutting depth, t 2.5

| force | temperature | wear | compres. ratio | tool resource | efficiency of sys |
|---|---|---|---|---|---|
| $F_z$= 28.7 | $\theta$= 582 ° | h= 0.06 | $\zeta$= 2.9 | R= 1.59 | $\eta$= 0.914 |
| speed | time | $R_z$ | $R_a$ | tool life | |
| V= 283 | $\tau$= 1 | $R_z$= 20.98 | $R_a$= 6.43 | T= 62.7 | |
| cutting work | $A_c$= 8457030 | | | | |
| limiting work | A= 535396221 | | | | |

***Fig. 3. Calculation of the turning process characteristics***

The time necessary for full machining of the workpiece is:

$$\tau_m = \frac{L}{n \cdot f},$$

where $L$ – workpiece length; $n$ – a rotational speed.

Thus the basic parameters of the cutting system and the elements of the set $Y$ are defined. The elements of the set $W$ are calculatd for the control of the designing process and for the analysis of its result. The full work of cutting:

$$A_c = A_1 V f t \tau_m.$$

If $A_c \geq A$ it means, that the tool wear has reached the critical value.

The blade working capacity resource consumption is equal

$$R_w = \frac{A_c}{A}.$$

The capacity resource consumption can be estimated up both by the cutting system efficiency as well as by the chip compression ratio. According to [2, 8] the chip compression ratio is functionally related with the cutting specific work $A_1$ and with the proportionality limit of the processed material $\sigma_{e.l}$

$$\zeta = e^{\sqrt[\chi+1]{\frac{A_1}{2\sigma_{e.l}}}},$$

where $\chi = \dfrac{\ln\sigma_f - \ln\sigma_{e.l}}{\ln\varepsilon_f - \ln\varepsilon_{m.e.d}}$ – parametre of the processed material reinforcement ($\sigma_f$ – strength limit, $\varepsilon_f$ – strain at fracture, $\varepsilon_{m.e.d}$ – maximum elastic deformation).

At choosing of the tool material, except mechanical properties, it is necessary to consider its critical temperature $\theta_{cr}$, should it is exceeded the tool material loses its properties.

The cutting temperature is defined as

$$\theta = k\left(A_1\right)^q.$$

Values of $k$ and $q$ are defined experimentally after not long tests. At designing of the turning operation it is necessary to control the cutting temperature value as at $\theta \geq \theta_{cr}$ the tool material loses its cutting properties.

Thus the mechanical properties of the tool material and of processed material allow to find out the functional relation among the basic characteristics of the cutting process.

## 6 CALCULATION RESULTS RELIABILITY

It is known, that results of the cutting conditions parametres calculations are the subject to correction on the working place. In spite of the fact that modern production technologies allow to produce the constructional and tool materials with the mechanical characteristics which the small difference from the nominal values, the interval of the tool life change at the same cutting conditions parametres is rather big. Tested under the same conditions at various times, the tool materials show different working capacity. The reason is that interactings in cutting system are the stochastic processes, $\{E(\tau, r), \tau \in T, r \in R\}$, – defined by family of random values $R$ which are function of time $T$.

For example, if during one experiment the measured forces values at the same cutting conditions parametres repeat (in the measurement device accuracy limits) but test-stand replacement follows to the sharp differences among the experiment results. The forces values can differ in a few times at the same test conditions.

It has appeared, that results of experiment of finding out of the tangential force component on cutting speed dependences can be approximated by the following expression [9]

$$F_z(V) = F_0 + F_a \sin \frac{2\pi}{V_p}(V + V_0),$$

where $F_0$ – a average value of function $F_z(V)$; $F_a$ – amplitude; $V_0$ – a starting phase; $V_p$ – the period of function $F_z = F_z(V)$.

Repeated experiment under the same conditions, but on other equipment shows, that the amplitude and the sinusoid period do not change. The coordinate of an average line and a sinusoid starting phase changes. It means, that the change of the consumed mechanical energy by the cutting system is observed at the same cutting conditions. The found out dependace was early proved during the experiments of Zorev, Isaev, Bobrov [5, 10, 11].

Therefore it is obvious, that it is possible to draw a sinusoid through experimental points of the cutting force dependence on the cutting speed. The amplitude of this sinusoid depends on the concrete cutting conditions. Approximating dependences for the ferrous metals have periods $V_p \approx 0{,}5$ m/s.

The position of an average line and of sinusoid starting phase are extremely sensitive to any changes (rake face roughness, a chemical compound, etc.) and they are the main reasons for the cutting forces experimental values dispersion and it is explained by stochasticity of the cutting process.

## 7 RESULTS AND DISCUSSION

Hence, taking into account the stochasticity inherent to the turning process, it is possible to come to the conclusion, that the calculated and practical results cannot match to each other at all. And this problem is not solvable until the mechanism of the cutting speed influence to the forming of the internal energy level in a processed material is found out at purposeful destruction.

However the new calculation concept advantage is that the flexible mathematical approach is offered convenient for the automated calculations. It is especially important, the mathematical model allows to calculate characteristics of the cutting process at turning without any joint tests of the instrumental and processed materials. Besides, the calculating complex created on the basis of the observed concept, is capable for adaptation to the specific production conditions in case of specification of dependence of $F_z$ from the cutting conditions parametres on a working place. If the calculations are based on the cutting force measurements during turning, their accuracy will be defined only by difference of the tool material mechanical properties from their average statistical values.

On the basis of the cutting process advanced physical model the mathematical model was developed. The model contains new concepts for the cutting theory, such as: the cutting system efficiency, the tool limiting work, a material plasticity index.

The created mathematical model is informative, that is allowing not only to represent necessary knowledge from the metal cutting theory, but it allows to join the new knowledges. The desing program is compact, it does not demand extensive databases. The processed materials database includes the parametres of the stresses/deformations dependence diagram gained at the standard strength tests, as well as factor and an exponent in expression for the cutting temperature calculation. For example, there is a workpiece material as ANSI 1045 steel: $\sigma_f$ = 0,7 GPa, $\varepsilon_f$ = 0,55, $\sigma_{l.e}$ = 0,36 GPa, $\varepsilon_{l.e}$ = 0,0017; $k$ = 11·104, $q$ = -1,2. The diagram parametres can be set in the form of dependence, as: . The tool materials database includes compression strength, critical temperature and limiting number of cycles. For the tool material Carbide P20 (15% TiC, 6% Co): $\sigma_f$ = 1,1 GPa, $\theta_{cr}$ = 800 °C, $u$ = 105. Designing by the proposed technique is a choice of acceptable parametres of machining at turning on the virtual equipment.

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