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CUTTING PROCCESS OPTIMIZATION ON THE BASE OF CNC ADAPTIVE PROGRAMMING

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ABSTRACT

Key characteristics of state-of-the-art CNC cutting machine tools – precision, rigidity, productivity are increasing permanently, while in major of cases they are not using accordingly. Reason of so called ravine is in implementation of non up-to-date approaches of process planning and calculation of process related parameters.

Paper describes Adaptive Part Programming (APP) approach which enables to carry out selection of parametrical optimization rules and calculation of tool path geometry directly on CNC machines according to actual values of workpiece parameters. Flexibility of optimization rules selection and possibility to calculate automatically tool path geometry for the each workpiece enlarges range of compensation of disturbances of traditional adaptive control systems with one, "unchangeable" rule.

Thus, implementation of APP with existing adaptive control systems makes possible implementation of cheap workpieces with considerable dispersion of hardness and geometry without arising the complexity of manufacturing processes and cost by using the advanced possibilities of CNC machine tools.

KEYWORDS

Adaptive control, Feedrate, Cutting Speed, Taylor equation, Tool life period, Optimization criteria, Expenses, Boundary conditions, Machining cost.

1. INTRODUCTION

Cost effective manufacturability is still remain the key factor of development of nowadays competitive manufacturing technologies. Total production cost of new product can be represented by the sum of *two* general components

$$Q_\Sigma = Q_W + Q_M$$

where, Q_W is the cost of workpiece and Q_M is the cost of machining.

They have mutual reverse action and cause non-monotone character of Q_Σ (see Figure 1). For instance, low precision workpieces are cheap while for their fabrication are using low cost technologies

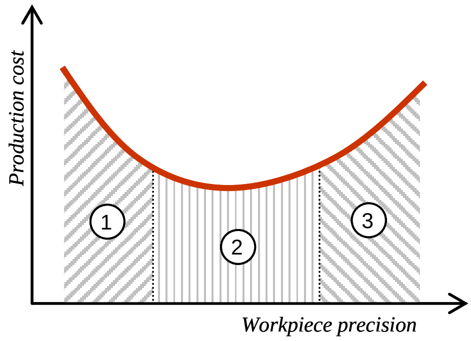


Figure 1 Non-monotonic function of total production cost

of welding, die casting, etc. However machining cost is high while requiring additional machining operations and cutting conditions are couple of time prediminished for ensuring reliability of machining processes. As a result total cost of production Q_Σ is arising (zone 1 in Figure 1). In case of usage of high precision workpieces cost of machining is low. However, workpieces are expensive because of usage of high cost process for their fabrication – casting in forms, pressing, etc. As a result total production cost is also arising (zone 3 in Figure 1). Low profitability of this way is especially strongly pronounced for small batch sizes [1].

Selection of optimal types of workpieces for given manufacturing conditions (zone 2 in Figure 1) is the scope of manufacturing process planning. Number of methods is belonging to this task. Most remarkable are approaches come from K.Swift [2] and Dewhurst&Boothroyd [3, 4].

Further decreasing of production cost is possible by development of existing technologies of workpiece fabrication or by development of manufacturing processes enables usage of cheap workpieces without arising additional cost of machining.

Paper represents way of improvement of manufacturing technologies enabling implementation of cheap workpieces for machining without increasing of additional cost for manufacturing. Production cost diagram in this case can be converted into monotonely decreasing function (see Figure 2).

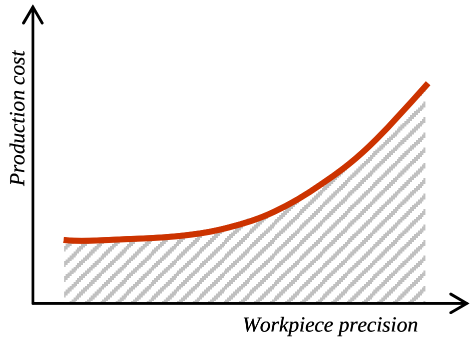


Figure 2 Monotonic function of total production cost

One of the possible ways in this direction is development of methods of parametrical optimization of machining processes. Machining parameters are preliminary diminished in order to ensure reliability of machining. So, here is reserve for reduction of production cost. There is certain number of methods of parametrical optimization of machining. They can be divided into *two* general classes: methods enables selection of machining parameters corresponding to minimal production cost without taking into consideration expenses on cutting tools and methods, optimize parameters on the base of optimal tool life period of cutting tools.

T.Toth [5], Detzky [6], Kundrak [7] suggest optimization of machining parameters by minimization of machining time. L.Deriabin [8], Kapustin [9], Komisarov [10] voted for minimization of length of cutting tool movement path. However all these methods don't consider expenses on cutting tool conditioned with wear of tool during the machining.

There are various models enable calculation of tool life period for given machining conditions. All of them are coming from the generalization of manufacturing experience and experimental data, while existing understendence of physical nature of wear of cutting tool during the machining is limited because of the influence on the process of plastic deformation of metal, large amount of parameters. Most complete representation gives extended equation of Taylor

$$T = \frac{C_T}{V^{\mu} \cdot S^{\nu} \cdot t^{\rho}} \qquad (1)$$

where, T – tool life period; V – cutting speed; S – feedrate; t – depth of cut; C_T, μ, ν, ρ – coefficients depending on the physical properties of workpiece and cutting tools.

Model (1) is supported by a large number of experimental data and manufacturing experience. Sandvic Coromant Co., (Sweden) [11] normalize experimental data corresponding to model (1) for selection of cutting parameters on the base of ISO standard. Typical values of machining parameters corresponding to type of cutting tools and workpiece are placed into tables. Company also provides rules of selection of machining parameters from the table which are corresponding to the optimal cost of machining. There are certain number of methods built on the base of (1). Tverskoi [12], Weibah [13] suggest methods of minimization of machining cost by finding the optimal value of tool life period (1). However, all above described methods of parametrical optimization foresee calculation of optimal parameters in respect of given manufacturing conditions before the machining, on the stage of CAPP. From the other point of view manufacturing process is always experiencing influence of disturbances. Disturbances, here and below, implying difference between the preliminary defined and real values of parameters associated with the machining process. For instance, values of workpiece hardness and geometry are fluctuated. Especially for cheap workpieces such as welding and die casting, for rough operations standard deviation of hardness of iron alloys will reach 46% of average value and 48%

Table 1 Dimensional dispersion ε of workpieces; D_{max}=*100mm*

	Hand-Books ε_1 (mm)	Experience ε_2 (mm)	Sources ε_3 (mm)
CASTING	2.6	2.6	1.8
PUNCHING	4	3.7	3.5
ROLLING	4.32	-	4.7
WELDING	5.3	8.1	16.8

for aluminum alloys [14]. Dimensional fluctuations of cheap workpieces are also considerable. Table 1 illustrates results of investigation done by reviewing of engineering hand books [15], manufacturing experience and literature sources [2], [8].

Thus, above considered methods of parametrical optimization cannot be implemented for the machining conditions where influence of disturbances is high. For such conditions considered methods can be used just for the normalization of process on CAPP.

It is possible to compensate the influence of disturbances by using of adaptive control systems. They enable calculation of process parameters in real time according to actual values of workpiece parameters and optimization rules. Typical representatives are systems of stabilization of cutting forces by control of feedrate for constant cutting speed [16], etc. However, optimization rule which is base for calculation of parameters can not be changed during the real time control. This rule remains the same during the full period of machining. In one's turn compensation of disturbances by control under the one, "unchangeable" rule cannot always brings the optimal value of parameters. For instance, it was confirmed [17], [18] that compensation of dispersion of depth of the cut by stabilizing the cutting forces for some cases will considerably arise the temperature in cutting zone and as a result increase wear of cutting edges. As a result adaptive systems bring non-optimal control while dramatically increase expenses connected with cutting tools. Control by the one, "unchangeable" rule is the main reason why adaptive control systems cannot find the wide implementation nowadays. They are usually using for very specific cases of machining. Improvement ability of adaptive systems in order to control process according to changeable optimization rules requiring controllers with high computing power in order to process feedback in real time. This is still an important consideration.

Paper describes Adaptive Part Programming (APP) approach which enables to carry out selection of parametrical optimization rules and calculation of tool path geometry directly on CNC machines according to actual values of workpiece parameters. By other words it means process control not only by the spindle and feedrate channels but also by the 3rd channel in face of tool path geometry. Flexibility of optimization rules selection and possibility to calculate automatically tool path geometry for the each workpiece enlarge range of compensation of disturbances of traditional adaptive control systems with one, "unchangeable" rule.

Thus, implementation of APP with existing adaptive control systems makes possible to use cheap workpieces with considerable dispersion of hardness and geometry without arising the complexity of manufacturing processes and cost.

2. OPTIMIZATION CRITERIA

The goal of machining operation can be formulate as follow: machining of desired quantity of workpieces with required technical characteristics in given period of time and provision in same time the minimal labor inputs and materialized labor.

General expenses of machining of one workpiece summarize prime cost of machining and capital investments in production assets. General expenses related with machining parameters can be calculated as follow [12]

$$Q = \left(\tau_M + \frac{\tau_I}{N}\right) \cdot Q_T + \frac{Q_I}{N} \qquad (2)$$

where, τ_M - machining period; τ_I - standstill of machine tool due by the changing of cutting instrument; Q_T - expenses on maintenance of machine tools and labor cost in one unit of time (cent); Q_I - expenses on maintenance of cutting tools and labor cost (cent); N - number of produced parts in the tool life period.

For the terms of turning of same parts with same machining parameters, it can be assumed that $N = \frac{T}{\tau_M}$ and $\tau_M = \frac{\ell}{V \cdot S} \cdot \frac{Z}{t}$ where, T - tool life period; ℓ - length of tool movement path; V - cutting speed (m/sec); S - feedrate (mm/turn); t - depth of cut (mm), Z - total allowance.

Thus, following expression can be received from (2)

$$Q = \ell \cdot Z \cdot Q_T \cdot \left(\frac{1}{V \cdot S \cdot t} + \frac{\tau_I + Q_I / Q_T}{V \cdot S \cdot t \cdot T} \right) \qquad (3)$$

where,

$$q = \frac{1}{V \cdot S \cdot t} + \frac{\tau_I + Q_I / Q_T}{V \cdot S \cdot t} \qquad (4)$$

represents machining expenses of one unit of volume of workpiece material.

By putting of described above Taylor model of tool life period (1) into (4) we will receive final optimization criteria characterizing minimal expenses of turning for optimal values of machining parameters

$$q = \frac{1}{V \cdot S \cdot t} + \frac{\gamma}{C_T} \cdot V^{\mu-1} \cdot S^{\nu-1} \cdot t^{\rho-1} \qquad (5)$$

where, $\gamma = \tau_I + \dfrac{Q_I}{Q_T}$.

Optimal value of q can be found from the condition as follow:

$$\frac{\partial q}{\partial V} = 0 , \quad \frac{\partial q}{\partial S} = 0 , \quad \frac{\partial q}{\partial t} = 0 \qquad (6)$$

For $\dfrac{\partial q}{\partial V} = 0$ we have

$$\frac{\gamma}{C_T} \cdot (\mu - 1) \cdot V^{\mu} \cdot S^{\nu} \cdot t^{\rho} = 0 \qquad (7)$$

By putting (1) into (7) we will receive well known equation of so called economical tool life period

$$T_V = \gamma \cdot (\mu - 1) \qquad (8)$$

For $\dfrac{\partial q}{\partial S} = 0$ we have $\dfrac{\gamma}{C_T} \cdot (\nu - 1) \cdot V^{\mu} \cdot S^{\nu} \cdot t^{\rho} = 0$ and as a result

$$T_S = \gamma \cdot (\nu - 1) \qquad (9)$$

According to results of investigations described in literature sources coefficients μ, ν, ρ have minimal dependence on parameters of machining conditions. Therefore, it can be admitted that right part in (8) and (9) have constant values and defined by τ_I, Q_I and Q_T. So, optimal values of V for different combinations of values S and t are corresponding to the same period T_V of tool life. Also, optimal values of S for different combinations of values V and t are corresponding to the same period T_S of tool life. Geometrically it can be interpreted as follow, on 2D plane ($V \times S$) equation (8) expressed by the line lying on the tangent points of q (5) and vertical lines which are corresponded to the constant values of feedrates ($S_1, S_2 \ \dots S_n$) Figure 3. In same way equation (9) can be described by the line which is lying on the intersection tangent points of q isochrones lines and lines of constant values of cutting speed ($V_1, V_2 \dots V_n$).

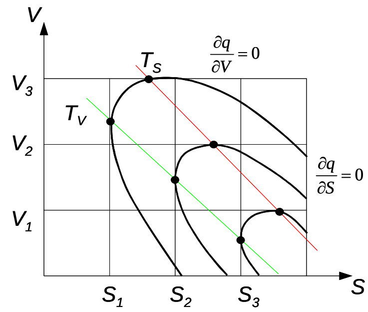


Figure 3 geometrical interpretations of optimization criteria

Thus, for the condition $\dfrac{\partial q}{\partial V} = 0$, T_V line is the minimum locus of q (5) and for $\dfrac{\partial q}{\partial S} = 0$ so place is T_S line.

Bare minimum of parameters (V, S) can be found from the equations (7) and (8) for the condition (6)

$$V^* = \left(\frac{C_T}{\gamma \cdot (\mu - 1) \cdot S^{\nu} \cdot t^{\rho}} \right)^{\frac{1}{\mu}} \qquad (10)$$

$$S^* = \left(\frac{C_T}{\gamma \cdot (\nu - 1) \cdot V^{\mu} \cdot t^{\rho}} \right)^{\frac{1}{\nu}} \qquad (11)$$

As usual $\mu > \nu$ while cutting speed has more strong influence on tool life period than feedrate. Therefore, value of q is decreasing along the T_V, T_S lines to the direction of S axis. So, minimum value of q can be reached in $V_0 = V_{\min}$. $V_{\min}$ in this case is the minimum value of cutting speed defined from the area of existence of Taylor model (1). Thus, unconditional optimum of q (5) exists in the point with coordinates (V_0, S^*), where

$$S^{*} = \left(\frac{C_T}{\gamma \cdot (\nu - 1) \cdot V_0^{\mu} \cdot t^{\rho}} \right)^{\frac{1}{\nu}} \tag{12}$$

Value of S^{*} calculated from (12) is too great and lying outside the area of technological limitations and area of existence of Taylor model (1) also. As a result, optimization criteria q (5) based on the Taylor model (1) has no unconditional optimum. It has just conditional optimum which is located on the boundary of the area of permissible values of (V, S). Same conclusions described also in several literature sources.

Permissible area of (V, S) is defined by the boundary conditions which are expressing dynamical limitations of technological system, *M̲achine-F̲ixture-T̲ool-W̲orkpiece* (MFTW). Generally these conditions can be expressed as functions of machining parameters (V, S, t)

$$C_{m_i} \cdot V^{\alpha} \cdot S^{\beta} \cdot t^{\gamma} = M_i \leq \left[\Pi_i \right] \tag{13}$$

where, C_{m_i} - constant described by the machining conditions; M_i-boundary condition; Π_i-permissible value of M_i.

While q (5) has just conditional optimum which is lying on the boundary of area, generally it can be concluded that optimal value of q located on the intersection point of *two* boundary conditions. Thus, it is possible to find this point by solving the system of equation as follow:

$$\begin{bmatrix} H = C_H \cdot V^{\alpha_H} \cdot S^{\beta_H} \cdot t^{\gamma_H} \\ \Phi = C_\Phi \cdot V^{\alpha_\Phi} \cdot S^{\beta_\Phi} \cdot t^{\gamma_\Phi} \end{bmatrix} \tag{14}$$

By substituting (14) into (5) we can receive equation enabling calculation of conditional optimum of q on the intersection point of *two* boundary conditions

$$q = a \cdot t^{\eta} + \frac{\gamma}{C_T} \cdot b \cdot t^{\lambda} \tag{15}$$

where,

$$a = \frac{\left\{ [H] \cdot C_H^{-1} \right\}^{\left(1/\beta_H\right) \cdot \left(\beta_\Phi / \alpha_\Phi - 1\right)}}{\left\{ [\Phi] \cdot C_\Phi^{-1} \right\}^{1/\alpha_\Phi}}$$

$$b = \frac{\left\{ [\Phi] \cdot C_\Phi^{-1} \right\}^{(\mu - 1)/\alpha_\Phi}}{\left\{ [H] \cdot C_H^{-1} \right\}^{\left(1/\beta_H\right) \cdot \left(\beta_\Phi \cdot \mu / \alpha_\Phi - \beta_\Phi / \alpha_\Phi - \nu - 1\right)}}$$

$$\eta = \frac{\gamma_\Phi}{\alpha_\Phi} + \frac{\gamma_H}{\beta_H} - 1 - \frac{\gamma_H \cdot \beta_\Phi}{\gamma_\Phi \cdot \beta_H}$$

$$\lambda = \left(\frac{\gamma_H \cdot \beta_\Phi}{\alpha_\Phi \cdot \beta_H} - \frac{\gamma_\Phi}{\alpha_\Phi} \right) \cdot (\mu - 1) - \frac{\gamma_H}{\beta_H} \cdot (\nu - 1) + \rho - 1$$

3. OPTIMIZATION RULES

Boundary conditions can be grouped as follow:

I. Force parameters of machine tools:

- Cutting power

$$N = \frac{1}{6120} \cdot V \cdot C_{P_Z} \cdot S^{\beta_Z} \cdot t^{\gamma_Z} \cdot HB^{n_Z} \tag{16}$$

where, HB is rigidity of workpiece

- Cutting moment

$$M = 0.5 \cdot 10^{-3} \cdot D \cdot C_{P_Z} \cdot S^{\beta_Z} \cdot t^{\gamma_Z} \cdot HB^{n_Z} \tag{17}$$

where, D is cutting diameter.

II. Kinematic ability of machine tools

- Permissible values of V and S

$$\begin{vmatrix} V_M \leq V_{\max} \\ S_M \leq S_{\max} \end{vmatrix} \tag{18}$$

- Lateral cutting force

$$P_x = C_{P_x} \cdot S^{\beta_x} \cdot t^{\gamma_x} \cdot HB^{n_x} \tag{19}$$

III. Strength of cutting tools expressed through the tangential cutting force

$$P_z = C_{P_z} \cdot S^{\beta_z} \cdot t^{\gamma_z} \cdot HB^{n_z} \tag{20}$$

IV. Quality of machined surface

- Dimensional accurateness and profile precision expressed by the longitudinal cutting force

$$P_y = C_{P_y} \cdot S^{\beta_y} \cdot t^{\gamma_y} \cdot HB^{n_y} \tag{21}$$

- Roughness of machined surface

$$R_z = \left[\frac{S_o \cdot t^{\gamma_z} \cdot (\varphi \cdot \varphi_1)^{z_c}}{C_s \cdot r^u} \right]^{\frac{1}{\gamma_s}} \qquad (22)$$

where, φ, φ_1 are cutting tool front and back angles on plane; r is radius of tool nose.

In case of admission that corresponded curves of above described boundary conditions are lines on ($V \times S$) plane it is possible to represent areas of permissible values V, S in 3 dimensional ($V \times S \times t$) space by the planes (see Figure 4).

Plane orientation and position are depending on the existing parameters of MFTW system. As picture indicates orientation and positioning of boundary condition planes for each value of t define the status, either the boundary condition is active, if it is describing area of permissible values of (V, S), or passive if it is lying outside of area.

For instance, for $t = t_a$ area of permissible values is formed from the boundary conditions $[N]$ and $[P]$ (section A in Figure 4); while for $t = t_b$ area has changed – boundary condition $[P]$ replaced by $[S]$ and condition $[V]$ also becomes active.

As it was mentioned above optimum of q is lying on the intersection point of *two* boundary conditions. These conditions can be taken from described above 4 groups. Therefore, so called optimization rules, in

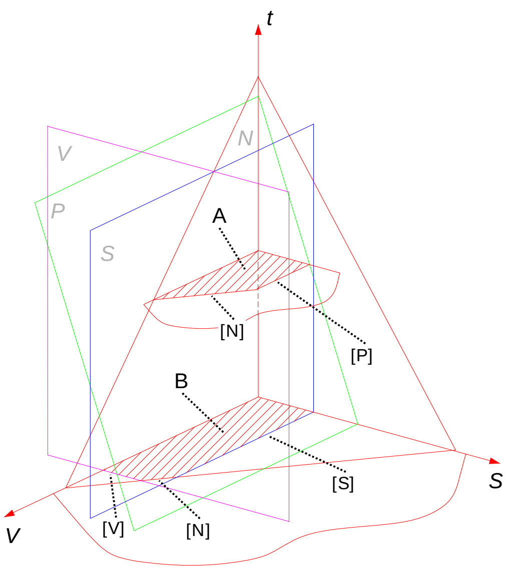


Figure 4 Area of permissible values of parameters on *VxS* planes

the form of pair of boundary conditions can be formed. However, there is a special condition which sets the limitation for ensuring constant value of predefined period of tool life ($T = Const$). This is the typical case during the manufacturing, when it is necessary to machine given quantity of parts into given period of tool life. This boundary condition can be found from (5) and (13) by implementing of method of Lagrangian coefficients. Thus,

$$T_0 = \gamma \cdot \left[\frac{\frac{\partial T}{\partial V} \cdot \frac{\partial M}{\partial S} - \frac{\partial T}{\partial S} \cdot \frac{\partial M}{\partial V}}{\frac{\partial M}{\partial V} \cdot \frac{\partial M}{\partial S}} - 1 \right]$$

where from

$$T_0 = \gamma \cdot \left(\frac{\alpha \cdot \nu - \beta \cdot \mu}{\alpha - \beta} - 1 \right) \qquad (23)$$

Investigations shows [24], [25] that for the conditions $S/t < 1$ it can be assumed that (23) permits calculation of fixed values of optimal period of tool life without taking into consideration the actual values of (V, S, t). Thus, these values of T_0 will be set the limitation of calculation V, S according to (1)

$$T \le T_0 \qquad (24)$$

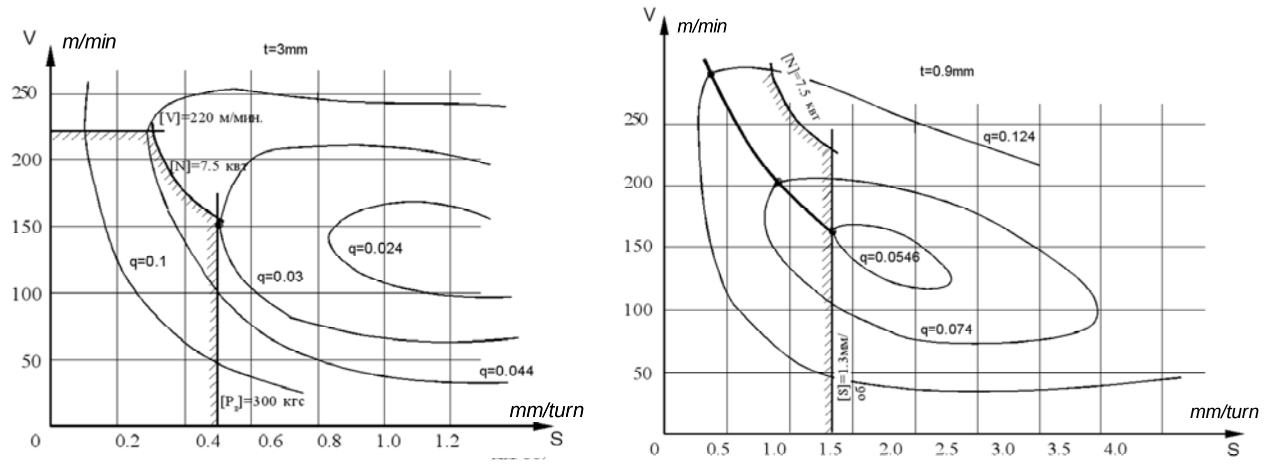
Boundary condition (24) will be active in case of existence of condition as follow

$$\frac{\alpha \cdot \nu - \beta \cdot \mu}{\alpha - \beta} > 1 \qquad (25)$$

because of tool life period cannot be negative.

Thus, changing value of depth of cut t cause deformation of area of permissible values of (V, S) by changing status of boundary conditions. If (25) is true, condition (24) will be active and optimum of q (15) will be lying on the intersection point of curve $T \le T_0$ with curve of one of the boundary condition from the 4 group described above.

Below is given example which illustrates received conclusions. Machining conditions are as follow: workpiece material – Stainless steels HB=180; Cutting tool GC415 (ISO standard) with front angle $\varphi_0 = 0.785 rad$ and back angle $\varphi_1 = 0.785 rad$.



a) t=3mm active conditions [V], [S], [N] **b)** t=0.9mm active conditions [T_v], [S]

Figure 5 Deformation of permissible area of (*V, S*)

Boundary conditions: $\left[P_z\right]=30n$, $\left[V\right]=220\, m/\min$ $\left[S\right]=1.3 mm/turn$; $\left[N\right]=7.5 kwt$.

For $t=3mm$ (see Figure 5, a) optimum of q ($q=0.03$) reached in the intersection point of $\left[N\right]$ and $\left[P_z\right]$. However, for the $t=0.9mm$ (see Figure 5, b) area is deforming, boundary condition $\left[P_z\right]$ goes into passive and $\left[S\right]$ becomes active. Also, condition (25) is true and optimal value of q ($q=0.0546$) corresponds to the intersection point of $\left[T_v\right]$ and $\left[S\right]$.

As it was described above optimization rules represent pair of boundary conditions. Corresponding curves for the given machining conditions and depth of cut will be intersected into the point of optimum value of q (15). One of the boundary condition in the pair will be condition from described above 4 groups. Another condition in the pair will be either condition of optimal period of tool life, or other boundary condition from the 4 groups. Formation of rules has to be based on the tipization of various cases of machining. One of the condition in the rule have to be equation expressing functional dependence on cutting speed while V is the control parameter. Therefore corresponding conditions will be as follow: $\left[V\right]$, $\left[N\right]$ and also $\left[T_v\right]$ (8) coming from $\dfrac{\partial q}{\partial V}=0$; Accordingly, while another control parameter is feedrate, corresponding conditions for formation of optimization rules will be $\left[S\right]$, $\left[P\right],\left[M\right]$ and also $\left[T_s\right]$ (9) coming from $\dfrac{\partial q}{\partial S}=0$.

However, T_s exists in very rear cases of machining so it can be excluded from the consideration. Thus, we have received two arrays of conditions (see Figure 6) and following set of optimization rules can be formed:

$\left[PV\right]$, $\left[SV\right]$, $\left[ST\right]$, $\left[PT\right]$, $\left[SN\right]$,$\left[PN\right]$, $\left[MV\right]$, $\left[MN\right]$, $\left[MT\right]$.

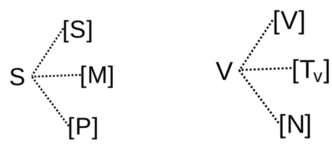
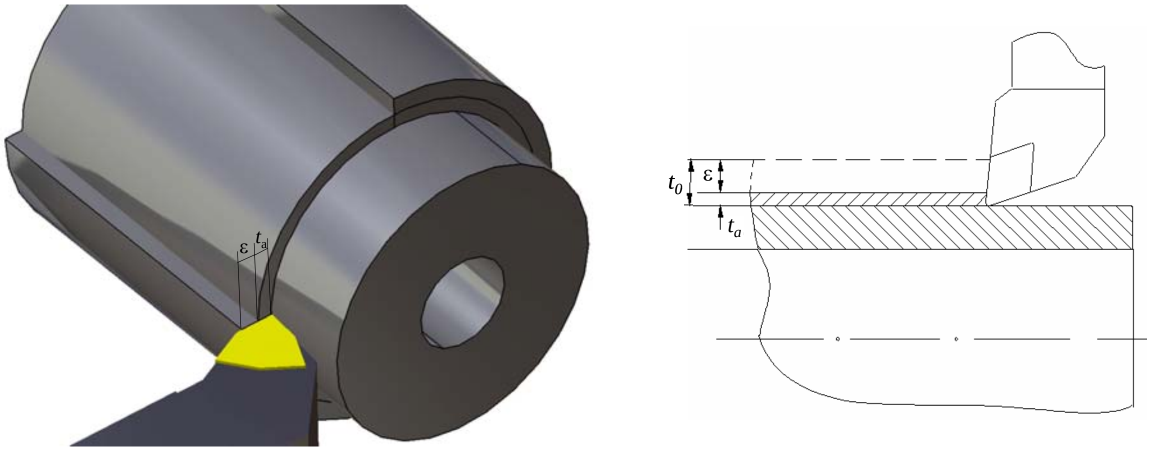


Figure 6 Arrays for the separation of optimization rules

4. COMPARATIVE ANALYSIS

APP foresee process control not only by V and S but also by changing the tool path geometry according to the actual value of disturbances. Below is given quantitive analysis of effectiveness to be expected in this case. Comparative estimation of *two* processes – fixed rule adaptive control and APP have to be done.

Five typical cases of turning have been chosen for analysis. Tools and workpiece types are selected according to ISO standards. τ_I and Q_I are from equation (4).



t_0 – calculated value of depth of cut
t_a – actual value of depth of cut
ε – value of disturbance

Figure 7 Fixed rule adaptive control without correction of tool path geometry

1) Workpiece - P20HB180; Cutting tool – GC415; $\tau_I =$ 2min; Q_I =6.7cent; $[P_z]$=30N; $[P_y]$=4N; $[R_z]$=0.002mm
2) Workpiece - K20HB260; Cutting tool – GC435; $\tau_I =$ 2min; Q_I =6.7cent; $[P_z]$=30N; $[P_y]$=7N; $[R_z]$=0.002mm
3) Workpiece – P30HB200; Cutting tool – GC415; $\tau_I =$ 2min; Q_I =6.7cent; $[P_z]$=30N; $[P_y]$=7N; $[R_z]$=0.002mm
4) Workpiece – P01HB100; Cutting tool – GC415; $\tau_I =$ 2min; Q_I =6.7cent; $[P_z]$=30N; $[P_y]$=7N; $[R_z]$=0.002mm
5) Workpiece - M20HB170; Cutting tool – GC435; $\tau_I =$ 2min; Q_I =6.7cent; $[P_z]$=25N; $[P_y]$=7N; $[R_z]$=0.002mm

Corresponding values of C_T, μ, ν, ρ, C_{P_z}, β_z, γ_z, C_{P_y} β_y, γ_y, n_{P_z}, n_{P_y}, γ have been chosen from machining hand books.

4.1. Fixed rule adaptive control WITHOUT correction of tool path geometry

For this case number of tool pass and tool path geometry including coordinates of support points of path remain the same without any changes during the full machining operation (see Figure 7). Adaptive control for actual value of depth of cut t_a is caring out by control of V and S according to optimization rule.

Exponent λ in (15) for all 5 typical cases of machining is negative. As a result for substantial diminution of depth of cut, $0 < \varepsilon \le t_0$ second item in (15) is increasing rapidly and involve growing of q. Physical explanation of this phenomenon is as follow, system reaction on reduction of depth of cut expressed in the growing of values of S and V according to optimization rule. For some changed values of t values of S and V can be reached margins where temperature in cutting zone is increasing rapidly. Thus, conditions of plastic deformation of metal are changing and wear of surface of cutting edge becomes more intensive. Therefore tool life period is reducing and expenses relating with cutting tool – number and time of tool changes, tool recovery and set-up operation are growing.

As a result for the big steepness of growing of q (15) , despite of reduction of volume of material to be removed connected with diminution of t, general expenses on machining Q (3) are growing accordingly.

For all of that as smaller is the value of λ the influence described above is stronger. For the optimization rule $[PV]$ value of λ is located in $\lambda_{[PV]} = -0.61 \div -1.73$. Corresponding curves of q and Q_Σ are presented in Figure 8.

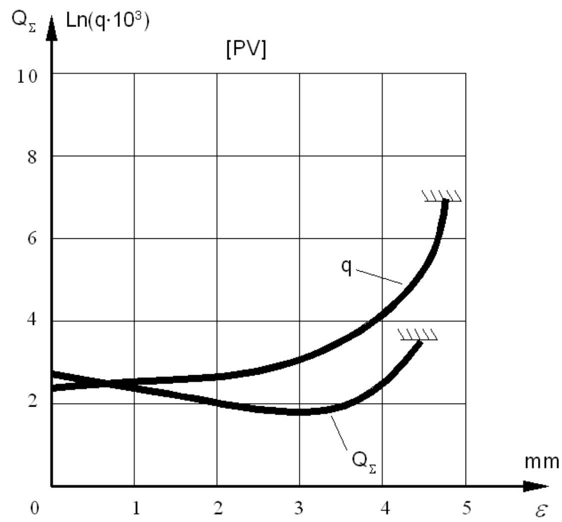


Figure 8 Workpiece K20HB260, ∅100mm; Cutting tool – GC435; P_z=30n; V=150m/sec; t=5mm

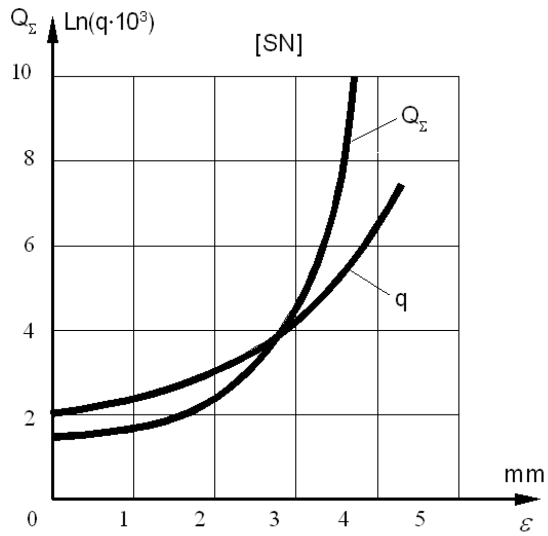


Figure 10 Workpiece K20HB260, ∅100mm; Cutting tool – GC435; P_z=30n; V=150m/sec; t=5mm

As it is apparent, growing steepness of q (15) is big and it has major influence on Q_Σ (3) in comparison of reduction of volume of material to be removed. Therefore, in case of growing ε and accordingly reduction of t, expenses on machining are increasing greatly. For all of that as great is value of $[P]$ and $[V]$ described influence becomes stronger.

For the optimization rule $[PT]$ values of λ are in the range of $\lambda_{[PT]} = 0.04 \div -0.18$. Corresponding curves of q and Q_Σ are presented in Figure 9. As it is apparent q (15) is growing lightly and almost it has no influence on total expenses Q_Σ which is decreasing pro rata to reduction of material to be removed.

For optimization rules $[SN]$ and $[PN]$, values of λ are in the range $\lambda_{[SN]} = -2.28 \div -4.25$ and $\lambda_{[PN]} = -0.62 \div -1.73$ accordingly. Therefore dependence Q_Σ on q has the same character as it was in case of $[PV]$ rule. However, it is expressed stronger (see Figures 10, 11).

Same results are received for rules $[MV]$ and $[MN]$. For the $[MV]$ rule value of λ is same as it was for $[PV]$ and character of Q_Σ is also the same. For the rule $[MT]$ values of λ are located in $\lambda_{[MT]} = 0.04 \div 0.18$. So, q has unimportant influence on Q_Σ.

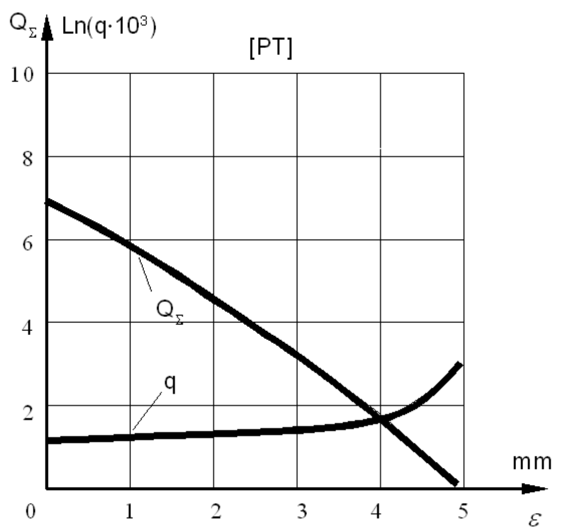


Figure 9 Workpiece K20HB260, ∅100mm; Cutting tool – GC435; P_z=30n; V=150m/sec; t=5mm

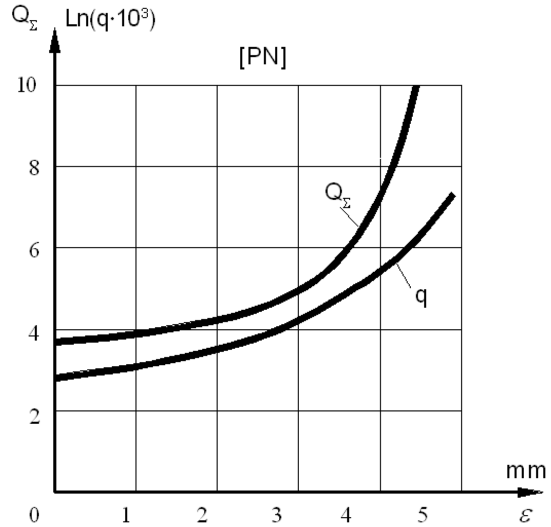
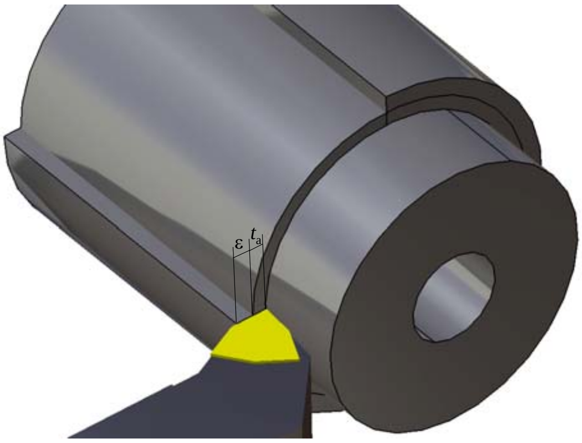
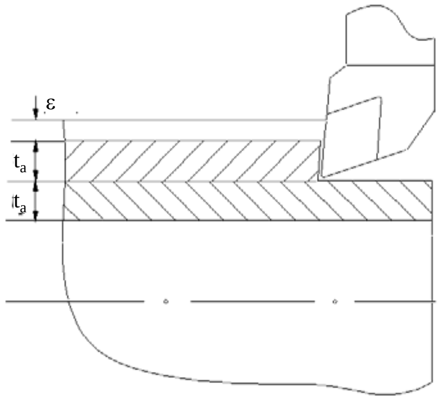


Figure 11 Workpiece K20HB260, ∅100mm; Cutting tool – GC435; P_z=30n; V=150m/sec; t=5mm





t_0 – calculated value of depth of cut
t_a – actual value of depth of cut
ε – value of disturbance

Figure 12 Fixed rule adaptive control with correction of tool path geometry

Thus, for the significant fluctuation of depth of cut t, process control under the majority of fixed optimization rules brings reduction of effectiveness of machining. Therefore, correction of V and S is desirable in the comparatively small range of changing of depth of cut.

4.2. Fixed Rule Adaptive Control WITH correction of Tool Path Geometry

For this case according to the actual dimensions of workpiece number of tool pass, depth of cut on each pass and geometry of tool path movement are re-calculating accordingly (see Figure 12).

Adaptive control for actual value of depth of cut is caring out by control of V and S according to optimization rule.

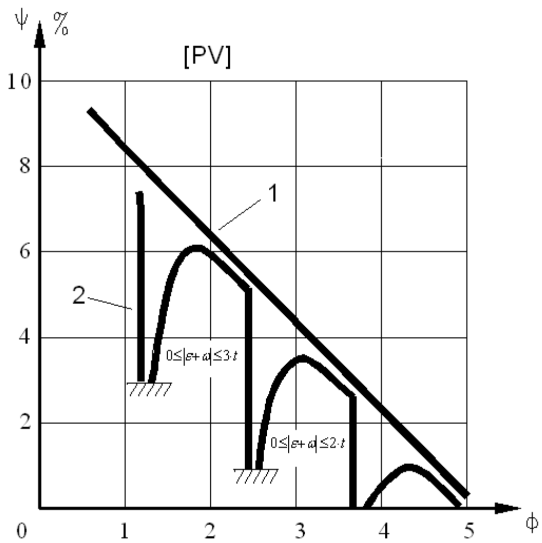


Figure 13

As a result fluctuation of workpiece geometry don't cause substantial changes of depth of cut as it was in previous case. Value of ε is redistributing on recalculated passes. Therefore t never reduced up to the value where increasing of q (15) caused by fixed rule adaptive control may have the considerable influence on Q (3). Thus total expenses Q_Σ are reducing pro rata to the volume of material to be removed. Corresponding curves for the optimization rules $[PV]$, $[SN]$, $[PN]$, $[MV]$, $[MN]$ have identical character (see Figure 13).

Here $\psi = \left(\frac{Q_0}{Q_a} - 1\right) \cdot 100\%$ describes effectiveness of correction of V and S, where Q_0 are total expenses before correction and Q_a, after correction of (V, S) according to actual value of t and optimization rule. Also, $\phi = t_0 / t_a$ describes decrement of depth of cut by value of ε. As the diagram is indicating (V, S) control under the fixed optimization rule with simultaneous correction of tool path geometry (curve 1 in Figure 13) ensure reduction of total expenses for the whole range of values of t, $0 < \varepsilon \le t$, $0 < \varepsilon \le 2t$, $0 < \varepsilon \le 3t$, etc. Whereas, adaptive control without correction of tool path geometry characterized with so called critical areas where effectiveness of (V, S) correction is reducing dramatically (curve 2 in Figure 13).

For the optimization rules $[PT]$, $[MT]$ there is no difference between the methods. Therefore, correction of tool path geometry has no purpose

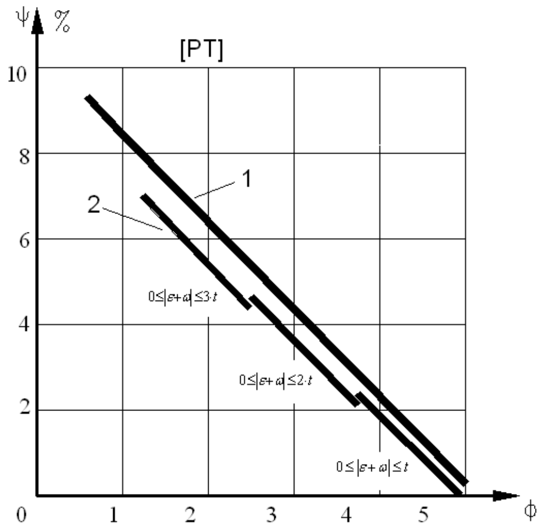


Figure 14

while there are no critical areas of reduction of effectiveness of correction (curve 2 in Figure 14).

5. APP CONCEPT

APP concept foresee calculation of tool path geometry according to actual geometry of stock, identified after fixation of workpiece on machine tool.

Workpiece geometry can be measured directly on CNC machines by implementation of entry control

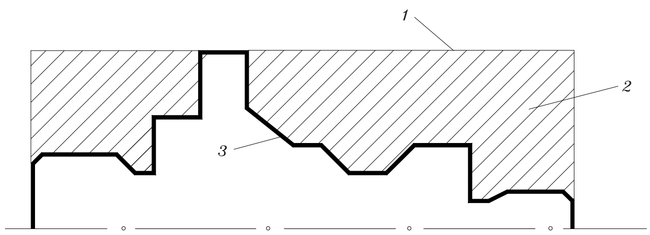


Figure 15 1-Workpiece surface, 2-Stock, 3-Part surface

systems. Nowadays it is widely implementing Ranishaw Co. contact tensors. They realize automated procedures of control with CNC and enables high precision of measurement of workpiece, part and also cutting edge geometry.

CNC can do calculation of tool path geometry on the base of corresponding mathematical models. They formalize the typical combinations of 3 main items – machining stock, cutting tool and tool movement scheme.

Machining stock is formed on one side by part surface and on another side by surface of workpiece (see Figure 15). Stock geometry defines possible nomenclature of cutting instruments for stock removal and finally each instrument describes corresponding types of tool movement plans. Schematically this kind of dependence can be represented by the hierarchical tree (see Figure 16), where the top element of hierarchy corresponds to the array of typical stocks of machining. Then level below describes array of cutting tools and final level represents the array of tool movement path. Each branch on this tree expresses the typical case of machining and can be used for the formation of particular model of tool path calculation. For instance branch $A-B-C$ in Figure 16 corresponds to the one particular model $M_1=\{A_1-B_1-C_1\}$. Another model represented by the formalism $M_2=\{A_1-B_2-C_4\}$, etc.

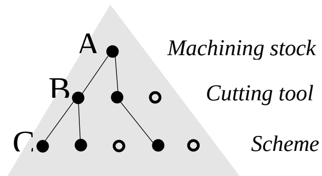


Figure 16 Hierarchical tree of formalization

Typization of turning stock is caring out on the base of *two* formal structures STHO and STCL enable description of all possible geometrical configurations of turning stock. They are described in [20] and presented in Figures 17, 18.

Rough cut turning of STHO preferable to realize [20]

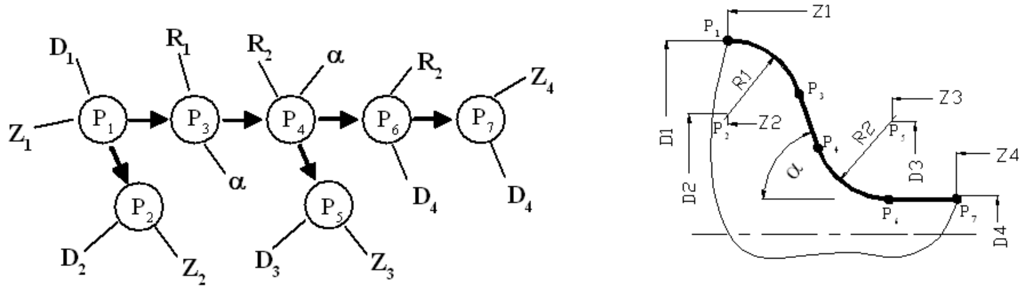


Figure 17 Half-open stair STHO with topology and parameterization

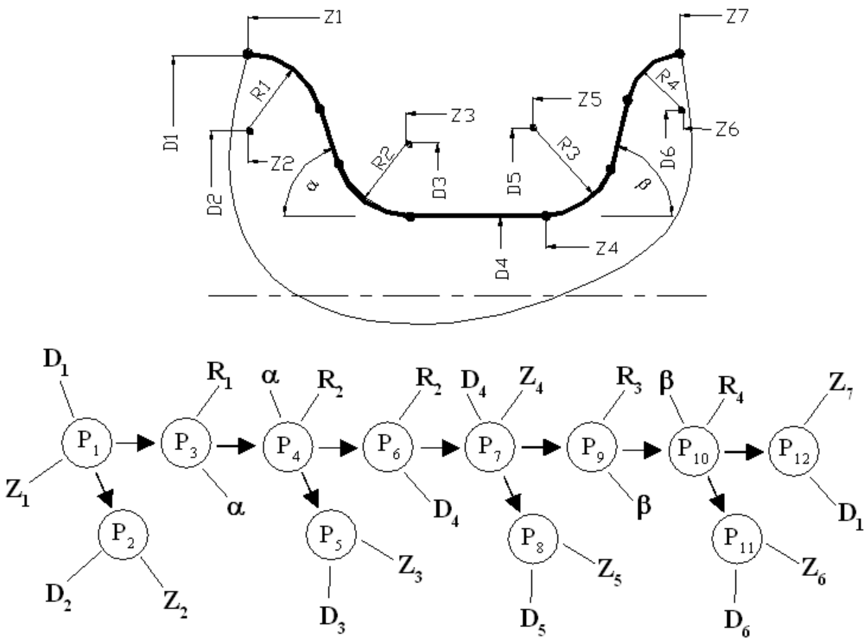


Figure 18 Closed stair STCL with topology and parameterization

by tool T_{1HO} with main angle in plane more than 90^0 $T_{1HO} = \{\varphi = 95^0 \varphi_1 = 5^0\}$ (see Figure 19).

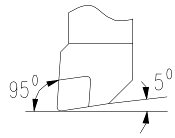


Figure 19 T_{1HO} tool

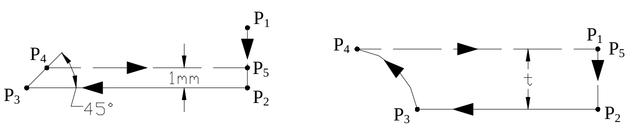
Roughing cut of STHO is possible according to 4 point closed cycle movement concept. Depending on weather this movement is caring out fast, or on feederate, two different sub-rules can be separated:

M_{1-1} –"Fast->Feedrate->Fast->Fast"

M_{1-2} – "Fast->Feedrate->Feedrate->Fast"

M_{1-1} rule describes tool fast movement from P_1 starting point to P_2 point, then movement on feedrate up to P_3 conjunction point, which is placed on the part surface (see Figure 20, a); then movement continue on fast speed across the 45^0 angled line up to P_4 point with passing on 1mm and backing in P_5 point.

M_{1-2} rule describes tool fast movement from P_1 starting point to P_2 point (see Figure 20, b) then



a) b)

Figure 20 Tool movement rules

feedrate movement up to P_3 point on part surface, then feedrate movement across the part surface in P_4 with passing on predefined depth of cut (t) and back fast movement in P_5 point.

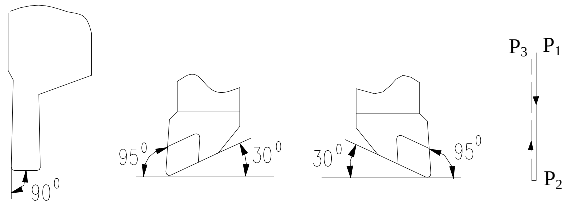
Therefore, for half-open cylindrical stair STHO following typical models can be separated:

$$\left| \begin{array}{l} Z_{HO}^{E} \rightarrow T_{1HO}^{E} \rightarrow M_{1-1}^{L} \\ Z_{HO}^{E} \rightarrow T_{1HO}^{E} \rightarrow M_{1-1}^{D} \\ Z_{HO}^{E} \rightarrow T_{1HO}^{E} \rightarrow M_{1-2}^{L} \\ Z_{HO}^{E} \rightarrow T_{1HO}^{E} \rightarrow M_{1-2}^{D} \end{array} \right| \qquad (30)$$

Where M_{1-1}^{L}, M_{1-2}^{L} - describe longitudinal movement and M_{1-1}^{D}, M_{1-2}^{D} - diametrical movement.

Machining of closed stair STCL can be done by grooving tool T_{1CL} (see Figure 21, a) according to 3 point closed cycle movement (M3). Tool movement is starting on feedrate from the P_1 point; continue moving along the X or Z axis parallel line up to P_2 point and finished by back fast movement in P_1 initial point (see Figure 21, d).

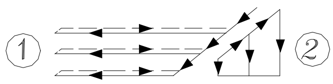
In case of machining of wide closed stair more efficient is implementation of T_{1HO} and $T_{2HO} = \{\varphi = 95^0 \varphi_1 = 30^0\}$ (see Figure 20, b) with combined rules of 4 point closed cycle movement. Different combinations of movement rules sequence can be separated:



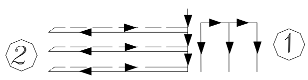
a) b) c) d)

Figure 21 Tool set for machining of STCL

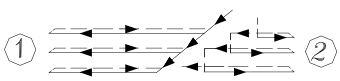
1) $M_{1\text{-}1}$ + M_3 – initially by T_{2HO} tool, according to 4 point closed cycle movement rule $M_{1\text{-}1}$ main part of volume of STCL is removing. Then the rest of the part is machining by the T_{1CL} tool according to 3 point closed cycle movement rule M_3 .



2) M_3 + $M_{1\text{-}1}$ – initially according to M_3 rule minimal volume of STCL is going to be removed by T_{1CL} tool. On the next step main part of STCL is machining by T_{1HO} tool according to 4 point closed cycle movement rule $M_{1\text{-}1}$.



3) $M_{1\text{-}1}$ + $M_{1\text{-}1}$ – machining is starting by T_{2HO} tool according to 4 point cycle movement rule $M_{1\text{-}1}$; rest of the part is machining by right handed tool T_{2CL} (see Figure 21, c) according to same $M_{1\text{-}1}$ rule.



Therefore, for closed cylindrical stair STCL following typical models can be separated:

$$\left|\begin{array}{l} Z_{CL}^{E} \rightarrow T_{1CL}^{E} \rightarrow M_3 \\ Z_{CL}^{E} \rightarrow \begin{array}{l} T_{2HO}^{E} \rightarrow M_{1-1} \\ T_{1CL}^{E} \rightarrow M_3 \end{array} \\ Z_{CL}^{E} \rightarrow \begin{array}{l} T_{1CL}^{E} \rightarrow M_3 \\ T_{1HO}^{E} \rightarrow M_{1-1} \end{array} \\ Z_{CL}^{E} \rightarrow \begin{array}{l} T_{2HO}^{E} \rightarrow M_{1-1} \\ T_{2CL}^{E} \rightarrow M_{1-1} \end{array} \end{array}\right| \qquad (31)$$

6. REALIZATION OF APP

Implementation of adaptive part programming causes necessity of development of special software for CNC. Majority of nowadays CNC permits creation of user software in the form of subroutines. They are representing program modules which are realizing the algorithm of calculation of tool path geometry and machining conditions according to data coming from the entry control systems.

Below is described the library of subroutines formed for *Sinumerik MS2-300* Heidenhain Co., permitting realization of APP. Machine equipped by contact probe *Marpos* and controller *Promess*. They are enabling adaptive control by stabilizing parameters of $[V] = Const$ and $[M] = Const$. Measurement by *Marpos* is carrying out through the standard cycle L93 and results are receiving in the form of numerical values of public parameters R01÷R20 accessible from the subroutines.

CNC *Sinumerik* enables several programming commands so called @ codes for conditional @01 and unconditional @00 breakpoints; trigonometrical functions; standard mathematical operations, assignment of value of parameters. 99 public parameters R01÷R99 can be used for the data exchange inside the subroutines and between the subroutines as well. However, there are also limitations which cause difficultness of programming, but even with this limitations it is possible to realize all described above models (30, 31) necessary for APP.

Subroutines are built as standard cycles of *Sinumerik*. Macrocommand for calling of subroutines has the structure as follow

$$N ... \{A_i\}\{X_j\}\{H_k\}\{Y_m\}$$

where, A_i - is array of subroutine names – 5 names L71÷L75 were reserved for this array

X_j - array of geometrical parameters of STHO/STCL; 19 parameters R11÷R30 were reserved

H_k - array of machining parameters, optimization rules and constants – 9 parameters R31÷R40 were reserved

Y_m - array of entry control parameters - 9 parameters R41÷R50 were reserved.

Conceptual algorithm realizing by each subroutine of is presented on (see Figure 22). First step defines the actual value of depth of cut according to workpiece geometry measured by *Marpos*. Then it is considering weather, activate in real time adaptive control system *Promess* or not. *Promess* enables control by $[V] = Const$ or $[M] = Const$ rule.

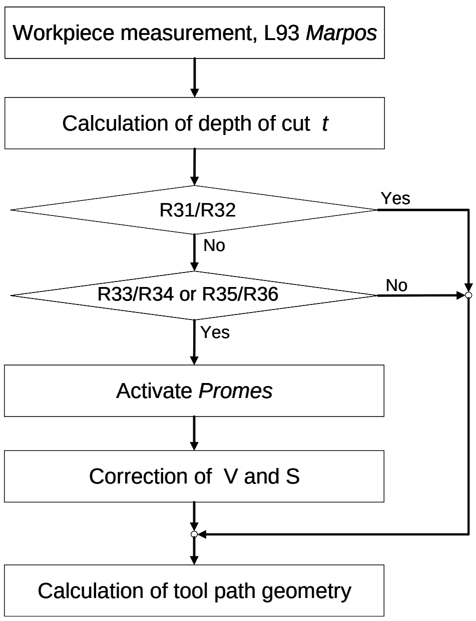


Figure 22 General algorithm realized by subroutines

Value V assigning to R31 and value of M to R32. But they are optional parameters and if they are not presenting in macrocomand subroutine realize that control of parameters V, S have to be done not in real time by *Promes*, but on the base of subalgorithm of V, S correction according to data coming from the *Marpos*. Finally, tool path geometry is calculated. Algorithm of V, S correction built for rules $[PV]$ and $[SN]$ presented in Figure 23. Value of P assigning to R33 and V to R34. Accordingly, value of S assign to R35 and N to R36. Pairs R33/R34 and R35/R36 are also optional and define optimization rule for correction. Actual value of hardness (array Y_m) assigned to R41 and value of C_p constant from (20), to R42. In case if there are no parameters from the pair in macrocommand V, S correction is not going on. Tool path geometry calculation algorithms realize typical models (30, 31) described above.

Separation of support points in tool path is carrying out in respect of shape geometry which is described

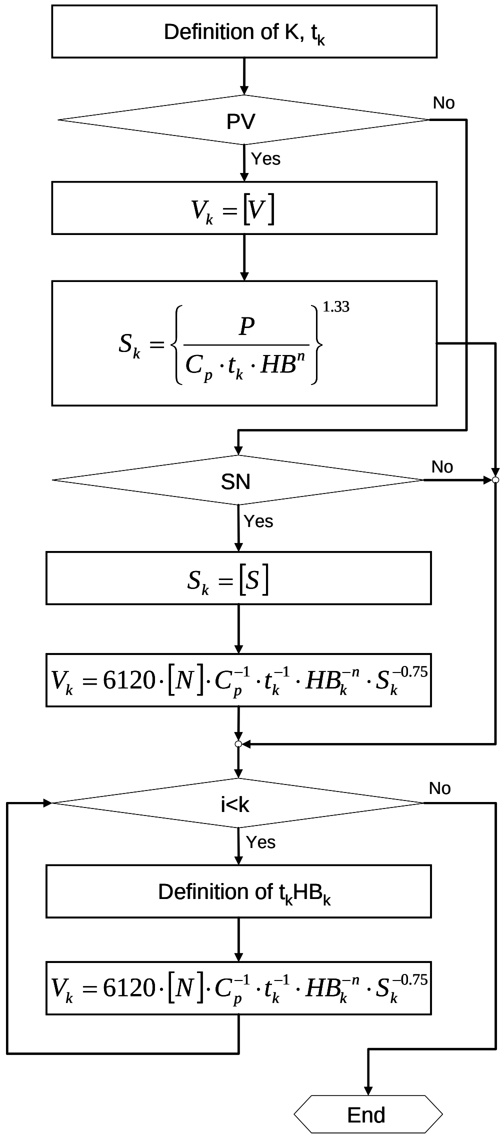


Figure 23 V, S correction algorithm in subroutines

parametrically by the X_j array of parameters. Here *two* classes of parameters were identified – basic and optional parameters. Basic parameters ensure shape description with minimum number of elements, while optional parameters add all shape modifications of STHO and STCL [21].

Thus, following collection of subroutines has been formed:

L71/L72 – Carrying out multipass rout cutting of STHO according to $M_{1-1}^{L} / M_{1-2}^{L}$ and $M_{1-1}^{D} / M_{1-2}^{D}$ models (30). Start point of cycle is identified by the parameters Z4 and D1. Tool movement into start point is carrying out automatically.

L73 – Carrying out multipass rout cutting of STHO according to M_3 model (31).

L74 – Carrying out multipass rout cutting of STHO according to M_{1-1} model (31) by T_{2HO} and T_{2CL} tools.

7. CONCLUSIONS

1. For rough cutting conditions it is identified that correction of tool path geometry according to actual value of workpiece dimensions brings enhancement of fixed rule adaptive control for $[PV]$, $[SN]$, $[PN]$, $[MV]$, $[MN]$ control.

2. For limitations concerning with cutting tool life period (rules $[PT]$, $[MT]$), correction of tool path geometry is not necessary.

3. Adaptive Part Programming approach can be realized through the customization of the standard cycle's library of CNC.

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