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CRITERIA FOR THE OPTIMIZATION OF PRODUCTION PROCESSES IN MACHINING OF METALLIC MATERIALS

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Abstract:
The paper deals with the optimization of production processes and the setting of criteria for reducing production costs. Any company is not just a leap in production, but a lean has to be gradually transferred to all its activities. This created the concept of a lean company first. The skill of an enterprise is to perform only the activities that are needed, to do them right for the first time, to make them faster than others and to spend less resources at the same time. The company's business is that the company does exactly what the customer wants, with a minimum number of activities that do not add value to the product or service. The Lean Production System focuses mainly on eliminating waste in every activity of the manufacturing enterprise.

Key words: *production process, criteria, optimization process, machine tool, mathematical methods*

INTRODUCTION

When optimizing cutting conditions, under certain conditions it is possible to determine optimal serviceability of a machine according to a certain optimizing criterion independently on cutting condition optimization. When coming out from optimal serviceability intended from the point of minimum production costs at cutting conditions optimizing, the criterion of maximum reduction is identical with the criterion of minimum production costs [13]. Cutting speed when considering certain cutting edge durability, surface roughness, degree of splinter deformation and resultant splinter shape and its proportions are utilised as evaluation of machinability indexes [10, 11].

LIMITATION OF CUTTING CONDITIONS AND THEIR MATHEMATICAL FORM

Optimization of cutting conditions is usually done by the following two ways:

- According to the optimization criterion,
- Or within the limits (restrictive conditions) given by the production conditions.

Machining process is limited all the time by a specific set of restrictions (restrictive conditions). These conditions can be mathematically formulated as in equations. Taylor's complex relation is an exception; it is an equation.

Restrictive conditions are, among others, given by a machine (by its performance, marginal moment of torsion of clamping agent, marginal force size, range of rpm or by feed rate, respectively), by a tool (tool material, geometry, edge surface roughness, etc.), by a material of a workpiece, cutting environment, by the required qualitative parameters, etc. [8, 9, 10].

For a complex optimization calculations of cutting conditions (see further), especially linear or linear parametric programming, respectively, has been often used. The mathematical apparatus is based on linear or linearizable restrictive conditions. In the connection with the development of production machinery, non-linearizable restrictive conditions started to appear in recent decades. They are, for instance, non-linearizable restrictive conditions in the view of torsion moment (torsion of a workpiece in the fixture) and bending moment (removal of a single-axis gripped part from the clamping agent) for high-speed machines.

In addition to continuous non-linearizable restrictive conditions, discrete restrictive conditions appear more often. They are particularly different performance characteristics of machines. Mathematical methods for optimization of cutting conditions within these restrictive conditions are carried out by the interval optimization tasks/problems.[10, 11, 12].

In the formulation of a restrictive conditions, firstly, restrictive value is expressed as a function of cutting conditions on the left side of the relation, then, marginal size of this value is indicated on the right side of the equation. Further, the relation is adjusted so that the variables remain on the left side and the rest of the values is on the right side of the relation. It is sometimes preferred, for computational reasons, to leave also variable durability T on the right side of the equation [1, 3, 5].

Next, selected restricted conditions of a machining process that often come into consideration, will be formulated. The first derivations, as an instruction on how to formulate other restrictive conditions are not published in this work. Derivation of other conditions is then analogous.

Limitation by performance of a machine tool

Limiting by the performance of a machine is one of the key restrictions in roughing.

Currently, in terms of the machines' driving mechanism, the following restricted conditions or fragments of restrictive conditions may occur, respectively (at a discrete performance characteristics).

Producers of machine tool define and describe their performance characteristics depending on the performance or on the torsion moment on rotating spindle [11].

Limitation by a constant performance of machine tool

This restrictive condition can be derived as follows. It is known that:

$$P_c \leq P_e \eta \tag{1}$$

where:

P_c is cutting performance in *W,*

P_e is a performance of electromotor in *W,*

η is a mechanical efficiency of machine.

Cutting performance is a function of cutting force F_c. Then:

$$60P_c = F_c v_c \tag{2}$$

where:

F_c is cutting force in *N,*

v_c is cutting speed in *m/min.*

Cutting force is a function of cutting conditions and can be expressed by the empirical relationship; e.g. for turning, drilling and slotting, the following equation is applicable:

$$F_c = k_{Fc} a_p{}^{x_{Fc}} f^{y_{Fc}} v_c{}^{z_{Fc}} \tag{3}$$

where:

k_c, x_{Fc}, y_{Fc}, z_{Fc} are empirical constants.

Substituting Equations (3) and (2) into Equation (1), restrictive condition in terms of constant performance can be written as follows:

$$a_p{}^{x_{Fc}} f^{y_{Fc}} v_c{}^{z_{Fc+1}} \leq \frac{60P_e\eta}{k_{Fc}} \tag{4}$$

After the substitution for cutting speed, it is possible, after the adjustment, to express the condition, as follows:

$$a_p{}^{x_{Fc}} f^{y_{Fc}} n^{z_{Fc}} \leq \frac{60P_e\eta}{k_{Fc}} \left(\frac{10^3}{\pi D}\right)^{z_{Fc}+1} \tag{5}$$

Having regard to the fact, that the dependence of cutting force on the cutting speed is relatively low (z_{Fc} is close to zero) and generally non-monotonic, bearing in mind that for certain cutting material, limited range of cutting speed is allowed, and taking in mind that the constant k_{cF} is considered with a specific safety (due to scattering of properties of processed material), then the Equation (5) is considered without affecting the cutting speed. Then, the restrictive condition can be written in the following form:

$$a_p{}^{x_{Fc}} f^{Y_{Fc}} \leq \frac{10^3 60 P_e \eta}{k_{Fc}\pi D} \tag{6}$$

For other production technologies, restrictive conditions can be expressed analogously. For instance, in milling, the cutting force can be expressed in empirical from as follows:

$$F_c = k_{Fc} a_p{}^{x_{Fc}} f_z{}^{y_{Fc}} v_c{}^{z_{Fc}} B^{\mu_{Fc}} z D_n{}^{w_{Fc}} \tag{7}$$

where:

f_z is feed per tooth v *mm,*

B is the width of milling surface in *mm,*

z is number of tool's teeth,

μ_{Fc}, w_{Fc} are empirical constants.

Without considering the impact of cutting speed, the following relation is applicable:

$$a_p{}^{x_{Fc}} f_z{}^{y_{Fc}} \leq \frac{10^3 60 P_e \eta}{k_{Fc}\pi B^{\mu_{Fz}} z D^{w_{Fz}+1}} \tag{8}$$

For drilling, roughing, turning, gouging, torsion moment without considering the impact of cutting speed can be expressed the following empirical formula:

$$10^3 M_k = k_{Mk} a_p{}^{x_{Mk}} f^{y_{Mk}} D_n{}^{w_{Mk}} \tag{9}$$

where:

M_k is moment of torsion in *Nm,*

k_{Mk}, x_{Mk}, y_{Mk}, w_{Mk} are empirical constants.

In cases, where machining is carried out fully, such relation does not include a_p. Restrictive condition can then be written in the following form:

$$a_p{}^{x_{Mk}} f^{y_{Mk}} \leq \frac{9{,}55.60.10^3 P_e \eta}{k_{Mk} D_n{}^{w_{Mk}}} \tag{10}$$

Restrictive conditions in terms of constant machine performance occur these days with machine tools usually in low speed range. For a description of other components of the performance characteristic across the whole rpm range, it is necessary to use other formulations.

In modern machine tools, performance characterizations are present in both, linear and non-linear forms.

LIMITATION OF THE PERFORMANCE CHARACTERIZATION IN THE LINE FORM

Some performance characterizations are discontinuous. Then, part of these characterizations may have linear course in the following form:

$$P_e = k_1 n + q_1 \tag{11}$$

where:

k_1, q_1 are constants.

For the previous performance course, the following restrictive condition can be expressed, e.g., for turning:

$$a_p{}^{x_{Fc}} f^{y_{Fc}} n - \frac{10^3 60 k_1 \eta}{k_{Fc}\pi D} . n \leq \frac{10^3 60 q_1 \eta}{k_{Fc}\pi D} \tag{12}$$

In the case, when $q_1 = 0$ (other possible variant) restrictive condition can be written in this form:

$$a_p{}^{X_{Fc}} f^{Y_{Fc}} \leq \frac{10^3 60 k_1 \eta}{k_{Fc}\pi D} \tag{13}$$

Limitation by the non-linear course of the performance characterization

Non-linear course of the performance characterization can be substituted by the following type of equation:

$$P_e = a_1 n^{b_1} \tag{14}$$

where:

a_1, b_1 are constants.

Restrictive condition then has the following form:

$$a_p{}^{x_{Fc}} f^{y_{Fc}} n^{1-b_1} \leq \frac{10^3 60 a_1 \eta}{k_{Fc}\pi D} \tag{15}$$

Limitation by different performance on rpm levels

On some machines, it is possible obtain significantly different effectiveness on different rpm degrees/levels. Then, one should consider with restrictive condition:

$$P_c \leq P_e \eta_i \tag{16}$$

where:

η_i is a mechanical efficiency of machine on *i*-th rpm level.

Then, for example turning can have its restrictive condition in the following form:

$$a_p{}^{x_{Fc}} f^{y_{Fc}} n^{z_{Fc}} \leq \frac{60 P_e \eta_i}{k_{Fc}} \left(\frac{10^3}{\pi D}\right)^{z_{Fc+1}} \tag{17}$$

or,

$$a_p{}^{x_{Fc}} f^{y_{Fc}} \leq \frac{10^3 60 P_e \eta_i}{k_{Fc} \pi D} \tag{18}$$

Limiting the performance by a constant moment of torque

Some machine tools' manufacturers present performance characterizations as a relation of torque moment on rpms. It is therefore possible to express the restrictive condition as follows:

$$M_k \leq M_{ke} \eta \tag{19}$$

where:

M_{ke} is a maximum torque moment of the drive in *Nm,*

M_k is a torque moment on the spindle in *Nm,*

For example, in the case of turning, the following expression is valid:

$$10^3 M_k = \frac{F_c D}{2} \tag{20}$$

After the substitution and adjustment, it has the following form:

$$a_p{}^{xFc} f^{yFc} \leq \frac{2.10^3 M_{ke} \eta}{k_{Fc} D} \tag{21}$$

Limitation of the performance by a linear course of torque moment

Linear course of the moment characterization can be expressed the following way:

$$10^3 M_{ke} = k_2 n + q_2 \tag{22}$$

where, after the substitution and adjustment, restriction condition has the following form:

$$a_p{}^{xFc} f^{yFc} - \frac{2 k_2 \eta}{k_{Fc} D} n \leq \frac{2 q_2 \eta}{k_{Fc} D}$$

Limitation of the performance by a non-linear course of torque moment

Non-linear course of the moment characterization can be substituted by the following mathematical expression:

$$10^3 M_{ke} = a_2 n^{b_2} \tag{23}$$

where:

a_2, b_2 are constants.

$$a_p{}^{xFc} f^{yFc} - n^{b_2} \leq \frac{2 a_2 \eta}{k_{Fc} D} \tag{24}$$

Other production technologies, such as turning can have the same restrictive conditions in terms of performance derived analogously.

LIMITATION GIVEN BY THE MAXIMUM ALLOWED MOMENT OF TORQUE

In the view of workpiece fixing/clamping (clamping force) or for other reasons, it is necessary to consider limiting the maximum allowed moment of torque.

$$M_k \leq M_{kmax} \tag{25}$$

where:

M_k is a moment of torque on the spindle in Nm,

M_{kmax} is the maximum allowed moment of torque in Nm.

Limitation of constant torque moment

In the case of e.g. chucks with low rpms, front grippers and jaws, such restriction can be considered as a constant value of maximum allowed moment of torque. After the substitution for e.g. turning, this restrictive condition can be written as follows (not considering cutting speed and cutting force):

$$a_p{}^{xFc} f^{yFc} \leq \frac{2.10^3 M_{kmax}}{k_{Fc} D} \tag{26}$$

where all symbols and variables have been presented earlier.

Analogously for milling, the following restrictive condition can be derived:

$$a_p{}^{xFc} f_z{}^{yFc} \leq \frac{2.10^3 M_{kmax}}{k_{Fc} B^{\mu_{Fz}} z D^{w_{Fz}+1}} \tag{27}$$

And for drilling:

$$a_p{}^{x_{Mk}} f^{y_{Mk}} \leq \frac{10^3 M_{kmax}}{k_{Mk} D^{w_{Mk}}} \tag{28}$$

Limitation by a non-linear course of torque moment

In the case of holding chucks, the clamping force is being reduced due to centrifugal forces at high rpms. Although, specifically designed chucks have been constructed to avoid this phenomenon, it can be stated that the decline in clamping force is given by the centrifugal force of the chucks. This is still valid for the majority of chucks. On one of the jaws, a dependency of clamping force F_u on rpms n can be considered as follows:

$$F_u = F_{uo} - k_n n^2 \tag{29}$$

where:

F_u is clamping force applied to a jaw in *N,*

F_{uo} is clamping force applied on a jaw for $n = 0$ in *N,*

k_n is constant.

Constant k_n can be determined by the percentage of decrease of the clamping force on maximum rpms (from the clamping force at specific rpms) given by the manufacturer for the specific type of holding chucks.

Then, the following relation can be stated:

$$k_{Fn} F_{uo} = F_{uo} - k_n n_{Fu}{}^2 \tag{30}$$

where:

k_{Fn} is the rate of the clamping force size at rpms n_{Fu} and size of the force F_{uo}.

CONCLUSION

Economics and optimization of the production, new modern industrial machinery equipment, new manufacturing fixtures and new technologies have nowadays increasingly wider application in the manufacturing and industry [19, 20]. All the relatively new technologies appeared in the second half of 20. century, however, new technologies appear every day. This fact demonstrates that their potential is far from being exhausted. The technologies are becoming dominant where there are high requirements on dimensional accuracy as well as satisfying the requirements on modern automation, energy, environmental and especially economic requirements.

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