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МАШИНОСТРОЕНЕ

Section 1
MECHANICAL ENGINEERING

THE EFFECT OF FRICTION AND JOINTS RIGIDITY ON THE POWER CHARACTERISTICS OF ROTATING CHUCKS

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Abstract
Authors carry out the influence analysis of friction forces, joints contact rigidity and "clamping element-clamping object" and "clamping element-clamping chuck" subsystems' rigidities proportion on the different clamping stages in the cases of non-rotating and rotating spindle, taking into account the centrifugal forces of unstable clamping elements. Recommendations on the improvement of clamping chucks power characteristics at high-speed treatment are given here.

Keywords: cam-and-lever clamping chuck, centrifugal force, coefficient of friction, contact rigidity, gain coefficient, clamping force

1. INTRODUCTION

One of the modern world tendencies in the mechanical engineering progress is high production cutting due to application of the new instrumental materials allowing to provide high speed cutting at high stability of the tool for edge cutting up to 30 m/s, diamond -abrasive - up to 150 m/s and supplies up to 0,5 mm/teeth – for final milling [5].

The maintenance of high-efficiency processing requires improvement of power characteristics of clamping chuck (CC) on high rotation frequencies as the centrifugal force of unbalanced clamping elements (CE), i.e. cams, has a great impact [7, 10, 12-14]

$$F_\omega = m_{CE}.\omega^2.R_K,$$

where m_{CE} – weight CE; R_K – distance from the CE center of gravity up to rotation axis; $\omega = \frac{\pi.n}{30}$ – CC circular rotation frequency; n – rotation frequency, rpm.

The work safety is of great importance in the case of high rotation frequencies because of a possibility of clamping object (CO), i.e. piece, breaking away due to decrease of clamping force [12-14], and because of a possibility of CC frame break [7] due to centrifugal forces compensation. That is why it is required the durable protective casings or the screens completely closing working space to be installed on the machine tool.

The analysis of earlier studies [5, 10, 15] has shown, that in the case of clamping forces definition in rotating CC the friction forces were assumed as constant and not dependent on clamping speed V_3 and rotation frequency ω, while the joints rigidity was not considered or assumed as identical for all joints. That fact did not allow to estimate the valid picture of clamping and cutting processes.

2. THE MATTER OF RESEARCH

Let's consider the widespread case of outside clamping of piece in CC with lever intensifying link at different conditions of CC-CO system, namely:

stage 1 – clamping the piece, when the spindle is stopped $(\omega = 0)$, and the friction in moving connections depends on moving speed V_3 and lubricating of wear surfaces;

stage 2 – accelerating the spindle with CC to the required rotation speed, when due to the action of centrifugal force there is a decrease of radial clamping force from F_r created on the stage 1 (Fig. 1, curve 1) to $F^1_{r\omega}$ established at specific working speed $n_p(\omega_p)$;

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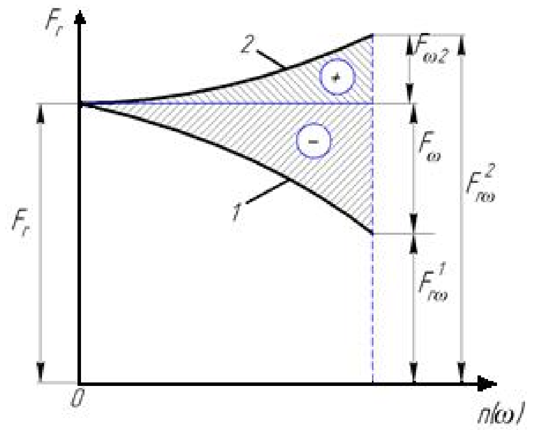


Fig. 1. The radial clamping force against clamping chuck rotation speed diagram in the case of external (curve 1) and internal (curve 2) clamp.

stage 3 – holding the clamped workpiece under the action of cutting force, which amount and variation character depends on a removal stock, a material of tool and workpiece, forced frequency during cutting. In other words the variation of clamping force depends on dynamics of clamping process that requires additional theoretical and experimental study.

In this paper the core attention is paid to first two stages. So, at the 1-st stage according to the loading diagram (Fig. 2), when the axial clamping force F_a is transferred from a drive, the friction loss arise in lever transmission 1 with shoulders a_p and b_p and slider 3 to which there is fastened CE, i.e. a cam cooperating with outer surface of CO, i.e. workpiece 5.

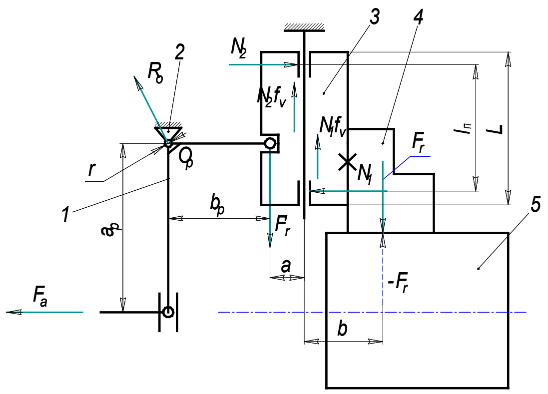


Fig. 2. The loading diagram for definition of power characteristics of cam-and-lever chuck at a stage 1 in the case of stopped spindle: 1- lever; 2 – lever fulcrum; 3 – slider; 4 – cam; 5 – workpiece.

Power characteristic of CC can be expressed through factor of strengthening:

$$K_{\Pi} = \frac{F_r}{F_a} = K_p . K_{пл} \tag{1}$$

where $K_p = \frac{F_r'}{F_a}$ is a lever transmission's factor of strengthening; $K_{пл.} = \frac{F_r}{F_r'}$ is a slider's factor of strengthening.

Let's consider a balance condition of lever 1:

$$\sum M(O_p) = 0$$

$$F_a . a_p - R_O . f_V . r - F_r' . b_p = 0 , \tag{2}$$

where $R_O = \sqrt{F_a^2 + (F_r')^2}$ is a resultant reaction force in pivot axis O_p of the lever 1; f_V – coefficient of kinetic friction.

Plugging R_O in the equation (2) and transforming the last we will obtain the second-degree equation:

$$A.(F_r')^2 + B.F_r' + C = 0 , \tag{3}$$

where $A = b_p^2 - r^2 . f_V^2$; $B = -2.F_a . a_p . b_p$; $C = F_a^2 . \left(1 - r^2 . f_V^2\right)$.

The real solution will be positive value

$$F_a' = \frac{-B + \sqrt{B^2 + 4.A.C}}{2.A} = \\ = F_r' . \left(\frac{a_p . b_p + r . f_V . \sqrt{a_p^2 + b_p^2 - r^2 . f_V^2}}{b_p^2 - r^2 . f_V^2} \right) \tag{4}$$

To simplify the calculations due to the smallness of friction torque in pillar O_p, let us assume that $f_V = 0$, and then we receive:

$$F_r' = F_a . \frac{a_p}{b_p} , \tag{5}$$

Then the lever transmission's factor of strengthening is:

$$K_p = \frac{a_p}{b_p} . \tag{6}$$

The balance condition of slider 3 appear as simultaneous equations:

$$\begin{gathered} \sum M(B) = 0 \\ -F_r' . a - F_r . b + N_1 . \ell_{\Pi} = 0 \\ \sum M(A) = 0 \\ -F_r' . a - F_r . b + N_2 . \ell_{\Pi} = 0 \\ \sum M(Y) = 0 \\ F_r' - F_r - (N_1 + N_2) . f_V = 0 \\ \sum M(X) = 0 \\ -N_1 + N_2 = 0 \end{gathered} \tag{7}$$

Solving simultaneous equations (7), we obtain:

$$F_r = \frac{F_r' . \left(1 - 2 . f_V . \frac{a}{\ell_{\Pi}}\right)}{\left(1 + 2 . f_V . \frac{b}{\ell_{\Pi}}\right)} , \tag{8}$$

where ℓ_{Π} is a distance between the reactions N_1 and N_2, concentrated in contact points A and B. The distance ℓ_{Π} is equal to $\frac{2}{3} L$ (L is the slider's length) [9]. From the expression (8) we get the slider's factor of strengthening as:

$$K_{пл.} = \frac{F_r}{F_r'} = \frac{\left(1 - 2 . f_V . \frac{a}{\ell_{\Pi}}\right)}{\left(1 + 2 . f_V . \frac{b}{\ell_{\Pi}}\right)} \tag{9}$$

As the previous experiments have shown [5], the friction factor f_V decreases with the increase of clamping speed V_3 (increase of speed of clamping mechanism due to a high-speed drive of a clamp). Assuming the linear dependence to simplify the calculations, we obtain:

$$f_V = f_0 - K_V.V_3\,, \tag{10}$$

where K_V is the factor depending on the properties of rubbing surfaces materials, for example, for collet chucks it is equal to (2,5÷5).10 s/mm. At the same time the experiments have shown [5, 9], that with an increase of a clamping force by the drive F_a the friction factor f_V increases. Assuming the linear dependence, we obtain:

$$f_F = f_0 + K_f.F_a\,, \tag{11}$$

where K_F is the factor depending on the tightness force of a system. It is defined by the experimental data, for example, for collet gripping units in automatic lathes $K_F = (1 \div 3).10^{-6}$ 1/кN.

Thus, taking into account (10) and (11), we can state that during the stage 1 of clamping process for nonrotating workpiece the friction factor is changing with the following dependence:

$$f_{V,F} = f_0 - K_V.V_3 + K_F.F_a\,, \tag{12}$$

which means that the friction factor does not remain constant.

Tendencies of influence of design characteristics and strengthening factor of CC can be shown by the charts (Fig. 3) under the following condition: $a_p = b_p$, $a = b$, for a proportion $\frac{a}{\ell_П} = \frac{b}{\ell_П} = 0.1$; 0.5 and 1.0.

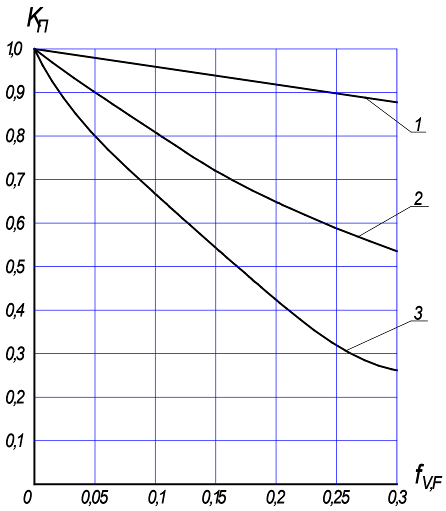


Fig. 3. The strengthening factor against the friction factor for cam-and-lever chuck at a stage 1 in the case of different proportion $\frac{a}{\ell_П}\left(\frac{b}{\ell_П}\right)$: $1-0.1$; $2-0.5$; $3-1.0$

The analysis of charts (Fig. 3) shows, that with an increase of friction factor in the case of low-speed clamping, the strengthening factor of CC essentially decreases with the displacement of forces from the slider in F_r and an cam out F_r on the workpiece. Consequently, at the design of the tightening mechanism it is necessary to increase its speed (clamping speed V_3) and to exclude skews when moving slider with cams, as well as to provide reliable lubrication of rubbing surfaces (especially for the slider in the slide-way).

At the stage 2 when spindle is rotating with CC, centrifugal forces result in a redistribution of tightness in the elastic system of CC, with taking into account the contact deformations in joints, variations of friction forces in moving connections, CC and CO rigidities ratios. The quasi-dynamic model of the cam-and-lever chuck at a stage 1 in the case of lever for an external clamping in longitudinal and cross-section directions is shown on Fig. 4 [1]. The signs on the Fig.4 are: $m_{3Э}$ and m_{O3} are the weights of accordingly each CE and CO; $C_П$ is the CC rigidity, which is defined by rigidity of the lever transmission in the case of an open contour; $\psi_П$ is a damping factor of CC; $C^{к}_{3Э}$ and $C^{к}_{O3}$ are the contact rigidities in the joints of accordingly CE and CO, depending on materials and a roughness of contacting surfaces; $\psi^{к}_{3Э}$ and $\psi^{к}_{O3}$ are the damping factors of joints between CE and CO; C_{O3} are the modified rigidity CO; ψ_{O3} is the modified damping factor of CO; F_T is the force of dry friction; R_K is the distance between the weight center of unbalanced CE and the rotation axis.

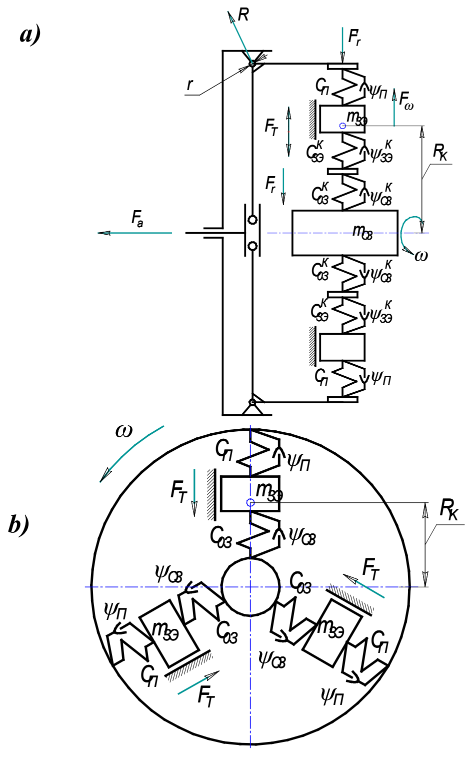
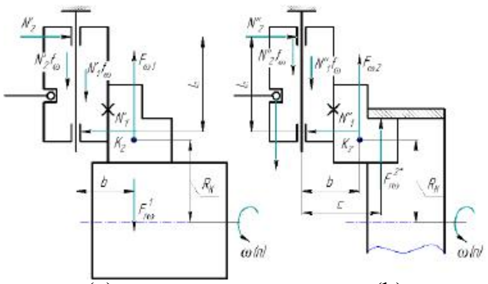


Fig. 4. Quasi-dynamic model of cam-and-lever chuck with two (a) and three (b) cams without taking into account the swashes of sliders and cams

This article does not have an objective to investigate the oscillatory process [1, 4]. Therefore let us consider the simplified diagrams of the centrifugal forces influence in the cases of the external (Fig. 5a) and the internal (Fig. 5b) clamping of solid workpiece and hollow workpiece, taking into account the friction in slider, which changes from a condition of rest $f_{\omega 0}$ (the beginning of rotation) during speeding-up to the established rotation frequency when the friction factor decreases during the certain time t up to $f_{\omega K}$ with the exponential dependency [5]:

$$f_{\omega(t)} = f_{\omega O}.e^{-\omega t} + f_{\omega K}.\left(1-e^{-\omega t}\right) \tag{13}$$



(a) (b)

Fig. 5. The forces operating in the cam-and-lever chuck in the case of a stage 2 when the workpiece is clamped from the outside (a) and from the inside (b)

Without taking into account the friction forces and a parity for an external clamp, when the centrifugal force acts, the radial force (Fig. 1, a curve 1) will be:

$$F^{1}_{r\omega} = F_r - F_{\omega 1}, \tag{14}$$

and for an internal clamp (Fig. 1, curve 2):

$$F^{2}_{r\omega} = F_r - F_{\omega 2}. \tag{15}$$

Dependences (14) and (15) reflect only the tendency of the influence of centrifugal force: negative in the case of the external clamp and positive in the case of the internal clamp. That could be used in the creation of new designs for CC.

Actually the phenomena occuring at a stage 2, are complex. Let us that on the elastic-frictional model of an external clamp (Fig. 6), which is corresponding any designs of CC.

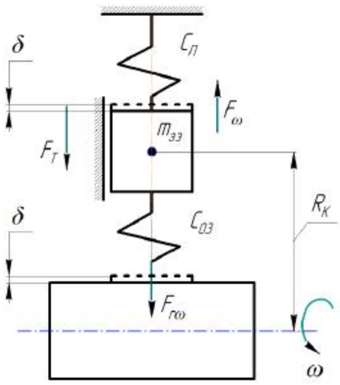


Fig. 6. Elastic-and-frictional model of a rotating CC at a stage 2

Due to the centrifugal force F, overcoming the friction force F_T in the contact points of CE with CO the part of tightness δ in a subsystem from the side of CO is removed. At the same time the subsystem from the side of CC body is additionally loaded on the same size of δ, if it is assumed that CE is absolutely rigid.

Then

$$\delta = \frac{F_\omega - F_T}{C_\Pi} = \frac{\Delta F_{r\omega}}{C_{O3}}, \tag{16}$$

where C_{O3} is the modified rigidity of CO considering consecutive connection of contact rigidities CE ($C^{\kappa}_{\text{ЗЭ}}$), CO (C^{κ}_{O3}) (Fig. 4) and rigidity of CO body (C^{T}_{O3}). If the processed workpiece is a hollow cylinder; this rigidity is defined by the formula:

$$C_{O3} = \frac{C^{\kappa}_{\text{ЗЭ}}.C^{\kappa}_{O3}.C^{T}_{O3}}{C^{\kappa}_{O3}.C^{T}_{O3} + C^{\kappa}_{\text{ЗЭ}}.C^{T}_{O3} + C^{\kappa}_{\text{ЗЭ}}.C^{\kappa}_{O3}}, \tag{17}$$

Contact rigidities $C^{\kappa}_{\text{ЗЭ}}$ and C^{κ}_{O3} can be defined from the works [2, 3, 5, 6, 10], and in the following part of the paper we would use the modified rigidity C_{O3}.

From the expression (16) the loss of radial clamping force is defined as:

$$\Delta F_{r\omega} = \left(F_\omega - F_T\right).\frac{C_{O3}}{C_\Pi}. \tag{18}$$

Let's use a designation $\alpha_C = \frac{C_{O3}}{C_\Pi}$ as a relative parameter of CC-CO system rigidity. This relative parameter in many respects defines the closed power contour of CC [5, 10]: opened ($\alpha_C > 1$) or closed ($\alpha_C < 1$).

Thus, at a stage 2 the total dynamic radial clamping force is:

$$F_{r\omega} = F_r - \Delta F_{r\omega} = F_r - \left(F_\omega - F_T\right).\alpha_C \tag{19}$$

or

$$F_{r\omega} = F_r + F_T.\alpha_C - F_\omega.\alpha_C. \tag{20}$$

Comparison of expressions (20) and (14) shows the refinement of the formula concerning the influence of the friction forces (the second component) and parity of rigidities (the third component).

For the internal clamp the total dynamic radial clamping force is:

$$F_{r\omega} = F_r + F_T.\alpha_C - F_\omega.\alpha_C. \tag{21}$$

There are some parts with apertures, for example, flanges, blocks of cogwheels etc., where at high processing speeds it is possible to use internal and external clamp at the same time (Fig. 7). The internal clamp maybe used for an automatic manipulation of the processed workpiece in loading-unloading.

The external radial clamping force defined by the expression (20). The internal radial clamping force is created by the centrifugal force of unbalanced elements with the weight m_y and is equal to:

$$F^{2}_{r\omega} = F'_\omega = m_y.\omega^2.r_k, \tag{22}$$

where r_K is a distance between the center of gravity K_2 of the elastic CE and the rotation axis.

The total force of a double clamp is:

$$F^{\text{сум}}_{r\omega} = F^{1}_{r\omega} + F^{2}_{r\omega} = F_r + F_T.\alpha_C - F_\omega.\alpha_C + F'_\omega. \tag{23}$$

Under condition of $F_T.\alpha_C + F'_\omega == F_\omega.\alpha_C$ the radial clamping force F_r, created at a stage 1 at nonrotating spindle, will not be changed under certain conditions, when spindle is rotating at a stage 2.

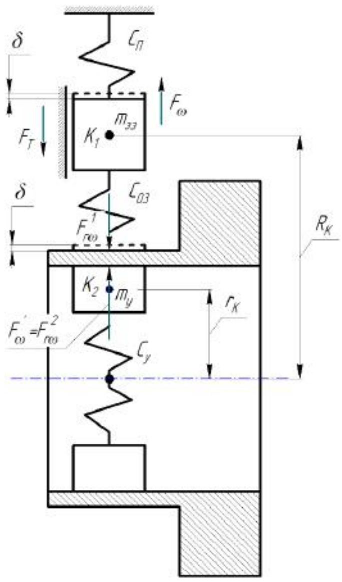


Fig. 7. Elastic-and-frictional model of a rotating CC with a double clamp at a stage 2

3. CONCLUSIONS

The researches have shown, that in the case of clamping the nonrotating workpiece in the cam-and-lever chuck the friction factor is not constant due to the influence of various dynamic factors: clamping speed, rotation frequency of the spindle, a unbalance of rotating weights, non-uniformity of rigidity and the proportion between CO, CE and CC rigidities.

For calculation of clamping forces and CC strengthening factors and its transfer-and-amplifying links the dependences considering variability of friction factors and a proportion of rigidities for subsystems «clamping element – clamping object» and «clamping element – clamping chuck» are offered.

It is reasonable to apply the simultaneous double internal and external clamping of the processed workpiece for the compensation of negative influence of centrifugal forces.

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