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SCIENTIFIC BASIS FOR THE SUBSTANTIATION OF PROCESS REGULATIONS FOR THE MICRO-CUTTING OF HARDENED GEARS

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Abstract: The paper considers scientific principles of technological procedure development for the selection and assignment of parameters of velocity machining by blade tool at gear milling with due regard to the required parameters of the gear surface layer. Optimum micro-cutting conditions are determined when full participation in stock removal of all mill teeth is provided. Technological regulation of selection and setting of machining parameters is spread for gear hobbing of the spur gear wheels with fine-modular and coarse-modular hardness (220...320 HV) and after heat treatment (HRC46...63). Correlation with essential parameters of the surface layer, cutting depth, feed, speed and radius of rounding of the cutting edge of milling cutters' teeth is established. It is scientifically grounded, tested, and proved at what modes of cutting, the radius of rounding of cutting edge of the cutting tool is made metal removal at oncoming and passing high-speed micro milling. The process of determining of minimal sliding angle, or maximum value (without the use of coolant and with coolant), in which there is no micro-cutting process taking into account variation of variable parameters of cutting conditions and geometrical parameters of hobbing cutters is modelled. For the first time, we ascertained the relation between the sliding angle and the maximum contact angle of the mill tooth with the work surface, which allowed determine the efficiency of the shaping process through coefficient (without coolant and with coolant).

KEYWORDS: Cutting Conditions, Minimum Sliding Angle, Largest Cutter Tooth Contact Angle, Efficiency, Process Innovation

1 Introduction

Technological regulation of choice and appointment of parameters of high-speed machining by a blade tool at hobbing, given the maintenance of demanded parameters of a surface layer of gears, establishes optimum conditions of micro cutting when full participation in the removal of the allowance of all gear's teeth of the miller are provided [1, 2, 3].

The technological regulation of selection and assignment of machining parameters is distributed for hobbing spur gears with fine-modular and coarse-modular, conventional hardness (220...320) HB, and hardened (46...63) HRC.

The regulation establishes geometric parameters of worm modular and special high-speed non-modular disc milling cutters about technological modes of cutting and surface layer parameters of spur gears [4, 5, 6].

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The purpose of developing the technological regulations for the selection and assignment of machining parameters for high-speed hobbing:

- To ensure high productivity with maximum tool life;
- Technological support of cylindrical gears surface layer with maximum machinability;
- Guaranteeing high technological stability of gear hobbing equipment, and costly tools when machining spur gears;
- Software for selecting and assigning the technological procedure of processing parameters in gear hobbing.

The scientific basis of the technological regulations for selecting and assigning machining parameters in gear hobbing is based on the fundamental theoretical concepts of friction theory, engineering technology, and cutting theory.

2 Literature review

Currently, works are carried out aimed at the development and mastering of new special technologies of gear hobbing of large-modular hardened gears [2, 4, 13, 15]. Technological process of gear hobbing must provide geometric accuracy and quality of gear teeth surface layer. At the same time the geometrical accuracy of gears is characterized by the accuracy of relative motion when shaping involute profile of the teeth, accuracy of relative motions of producing cutting tool edges relative to the machined gear article and roughness of executing and generating surfaces.

Another important indicator of the quality of machining of large-modular gears, ensuring compliance with the service purpose, the achievement of which is associated with significant costs during the pre-finishing and finishing is the quality of the sur-face layer, which consists in achieving the required quality of both the surface layer itself and the adjacent layer of material [1, 8, 10, 14, 19, 25].

Gears work in conditions of high contact pressure, under high alternating and re-versing loads. The surface layer of gear teeth is characterized by macro deflections, waviness, roughness, sub-roughness, adsorbed zone, oxide zone, material boundary zone, zones of material with changed physical and chemical properties. Therefore, quality assurance of surface layer is a very complex technological task to be solved in gear generating blading, used as a preliminary operation to reduce the allowance for gear grinding or as a final finishing operation.

One of the technological directions of equipping the machining process of large-sized toothed gears is the development and creation of new technological processes of shaping and tooling equipment.

Many studies describe the quality assurance of toothed gears as one of the most critical machine components subjected to intensive alternating loads during operation [26, 27, 28]. The importance of the on-machine surface measurement of micro-scale components after micromachining has also been noted [29]. The features of the high-speed micro-milling process have been described by researchers [30-32] and others.

Researchers found that the special features of the high-speed gear micro-milling process include shorter processing cycles [28], improved cutting performance [34], greater flexibility, and better surface quality [29]. The process is often used to create gears with small modulus and aspect ratio and produce complex shapes. It is also possible to modify the cutting parameters to achieve desired results [30].

3 Research Methodology

In the process of hobbing when the first tooth of cutter 1 is plunged (Fig.1), the temperature in the cutting zone rises sharply, which is one of the reasons for the increased wear of cutters on the back surfaces. After reaching a certain layer thickness a_i at sliding angle Ψ_{sl} the plastic deformation process is converted into cutting.

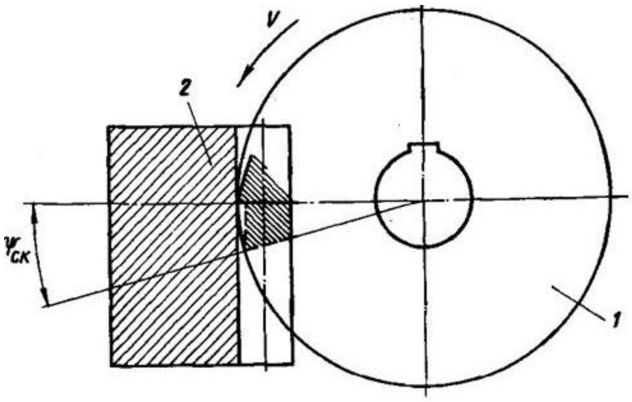

Fig. 1 Gear hobbing scheme

During the chip removal process, deformation of the machined material layers occurs in the area of the chip plane, in front of the cutter tooth, and under the cutting plane.

The metal crushed by the cutting blade does not pass into the chip. After the cutting blade's passing, the deformed layer determines the build-up depth (hup).

The friction of the surface layers of rubbing materials is of a dual molecular-mechanical nature. Friction is caused by the volume deformation of the material and by overcoming the intermolecular bonds between the adjoining parts of the rubbing surfaces.

If we consider an embedded element, an indentor, moving in the tangential direction, deforms the underlying material as a cutting blade with radius ρ, and the embedding depth as ai, the depth relative to the embedding can be represented as Fig.2.

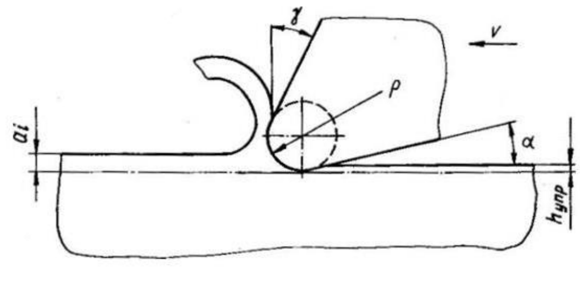

Fig. 2 Cutter tooth plunging scheme for gear hobbing

As the sphere deepens into the material, there comes a moment when the pushing back of the material is replaced by its braking relative to the indentor, resulting in the heating of the material.

The considered plasticity theory of a rigid spherical indentor sliding into a plastically deformed space, at the boundary between which there is an adhesion bond with shear strength, defines the conditions for the transition from plastic pushing to cutting:

$$\frac{h_i}{R} = \frac{a_i}{\rho} \geq \frac{1}{2}\left(1 - \frac{2\cdot\tau}{\sigma_S}\right), \text{ i.e. } \frac{a_i}{\rho} = \frac{1}{2}\left(1 - \frac{2\cdot\tau}{\sigma_S}\right) \quad (1)$$

where $h_i = a_i$ – thickness of cut layer, mm; $R = \rho$ – radius of cutting blade, R – radius of indenter, mm; τ – shear strength of adhesive bond, n/m^2; σ_s – yield strength of work-piece material, n/m^2.

As follows from (1), at $\sigma_s \leq 2\cdot\tau$ external friction is impossible at any relative embedding; it is also impossible at $h_i/R = a_i/\rho \geq 0.5$ even if the adhesion bond shear strength is zero [1, 3, 12, 16].

In the presence of grease, the limit will be the relative penetration

$$h_i/R = a_i/\rho \geq 0.31$$

in the presence of a lubricating film on the interface, the coefficient of friction depending on the ratio $h_i/R = a_i/\rho$ is determined from the molecular mechanical theory of friction in the case $\tau = 0$:

$$f = \frac{\tau_o}{p_r} + \beta + 0{,}4 \cdot a_r \cdot \sqrt{\frac{h}{r}} \quad (2)$$

where τ_o is the specific shear strength of the molecular bonds; β is the coefficient of strengthening of molecular bonds under compressive stress; ag is the coefficient of hysteresis loss on sliding; p_r is the pressure at the actual contact sites, h is the indenter depth, r (R) is the indenter radius.

For our case:

$$f = 0{,}4 \cdot \sqrt{\frac{a_i}{\rho}}, \quad (3)$$

By substituting in (3) the value $a_i/\rho = 0.31$, at which external friction is impossible, we obtain $f = 0.22$. This value is the limiting value of the strain component of the friction coefficient. At transition of critical value, i.e. at $f \geq 0{,}22$, jumps of contact surface and indentor are observed.

At cutting with application of surface and chemically active cooling-lubricating fluids the adhesive interaction between a chip and tool is absent, an adhesive component is equal zero and mean friction factor becomes constant, not depending on cutting conditions, i.e. at $\tau/\sigma = f_2 \rightarrow 0$:

$$f = f_1 + f_2 \rightarrow f_1,$$

where f_1 is coefficient of friction depending on molecular-atomic roughness of surfaces, and f_2. average coefficient of friction becomes constant, not depending on cutting conditions, i.e. at $\tau/\sigma = f_2 \rightarrow 0$.

Thus, the depth of relative penetration leading to cutting without the use of lubrication corresponds to: $a_i/\rho > 0.5$, lubricated $a_i/\rho > 0.31$.

Given that the initial thickness of the shear layer during shaping of gear teeth is defined as

$$a_i = S_Z \cdot \sin \Psi_{sc} \cdot \sin \varphi$$

where S_z is the feed per tooth; Ψ_{sc} is the sliding angle at which cutting starts; φ is the profile angle of the cutter at the point in question.

Specifying the specific values of ρ and S_z, the minimum values of sliding angles without lubrication and with coolant are determined according to the formulas:

$$\text{without coolant: } \varphi_{scmin} = \arcsin \frac{0{,}5 \cdot \rho}{S_{Zmin} \cdot \sin \varphi} \quad (4)$$

$$\text{with coolant: } \varphi_{scmin} = \arcsin \frac{0{,}31 \cdot \rho}{S_{Zmin} \cdot \sin \varphi} \quad (5)$$

where S_{Zmin} is the minimum feed per tooth at which the cutting process begins.

The change in thickness of the sheared layer when the minimum sliding angle Ψ_{scmin} is reached changes the coefficient of friction in the presence of the obligatory surge (jump) (Fig. 3 a, b), which adversely affects the cutting dynamics and the quality of the machined surface.

Thus, the start of cutting at lubrication starts at $a_i > 0.31$ ρ. Then, given a value of S_{Zmin}, the sliding angle ψ_c is determined.

The sliding occurs at a certain sliding angle ψ_{sc} until the plastic deformation changes from micro-cutting directly to cutting, i.e. when the thickness of the cut reaches a certain depth value, relative to the introduction by the cutting tool, having a radius of rounding of the cutting edge ρ. Thus, an increase in the quality of the surface layer of the toothed workpieces, a decrease in the roughness value, a significant increase in the productivity and the regulated tool life is achieved by setting a fixed feed value at which the ratio of the initial cutting thickness to the radius of rounding of the cutting edge of the cutter corresponds to the smallest value of the sliding angle. The use of the developed technological regulation on a choice and appointment of parameters of processing at hobbing taking into account maintenance of the required parameters of a surface layer of gears establishes optimum conditions of cutting at which full participation in removal of the allowance of all gears of the mill is provided.

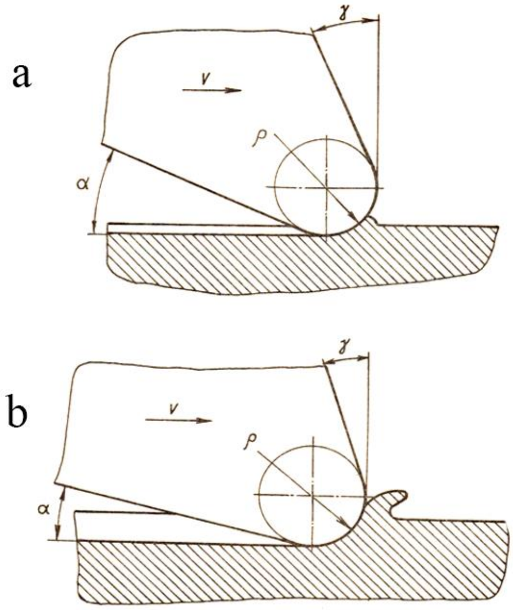

Fig. 3. Indentor displacement: a) in the case of material push back, b) indentor displacement in the case of cutting, γ - anterior cutting angle, α - posterior cutting angle

Determination of minimum sliding angles for milling large-sized toothed gears, based on physical and chemical processes of friction mechanics, can significantly improve the efficiency of the tooth forming process and operational properties of their surfaces.

4 Results and discussions

The carried out theoretical and experimental researches allow determining optimum sliding angles Ψ_{sc}, at which the stability of the process of micro gear milling, quality of the processed surface with respect to the maximum contact angle of the cutter tooth Ψ_{max} (Fig. 4) and necessary conditions for creation of a scientific platform for study and research ways to improve tool durability is provided.

The relationship between the sliding angle Ψ_{sc} and the maximum contact angle of the cutter tooth Ψ_{max} with the machined surface allows the efficiency of the shaping process to be established through the shaping efficiency factor K_ρ [1, 12, 13]:

$$K_\rho = \frac{\sin\Psi_{max} - \sin\Psi_{sc}}{\sin\Psi_{max}} \cdot 100\% \quad (6)$$

Substituting in (6) the technological parameters of machining we obtain an expression of the coefficient of forming efficiency, convenient for theoretical and experimental research:

$$K_\rho = \left(1 - \frac{\arcsin\left(K_{mc} \cdot \frac{\rho \cdot 10^3 \cdot V \cdot Z}{S_{min_i} \cdot \pi \cdot d_{cut} \cdot \sin\varphi}\right)}{\arcsin\frac{2 \cdot \sqrt{t \cdot (d_{cut} - t)}}{d_{cut}}}\right) \cdot 100\% \quad (7)$$

where K_{mc} = 0.5 for machining without coolant, K_{mc} = 0.31 for machining with coolant.

Analysis of changes in the milling efficiency coefficient $K\rho$ of hardened large-modular gears depending on cutting modes without and with coolant has shown the areas providing a normal process of shaping working surfaces. A favorable area for technological assurance of surface layer condition parameters of hardened large-size gearwheels is the value of milling efficiency coefficient K_ρ from 30% to 80%, which is governed by the cutting blade rounding radius ρ or the amount of wear on the back surface, as well as cutting conditions: feed, cutting speed, roughness parameters, cutting forces, depending on the accepted scheme of cutting [15, 18, 21].

Determination of specific machining conditions is solved in conjunction with the functional parameters of the state of the machined surfaces of hardened gears. The surface roughness condition parameters for machining hardened gears have the following form:

$$R_z = 5 \cdot R_a = P_z \cdot \frac{S_z^{1,69} \cdot a_i^{0,5}}{V^{1,23} \cdot \rho^{0,14} \cdot \gamma^{0,41} \cdot K_\rho}$$

$$W_z = P_z \cdot \frac{S_z^{1,01} \cdot a_i^{0,46} \cdot \rho^{0,16} \cdot \gamma^{0,54}}{V^{1,55}}$$

where R_z – profile roughness height by ten points in mm, R_a – arithmetic mean deviation of profile in mm, W_z – roughness profile smoothing height by ten points in mm, P_z – main component of cutting force, in n, S_z – feed on tooth in mm/tooth, a_i – thickness of cut layer in mm, ρ – radius of cutting edge rounding in mm, V – cutting speed in m/s, γ – rake angle of cutter in deg, K_r – coefficient of forming efficiency.

$$R_z = 5 \cdot R_a = \frac{P_z \cdot S_z^{1,69} \cdot a_i^{0,5}}{V^{1,23} \cdot \rho^{0,14} \cdot \gamma^{0,41}} \cdot K^{-1}{}_{-1\rho} =$$

$$= \frac{10{,}16 \cdot \left(\frac{\sigma_T \cdot E}{\pi \cdot (1-\mu^2)}\right)^{3/4} \cdot \left(\frac{10 \cdot I \cdot n}{\chi \cdot p}\right)^{3/2} \cdot S_m^{3/2} \cdot k^{-3}}{H_p^{1/4} \cdot W_p^{1/4}}$$

where σ_τ, – yield stress, E – modulus of elasticity, μ – Poisson's coefficient, n – number of impact cycles, which leads to destruction of gearing surface, I – intensity of gearing wear during normal wear, χ – factor, considering parameters of bearing curve, p – specific load, which falls on geometrical area of contact, H_p – height of macro deflection smoothing, W_p – height of waviness profile smoothing, S_m – average step of irregularities, k (Hμ0) – degree of hardening [17, 22, 32].

Obtained data are used as technical limitations on system of parameters of gear wheels surface layer, that define their operational properties, at choice of technological methods and modes of treatment.

Technological conditions for surface layer quality indexes from sliding angle in machining of hardened coarse-milled gears are considered.

Calculation scheme for the maximum cutter tooth contact angle with the workpiece (maximum sliding angle) Ψ_{max} (Fig. 4) [21, 22, 23, 25].

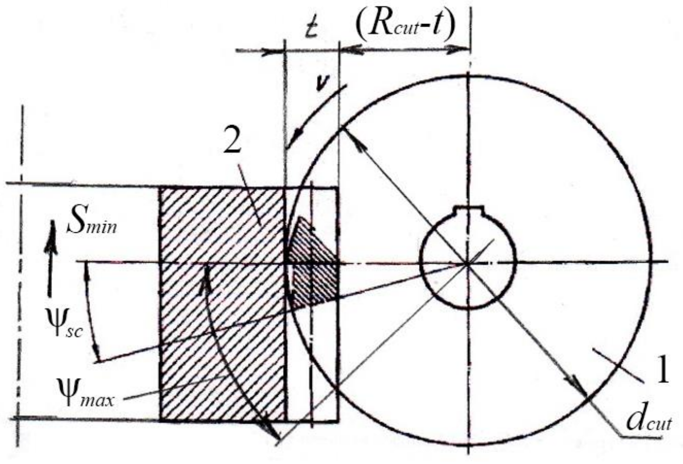

Fig. 1. Schematic diagram for calculating the machining parameters for micro gear milling

Angular tooth pitch of the cutter ω = 360° / z,

Maximum contact angle of the cutter tooth with the gear to be machined (maximum sliding angle) Ψ_{max}:

$$\sin\Psi_{max} = \frac{H_i}{R_{cut}} = \frac{2\cdot H_i}{d_{cut}} = \frac{\sqrt{t\cdot(d_{cut}-t)}}{d_{cut}},$$

$$\Psi_{max} = arcsin\frac{H_i}{R_{cut}} = arcsin\frac{2\cdot H_i}{d_{cut}} = arcsin\frac{2\cdot\sqrt{t\cdot(d_{cut}-t)}}{d_{cut}}$$

where t = 2.25m is the tooth height of the gear.

Table 1. Summary table for optimizing process parameters for quality, accuracy and productivity

Radius of the cutting edge of the cutter ρ, mm	Cutter diameter, d, mm	Number of cutter teeth, Z	Minute feed rate, S min, mm/min	Cutting speed, V, m/s	Maximum contact angle of the cutter tooth with the workpiece (maximum sliding angle), Ψ_{max}, rad/°	Maximum tooth length of the wheel H, mm	Minimum sliding angle Ψ_{sc}, rad/°	
							With coolant	Without coolant
0,02	180	10	20	0,5	0,43/24,69	200	0,008/0,46	0,013/0,74
0,04	220	12	30	1,0	0,40/22,99	300	0,021/1,20	0,034/1,94
0,08	250	14	40	1,0	0,38/21,56	300	0,032/1,85	0,052/2,99
0,10	280	16	60	1,0	0,36/20,35	300	0,028/1,58	0,044/2,54
0,12	180	10	20	2,0	0,43/24,69	200	0,194/11,10	0,316/18,09
0,15	220	12	30	3,0	0,40/22,99	300	0,238/13,67	0,391/22,40
0,20	250	14	40	3,0	0,38/21,56	300	0,245/14,04	0,402/23,03
0,25	280	16	60	3,0	0,36/20,35	300	0,208/11,91	0,339/19,43
0,30	350	20	150	3,5	0,32/18,43	500	0,116/6,63	0,187/10,74
0,40	400	30	200	4,0	0,27/15,28	600	0,174/9,98	0,283/16,23
0,50	400	40	300	4,0	0,23/13,33	800	0,194/11,10	0,316/18,09

CONCLUSION

1 The relationship between K_ρ and the main parameters of the surface layer is established. The tool life period T is determined by cutting depth t, feed S_f, speed V and radius of rounding of the cutting edge of milling teeth ρ, i.e. parameters of cutting mode and conditions of forming with regard to the parameter of functional formation of surface layer at microchiselling $K\rho=f\,(a/\rho, Rz, t_m, (k)H\mu0, \sigma_0, hH\mu)$ and machinability of material C_v.

2.It is set, tested and proved at what modes of cutting, radius of rounding of cut-ting edge of cutting tool is made metal removal at oncoming and crosscutting high-speed hobbing.

3. The process of determining of minimum value of the sliding angle Ψ_{sc}, or maximum value (without the use of coolant and with coolant), in which micro-cutting process is absent with account of variation of cutting regimes variable parameters (S_{min}, V) and geometrical parameters of hobbing cutters (ρ, d_{cut}, Z) is modelled.

4. The relation between the sliding angle Ψ_{sc} and the maximum contact angle of cutter's tooth Ψ_{max} with workable surface is established and allows to establish the efficiency of shaping process through factor K_ρ (without use of coolant and with coolant).

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