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Hob wear prediction based on simulation of friction, heat fluxes, and cutting temperature

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Based on comprehensive interrelated mathematical and graphical-analytical models, including 3D cut layers and simulation of contact, strain, force, and thermal processes during gear hobbing friction forces, heat fluxes, and temperature on the teeth of the hob surface are investigated. Various physical phenomena are responsible for their wear: friction on contact surfaces and thermal flow. These factors act independently of each other; therefore, the worn areas are localized in different active parts of the hob. Friction causes abrasive wear and heat fluxes result in heat softening of the tool. Intense heat fluxes due to significant friction, acting on areas of limited area, lead to temperatures exceeding the critical temperature on certain edges of the high-speed cutter. Simulation results enable identification of high-temperature areas on the working surface of cutting edges, where wear is caused by various reasons, and make it possible to select different methods of hardening these surfaces. To create protective coatings with maximum heat resistance, it is advisable to use laser technologies, electro spark alloying, or plasma spraying, and for coatings that provide reduction of friction on the surfaces – formation of diamond-containing layers with minimum adhesion properties and low friction coefficient on the corresponding surfaces.

1. Introduction

Currently, despite achievements in the development of new gear-cutting methods and cutting tools, hobbing with worm hobs remains the most versatile, productive, and widely used method of gearing production. The main task of designing hobbing cutters (design specification) is formulated as follows: to determine the

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design and geometric parameters of the tool, which would provide the required thickness and height of the teeth and effective machining overlap of the teeth of the cut gears.

It is known that one of the important factors influencing the intensity of cutting tool wear is the heat generated during cutting, as well as friction in the "tool-workpiece" contact areas. This applies in full measure to hob cutters. Given the high cost of these tools, measures to improve their performance and increase their life remain relevant for modern mechanical engineering. Since a complete idea of the nature of edge wear contains information about the thermal and temperature mode of hobs, the problem of modeling thermal processes and cutting temperature is of important scientific and practical importance for solving this problem.

2. Literature analysis

Numerous studies have been devoted to the problem of hob wear. Some of the known works present the results of experimental studies [1–4]. However, such data are of limited use because they can only be applied to initial conditions of a similar kind: cutting parameters, structure and geometric parameters of cutters, workpieces, tool material, etc. In [1], the authors propose to predict wear visually, based on the shape of 3D chip models. However, in this case, only the wear on the rake face of the teeth can be assessed. At the same time, it is known from the practice of gear-making that the largest wear areas are those on the back surface of the hob's teeth.

Thermal processes, cutting temperature, and their influence on various aspects of gear hobbing are considered in many works, in particular, [5–9]. The common shortcoming of these studies is that one assumes a certain value of the cutting heat. However, the knowledge of the total amount of heat generated during the operation of a hob cutter is not sufficient for detrmining heat distribution between the cutter's teeth and edges and to predict its actual wear.

The well-known factor influencing wear are the cutting. Their influence is due to the cutting force and friction, which cause abrasion and destruction of the edges. For gear hobbing, the determination of the cross-sectional area, thickness, and width of the cuts is based on modeling the undeformed chips cut by the hob. To adequately represent the shape and size of the chips, it is necessary to take into account all the factors involved in this complex process. In known works, these conditions are not fully met. For example, in [10], a planar scheme was used that takes into account only the circular generation of wheel profiles in the motion of wheel and cutter rotation.

In [1, 10], it is assumed that the modeling of undeformed chips describes the spatial trajectory of the cutter tooth and the angular rotation of the workpiece at different stages of tooth gap formation. However, the authors do not take into account the shape and size of the transition surface in the gap between the teeth of the machining gear. At the same time, this surface forms the inner surface of the chip and decides on the actual shape of the chip and the thickness of the cut layers.

Another type of simplification is to replace this actual transitional surface in the gap with a quasi-transitional surface in gear hobbing (Fig. 1) [11]. This approach does not take into account the circular motion of the gear. Therefore, this model does not reflect the result of cutting by all active teeth on the helical surface of the hob, which previously cut in given gap both in the angular position and in the axial direction.

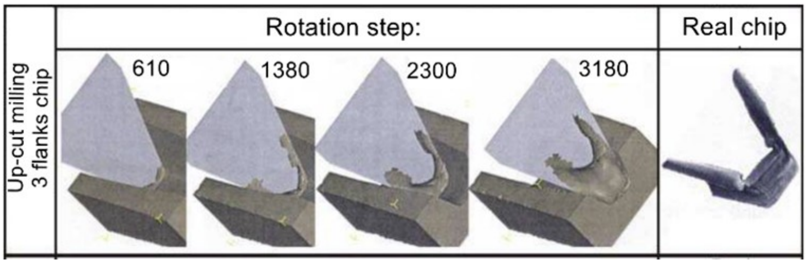


Fig. 1. Simulation of chip formation [11]

In [12], the studies are based on the assumption that hob wear is proportional to the chip thickness ratio. Undoubtedly, this is an important factor, but friction on the contact surfaces of the cutter teeth must also be taken into account.

Many studies of hob cutter operation are based on cutting with a single-tooth flying cutter [1, 5, 10, 13–18]. Single-tooth cutters are used for research. In such cutters, the cutting tooth profile corresponds to the tooth of a hob. However, this approach disrupts the cyclicity of the process and the thermal load, which can have a significant impact on wear. In addition, such experiments also do not take into account the shape of the actual transition surface, as determined by the internal contour of the chip, its actual shape, and its dimensions. As noted above, this reduces the reliability of the research results.

Work [19] suggests that the load on the worm cutter (and, accordingly, its wear) should be determined as proportional to the chip thickness and width. However, simultaneously with a decrease in chip thickness, length, and cross-sectional area, the cutting force can both decrease and increase. This is because at small cut thicknesses, the intensity of chip deposition increases, which leads to an increase in cutting force, not a decrease. At the same time, at low cut thicknesses, the phenomenon of crushing the layer to be cut occurs instead of cutting, which leads to rapid wear on the flank surface of the teeth.

Based on the analysis of primary sources, the following conclusions can be drawn.

1. Despite many studies devoted to this problem, predicting the wear hobbing resistance is still an actual and not fully solved the problem. The results obtained from experimental studies are of limited use – on the one hand, due to the differences in kinematics when reproducing the hobbing process on CNC

machines, and on the other hand, through the narrow range of initial data in which these studies were conducted.

2. A significant problem for adequate simulation of wear is the imperfection of 3D slice models of the hob cutter. To fully simulate the temperature of a hobbing process, data on the cutting force and friction force on the rake and flank surfaces of all edges – top and sides – as well as on the heat fluxes on these surfaces are needed. In turn, these parameters are based on the parameters of the chip and its cross-sections. The known chip modeling methods used for this purpose do not adequately describe these parameters.
3. The theoretical research in this area insufficiently exploits the scientific basis accumulated in the theory of metal cutting, which should be used to model the entire complex of processes and phenomena during wheel cutting with hobbing cutters – strain, force, friction, thermal, etc.

Thus, the purpose of the given work is to investigate the principles and obtain relationships to assess the impact of factors in the hobbing process and parameters of machining cutters on the heat of cutting, the temperature of the teeth and edges, their heating, and wear.

3. Research results

3.1. General assumptions and considerations for modeling

The model of heat exchange and temperature state of the components of the technological system "Machine-Fixture-Tool-Workpiece" can be considered the final stage of the study of the process of forming during hobbing. Its initial data should serve as the parameters of this process determined at the previous stages: loads and cutting forces, shape and sizes of sheared layers, the intensity of stress-strain processes in the plastic shear zone, contact processes, and friction on the surfaces between the chip and the tool, as well as between the tool and the machined surface. It is necessary to take into account the special conditions of the hobbing process, which mean that:

- the process is multi-toothed, and the number of teeth on the helical surface involved in cutting amounts to dozens;
- the process is multi-blade: each cutting tooth has three cutting edges, of which one, two, or simultaneously three edges can work depending on the place of the tooth in the hob;
- the shaping process is discontinuous, with cyclic loads. The number of cutting cycles per tooth in a high-speed steel cutter is 1.5 to 2.5 Hz, and 15 to 25 Hz for a carbide cutter;
- most of the teeth have non-free cutting, and the chips coming off the different blades are layered on the rake face, which increases the cutting force;
- the flank angles of standard hobs have a zero value on the side edges, but the kinematic angles are different: positive flank angles are on the rake side edge

and negative flank angles are used on the relief side edge; therefore, in absolute terms, these angles are equivalent to the angle of the hob's helical groove;
- the parameters of the cut layers on each tooth are different, and also on each tooth, they change according to the dynamically changing angle of contact of the cutting tooth with the workpiece.

The above features of this process introduce significant changes in the patterns of heat generation, heat distribution, and heating of the hobbing. For adequate modeling of these processes, it is possible to apply the basic foundations of the theory of cutting, tested and confirmed experimentally, the results of modeling this process performed in the previous stages, as well as the capabilities of modern computer systems and software.

To simulate thermal processes, we use studies of plastic deformation and friction processes during cutting with a hob, the results of which are described in the article [20]. This work takes into account the cutting forces on teeth and edges as a function of cutting parameters and the intensity of chip thickness ratio and cutting thickness; the influence of kinematic angles on the friction between the chips and the rake face; the increase of friction intensity under compressed cutting conditions, and the contact friction on the flank face of the teeth with the formed gap. These studies allowed the simulation of thermal processes and temperatures at the level of selected edges and teeth of the hob.

To solve the problems of simulating the process of gear machining, the method of geometric modeling in the AutoCAD program and the method of stress-strain and thermodynamic analysis in the Deforms system were used. The initial conditions for DEFORM to simulate the gearing operation are the 3D model of the workpiece and the hob created in Autodesk AutoCAD Inventor; cutting parameters; tool and coating materials; mechanical and thermal characteristics of the material being machined (AISI 1045 steel); tool wear model (Archard and Usui); type of strain modeling (Lagrange Incremental); iteration method (Direct Iteration); type of strain and temperature solver (Skyline method).

The basic solver for FEA analysis (including irregular structure matrices), the Skyline Conjugate Gradient, is faster and requires less memory than the Sparse matrix solver. For problems with a large number of tetra-type elements, the Sparse matrix solver requires more memory than the computer can allocate. The maximum number of elements in a four-node Lagrangian grid for the Sparse solver is 140 thousand elements.

3.2. Frictional forces on the rake face of the hobbing cutter teeth

3.2.1. Scheme of forces on the hob's cutting edges

To determine the forces of friction and thermal processes, it is necessary first of all to determine the system of forces acting on the cutting edges of the tool. As it is known, in contrast to other methods of physical testing of metal (compression, tension, torsion, etc.), stress and strain during cutting are the results not of external action, but of internal state, which leads to the cutting force. This force arises as a result of the deformation processes of shear and friction on the cutting surface. The scheme of forces corresponding to this process is shown in Fig. 2a. Cutting force R here is determined by the vector sum of the plastic shear deformation force P_τ and the friction force F on the tool's rake face.

In other well-known schemes, which are used to calculate the cutting force and its components [21, 22] (Fig. 2b), the force R is considered as equidistant normal to the rake face force N, and the friction force F on this surface. In such an interpretation, the shear force P_τ is the result of these forces, rather than their original cause, which does not correspond to reality.

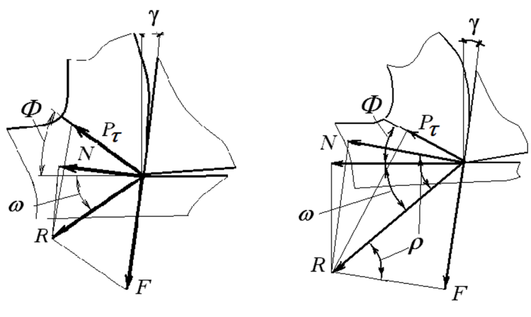
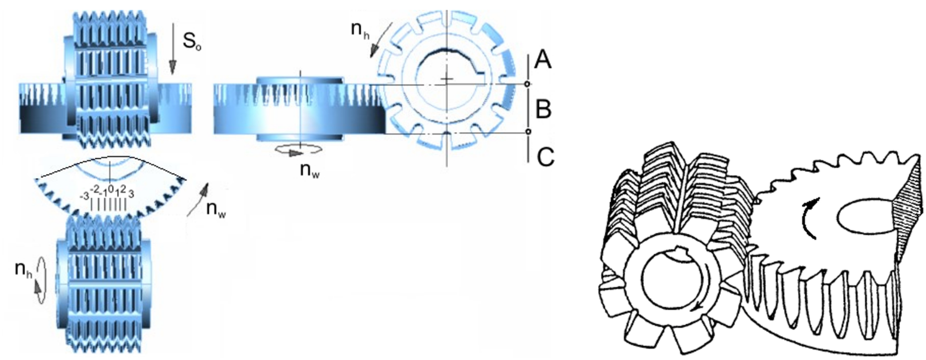


Fig. 2. Schemes of forces acting on the cutting edge of the tool: a – according to the method of load application used in the given work, b – according to the generally accepted scheme of cutting

The proposed scheme (Fig. 2a) allows for explaining the non-Coulomb friction, which takes place in most cases of the cutting process when the friction force exceeds the force of normal pressure and the friction coefficient turns out to be greater than 1. In the traditional scheme, shown in Fig. 3b, it is not possible to reproduce such a phenomenon, because increasing the friction force and turning vector R in a counterclockwise direction doesn't entail increasing the shear force P_τ, but its reduction – that contradicts the physics of this process.

According to the scheme (Fig. 2a), if the rake angle $\gamma = 0$, the transition from Coulomb to non-Coulomb friction, occurs under the condition: $P_\tau \cdot \cos\Phi \rhd R \cdot \cos\omega$.

Since the operating principle and the cutting scheme of the hob cutter tool is complex, it is necessary to explain the designations adopted in this article. For the given initial values, there are 7 teeth of the hob's rack in contact with the machined wheel at the same time (Fig. 3a). The central tooth of the cutter's basic rack is on the centerline line connecting the center of the gear blank with the axis of the hob. Its symmetry axis coincides with this line. This tooth is designated as "zero" and divides the active part of the cutter into a leading (left) and a trailing (right) segment. The teeth on the input section are marked as (–1), (–2), (–3), and those on the right are marked as (+1), (+2), and (+3), respectively, on the output section. At the same time, these teeth belong to the helical surface of the hob, and the number of such teeth in one turn equals the number of columns (hob face teeth). Since, in our case, the number of hob columns is 10, the total number of teeth of the helical surface cutting will be 70. The hob in the axial feed is in the section of the full-cut position “*B*” (Fig. 3b)



(a) (b)

Fig. 3. Schemes of forces acting on the cutting edge of the tool: a – according to the method of load application used in the given work, b – according to the generally accepted scheme of cutting

According to the scheme (Fig. 2a), the friction force on the rake face of a certain tooth of the hob is a function of three parameters – the sheer force P_τ, the shear angle F, and the angle of the resulting cutting force vector ω (“the action-angle”). All these parameters have been investigated in the previous works of the authors mentioned above. In particular, the shear force is presented as a function of the shear strength of the material $[\tau]$, the cross-sectional area of chip S, and the chip thickness rate ξ. The parameters of the shear cross-section (thickness a and cross-sectional area S) were modeled beforehand based on the authors’ methodology [23]. The analysis of the factors that influence the parameters under study and the established patterns of their change on the teeth and edges make it possible to model these parameters as a function of the angle of rotation of the cutter. This makes it possible to analyze the change in friction forces, as well as heat flows and temperature at the level of teeth and edges, and to recreate the overall picture of the thermal load on the tool.

Following the above prerequisites and the initial data, Fig. 4 shows graphs of friction forces that occur on the edges of the rake face of the hob teeth. On each turn of the cutter, one tooth is selected where the maximum friction occurs; this tooth represents the corresponding turn of the cutter (from –3 to +2).

The value of the chip compression ratio was determined for the given initial conditions depending on the patterns of change in the thickness of cuts. The angle ω was determined depending on the shear angle (function of the chip thickness ratio ξ) and chip thickness. Thus, based on the results of previous studies, it is possible to

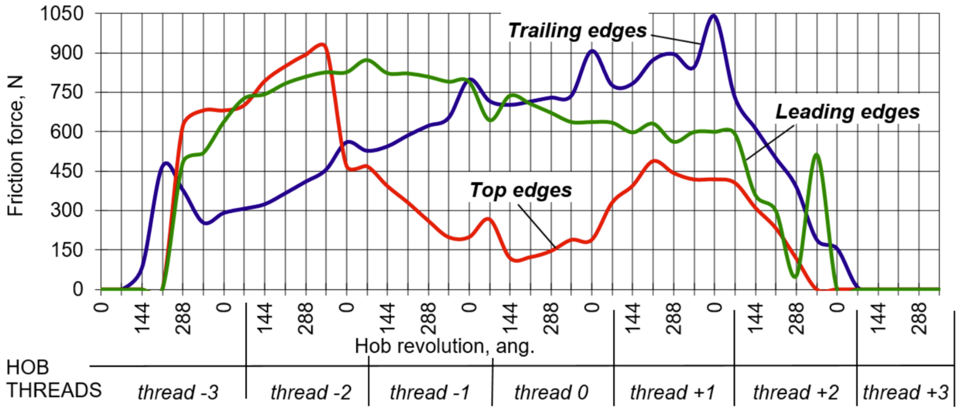


Fig. 4. Change of friction on the edges of the teeth on the helical surface of the hob along its turns as a function of the angle of rotation of the cutter

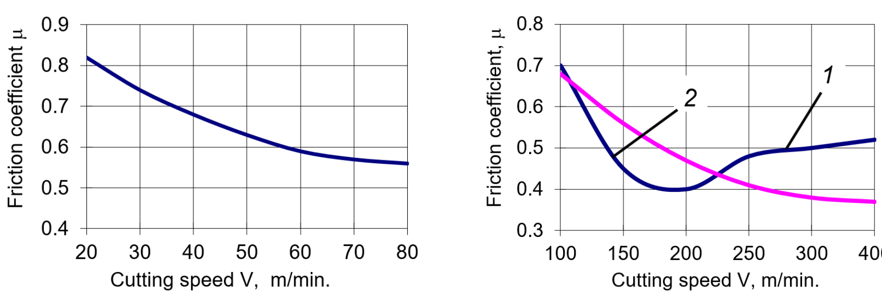
simulate the parameters and patterns of thermal processes in the shaping zone of the gap of the machined gear wheel.

Considering that for hob cutters the rake angle $\gamma = 0$, the friction force on the rake face of the cutter tooth can be described by the following equation:

$$F = P_\tau \cdot (\sin\Phi + \cos\Phi/\tan\omega) \,. \tag{1}$$

3.2.2. Frictional forces on the relief surface

To determine the intensity of friction on the flank surface using the system of rheological modeling Deform 2D, one needs to resolve the dependence of the intensity of external dry friction when cutting steel and cast iron by a tool from high-speed steel and carbide at a constant cutting depth of 0.6 mm and feed rate of 0.15 mm/rev. The results of the simulation of the dependence of the friction coefficient on the cutting speed are shown in the graphs (Fig. 5).



(a) (b)

Fig. 5. Dependence of friction coefficient on cutting speed: a – high-speed tool steel T11302 on steel AISI 1045; b – tool-hard alloy MC131 on steel AISI 1045 (1); tool-hard alloy WC92 on grey cast iron (2)

Let's assume a coefficient of friction of 0.67–0.7 for a high-speed steel hob and a cutting speed of 38.5 m/min.

The friction force on the flank surface of the cutting teeth depends on the force on the tool side normal to the machined surface of the workpiece and the friction coefficient. When the rake angle is zero, the pressure on the flank face arises because of the force must overcome the friction on the rake surface. Because of that, the general pattern of changes in the friction forces on the rear surfaces corresponds to the friction forces on the rake surfaces of the teeth on the leading, top, and trailing edges and differs from them by the value of the friction coefficient on the rear surface of the cutting teeth, i.e. $F_\alpha = F \cdot \mu$.

The results of friction force calculations show that the maximum friction occurs on the rake face of the teeth at the trailing edges. This is the result of the maximum shear force due to the great width of the shear and the large cross-sectional area of the chip on these edges. The maximum friction forces on the flank face will occur on the same teeth.

3.3. Heat flows on the teeth of a hob

The result of deformation and contact processes during cutting is the heat and intensity of its distribution in the body of the cutting wedge in the form of heat fluxes arising on the rake and flank faces of each edge of a particular tooth. The value of heat flow from a certain energy source can be represented by the heat flow density q, N·m/(mm^2/s), conveyed by heat transfer into the solid body through the unit of cross-sectional area per unit time. The heat generated in the shear section can be neglected since this heat almost completely passes into the chip and is carried away from the cutting zone, and only a small portion of it passes into the workpiece.

The established relationships of changes in shear parameters and power load and friction [20] make it possible to determine the patterns of heat fluxes on each of the active teeth, putting them following the cutting force, shear parameters, and length of contact areas on the rake and flank faces of the cutting edges.

To simulate the heat due to friction, we will make the following assumptions.

1. The sources of heat energy arising on the contact surfaces of the cutting edge during one cut will be taken as conditionally stationary since the positions of these sources relative to the tool surface during one cut are constant, although, relative to the chip, these sources are fast-moving. On this basis, we will assume that all the heat from friction on the flank and rake surfaces is generated only in the tool.

If we consider the cutting process over a longer period, these sources act periodically with the frequency of rotation of the hob. For the range of cutting speeds used for fast-cutting hobs – 30–60 m/min. the cutting frequency is 2–4 Hz, and for hobs equipped with hard alloy – 15–35 Hz. At such frequencies, the heat input to the cutting edge of a certain tooth can be taken as a continuous process.

According to their geometric form, these sources are assumed flat, the dimensions of which are determined by the length of the corresponding contact areas and the active width of the cutting edges, equal to the width of the shear section.

2. Thermophysical characteristics of tool high-speed steels do not depend much on temperature [24]. Therefore, the coefficients of thermal conductivity and heat capacity will be considered constant, similar to their values at a temperature of 200–300°C.

3. In our case, heat sources and, respectively, heat fluxes within one tooth of the cutter act simultaneously on the leading, top, and trailing edges. In addition, heat fluxes act on the rake and flank surfaces of each of the blades. Other rules, such as the law of exponentials, determine the flux density at the contact areas of the cutting faces. However, when summing the fluxes from all sources, their density will obey the truncated normal law. This is because the maximum resulting heat flux density will be in areas close to the tops of the teeth, which will have the highest temperature.

3.3.1. Heat fluxes on the flank faces of the hob teeth

The heat source on the flank surface has the dimension C by b, where C is the width of the contact area of the flank surface with the machined surface, b is the length of the contact area equal to the shear width, mm:

$$q_\alpha = \frac{F_\alpha \cdot V}{60 \cdot C_\alpha \cdot b}, \quad \mathrm{J/mm^2 \cdot sec.} \tag{2}$$

The contact area on the flank surface of the tool is formed due to rounding of the cutting edge, elastic depressing of the formed surface, and formation of the wear area on the flank face. For high-speed hobs in the middle of the stability period, the width of the wear area is taken to be 0.25 mm, other components are an order of magnitude smaller, so they can be neglected.

For the pre-accepted initial data, the plots of heat flux density acting on the flank surfaces of the hob teeth edges are shown in Fig. 6.

3.3.2. Heat fluxes on the rake surfaces of the hob teeth

The intensity of heat fluxes on the rake surface is described by the equation:

$$q_\gamma = \frac{F \cdot V}{60 \cdot C \cdot b} \cdot \frac{1}{\xi}, \tag{3}$$

where $V/\xi = V_{ch}$ is the velocity of the chip movement on the rake surface in the area of secondary plastic strain, m/min; F is the friction force on the rake surface, N; C is the length of the plastic contact area, mm, b is the shear width, mm.

The contact length of the chip with the rake surface of the tool can be determined by the formula [25]:

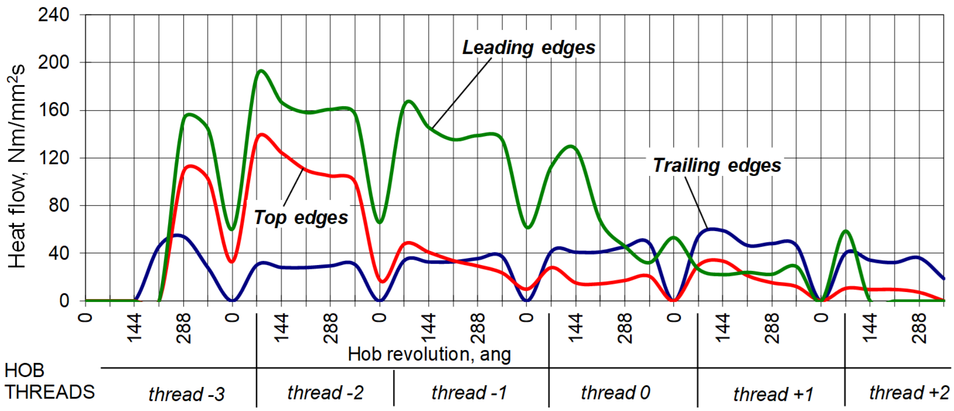


Fig. 6. Heat flow on the flank face of the trailing, top, and leading edges on the screw surface of the hob

$$C_\gamma = a \cdot \xi^{0,1} \cdot \left[\xi \cdot (1 - \tan\gamma) + \frac{1}{\cos\gamma}\right], \tag{4}$$

where γ is the rake angle of the tool (when $\gamma = 0$).

As follows from equations (2) and (3), the intensity of the heat flux depends on three factors: the friction force on the surface, the contact area on the surfaces, and the speed of the heat source. On the rake face, the chip slows down due to friction in the secondary deformation zone. As a result, the speed of the moving heat source is lower than the cutting speed by a factor equal to the chip compression ratio. That is, according to this parameter, the heat flux on the rake face will be smaller than that on the flank face, where the speed of the heat source is equal to the cutting speed.

On the other hand, the heat on the rake face is concentrated in a very small contact area, the length of which depends on the thickness of the cut. Since for some edges the thickness of the cut is very small (the laws of change of this parameter and its value are established in [23]), the intensity of heat fluxes on the rake face is much higher than on the flank faces of the hobbing teeth. This corresponds to the physical nature of the parameter q as the rate of thermal energy propagation through a unit body area.

3.4. The temperature of the teeth and edges of the hob

The results of the study of heat fluxes on the tooth surfaces allow us to calculate the average and maximum cutting temperatures. In the general case of a flat fast-moving uniformly distributed heat source, the dependence for the maximum surface contact temperature $\theta^*_{\max}$ is as follows [25]:

$$\theta_{\max} = \frac{2 \cdot q}{\lambda_0} \cdot \sqrt{\frac{b \cdot \chi}{\pi \cdot V}} \cdot K_{sh}, \tag{5}$$

where λ_0 is the thermal conductivity coefficient of tool material, J/cm·s·°C; χ is the thermal diffusivity coefficient of tool material, cm^2/s; q is the heat source intensity, J/cm^2·s; b is the linear length of the source, equal to the active blade width, mm; V is the cutting speed in mm/s; K_{sh} is the shape factor of fast-moving source [25].

Let accept conditionally the thermal-physical properties of the tool and machined materials as the same: thermal conductivity $\lambda_0 = 0.04$ J/cm·s·°C; diffusivity coefficient of high-speed steel $\chi = 6.6$–7.2 mm^2/s; $K_{sh} = 1$.

The graphs of temperature on the edges of the hob teeth on the screw surface, pertaining to specific turns, are shown in Fig. 7.

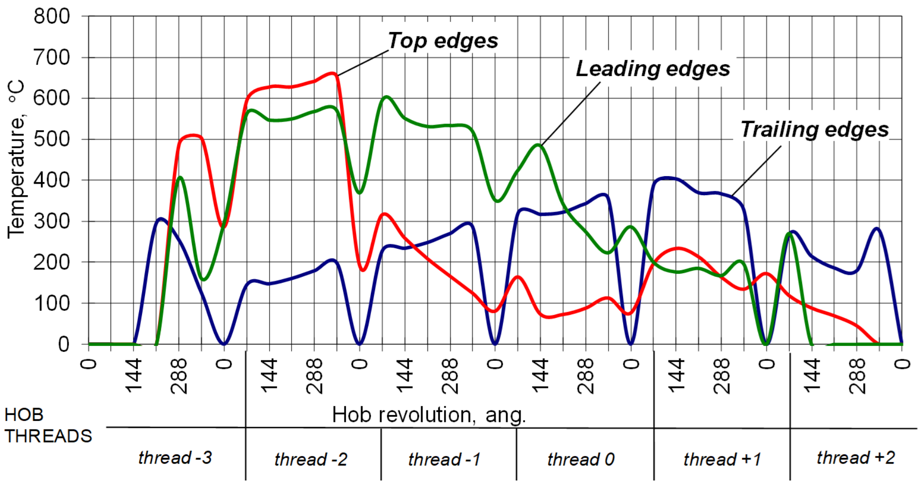


Fig. 7. Temperature on the cutter teeth depending on the rotation of the hob

The simulation results obtained show that the maximum temperature occurs on the rake surface of the top and leading edges of the cutter, which corresponds to the pattern of heat flow on these edges. This conclusion is explained by the small width of the cutting layers and cross-sectional thickness of the chips removed by these teeth and the high concentration of heat within the small contact area between the chip and the rake surface on the top and leading edges of the hob cutter teeth.

4. Experimental verification of the results of simulation of hobbing wear

Experimental studies were conducted to verify the modeling results. The parameters of the cutter and cutting parameters, as well as the material of the workpiece, correspond to those used for modeling. The cutter speed of 129 rpm corresponded to a cutting speed of 40.1 m/min. Cutting was performed dry for 40 minutes at an intensive feed rate to the full depth of the profile for accelerated tool wear.

In about a half of the time of continuous operation of the hob, after the onset of thermal equilibrium in the tool and system, a build-up was detected on individual teeth of the –2 turn, where it was predicted. This tooth is shown in Fig. 8. The location of this build-up also corresponds to the edges that are expected to be exposed to significant heat fluxes – the trailing side edge and the top edge of these teeth. The build-up, as a molten chips welded to the tooth face, initially protects this surface, but when it is torn off, it damages the edge, which accelerates further wear of the edge. The thermal stress marks on the original edge of the blade are also clearly visible as a dark-colored stripe. This indicates that the temperatures in these areas are above the permissible temperature for the HSS.

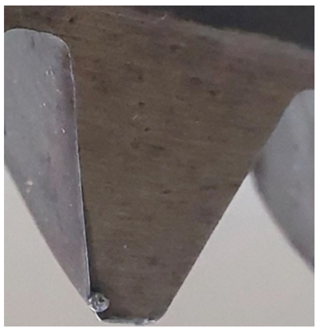


Fig. 8. Tooth with a build-up

This photo also clearly shows the wear of the top edge of this tooth from turn 2, which, as can be seen from the heat flux diagram in Fig. 7, is subjected to the most intense heat load.

A general pattern of tooth wear after cutting the gear for 40 minutes and a photo of the corresponding teeth with wear marks are shown in Fig. 9.

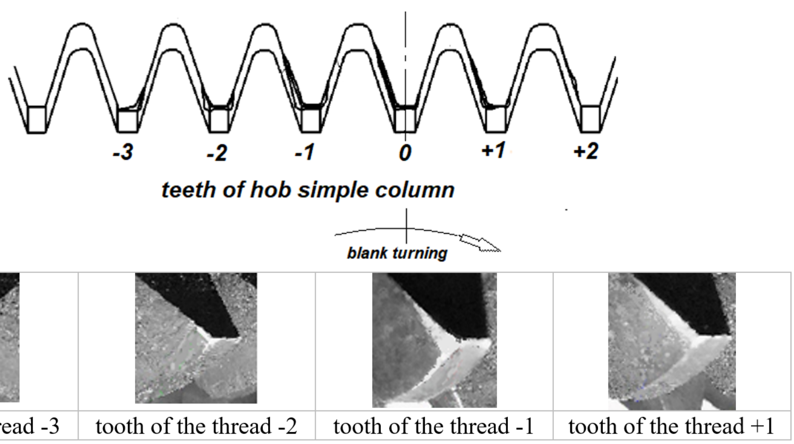


Fig. 9. The pattern and photos of the wear of the hob teeth

The analysis of experimental data shows that the wear areas of the edges along the length of the rail and the size of the worn areas correspond to those predicted by the modeling presented in this article. Thus, we can conclude that the developed methodology and its basic provisions are suitable for predicting hob wear.

5. Conclusions

The results of the research presented in this article, the analysis of power and thermal processes and their relationship with hob wear showed the following:

1. It has been established that the basis of the wear of the hobbing cutter teeth is a phenomenon of different physical nature: friction on the contact surfaces and thermal flows. The cause of the loss of thermal stability of certain teeth and cutter edges is not only the friction on their contact surfaces, as it is traditionally interpreted in the classical literature on mechanics of gear machining. Another factor of significant thermal action is the intensity of heat fluxes. The places of localization of maximum friction and the area of maximum temperature on the tooth surfaces of the cutter do not coincide. This means that intense friction is not a sufficient factor in predetermining a high cutting temperature. More precisely, the necessary condition for the occurrence of high temperature is the small contact area on the rake and flank surfaces of the teeth, which creates intensive heat fluxes in such areas. Their temperature can be higher than critical, so local thermal hardening will take place here. In addition, the surface layers of the teeth heated to temperatures above 300°C interact with air oxygen, which additionally leads to a loss of initial strength due to oxidation.

2. At the same time, intense friction is also the cause of increased wear. As a result of the shear forces that cause this friction, extremely high contact pressure occurs on the cutter teeth' rake surface in the second strain of the chip, which is several orders of magnitude higher than what is applied to machine parts' mating surfaces. This factor is the cause of abrasive wear of the hob.

3. Based on comprehensive modeling of the gear hobbing process, it is possible to indicate with high probability the areas of localization of two groups of teeth on the working surface of the cutter, for which wear is caused by increased friction on the rake and flank faces of the cutting wedge and the increased temperature. Thus, for the assigned study data, significant friction forces on the rake edges occur on the exit blades of the teeth of the two turns (+1) and (+2) of the leading part of the hob cutter. The reasons for the increased friction are the large values of shear width, shear area, and shear force. The most intense friction on the rake surface also results in increased friction forces on the flank faces on those edges. This is the result of the reaction of the elastic "tool-workpiece" system to the localization of the increased cutting force. A protective coating applied to their rake and flank surfaces with a maximum anti-abrasion effect and a minimum coefficient of friction reduces the abrasive wear of these teeth.

4. The highest cutting temperature (640°C – for the proposed initial hobbing data) occurs on the top edges of the teeth belonging to the input turn (+2) and on the leading edges of the teeth of the turns (+1) and (+2) (600°C). Since the temperature resistance of high-speed steels is in the 600°C range, these teeth of the hob cutter will be subject to intensive wear due to a decrease in their initial strength and hardness as a result of plastic thermal deformation of the hob edges. To prevent this type of wear, heat-resistant coatings should be used in the main.

5. Various physical and mechanical methods can be used to apply protective coatings with different properties to the teeth in different areas of a high-speed steel cutter, allowing the formation of different suitable coatings in local areas of the tool. For example, laser techniques, electro-spark alloying, or plasma spraying can be recommended to create maximum heat resistance, while diamond coatings can be used to reduce friction on the surfaces.

6. The methodology of the study presented in this paper makes it possible to select hobbing cutting conditions and parameters that allow avoiding thermal overload and intensive abrasive wear of hobs.

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