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DEVELOPMENT OF A METHOD FOR MODELING THE PROFILE OF A MULTI-SLOT WORM CUTTER FOR MACHINING HELICAL GEAR GEARS IN WEAPONS AND MILITARY EQUIPMENT

With the advent of the latest technologies for manufacturing military equipment and weapons, along with the progress of modern computing technology, designers are faced with the need to develop new, more effective methods for modeling conjugate curved surfaces of kinematic pairs of gearing without interference. The article considers the issues of creating a method for modeling the profile of a multi-cut worm cutter for machining helical gears in weapons and military equipment. This modeling method is aimed at improving the processing of toothed conjugate curvilinear gears used in gun lifting mechanisms, tank turret turning mechanisms, and self-propelled artillery installations.

The reliability and durability of modern mechanical engineering products, which include a large number of elements with complex conjugate curved surfaces of gearing, are largely determined by the accuracy of their manufacture. In the practice of modeling kinematic pairs of conjugate curved surfaces, certain difficulties often arise that are closely related to the creation of gear products for military equipment and weapons. In this regard, the development of an effective method for modeling the profile of a rich-lead worm cutter for machining conjugate curved tooth surfaces, which allows avoiding interference at the product design stage, becomes relevant. The proposed method will help improve the modeling process, as well as increase the accuracy of gear machining and the overall productivity of production processes with the proposed milling cutter.

Keywords: *gearing; technical solutions; technological process of profile modeling; conjugate surfaces; parameterization; development process; Archimedes spirals; kinematic pairs; interference; weapons and military equipment.*

Problem statement in general terms. Today, the technological process of developing new methods for modeling the profile of a cutting tool with a helical curved surface, namely a multi-start worm milling cutter, for machining gear conjugated engagements of kinematic pairs in gun lifting mechanisms, turret rotation mechanisms of tanks, and self-propelled artillery units, requires thorough research.

One of the most critical issues in machining the curved surface of the profile of a cutting tool such as a multi-start worm milling cutter is the elimination of interference. If the interference is significant, the machining of the cutting tool leads to edge undercutting of the cutter (reduced accuracy, impossibility of further machining).

As a result of these deformations, significant tooth interference leads to slippage. Such machining of the curved surface of the cutting profile of a multi-start worm milling cutter is unacceptable, as it causes increased dynamic loads and wear, which contaminate the lubricant and may result in damage to the machining mechanism used for producing the cutting tool.

Analysis of last research and publications. The fundamental principles of the study are outlined in [1]. The phenomenon of interference is described as follows: “Interference occurs when a certain part of space lies simultaneously within the volumes of two bodies.” If one of the bodies is a cutting tool and the other is a workpiece, interference causes undercutting and reduced accuracy during machining. If both bodies are solids, then the manufacturing of the cutting tool leads to tooth removal.

Different definition is proposed in [2]: “Interference is defined as any incorrect contact of profiles outside the active zones of the line of engagement, that is, a phenomenon where the trajectory of the edge of one tooth in relative motion intersects the profile of the conjugated tooth.” However, the study of interference in this case required the construction of a large number of axoids, which renders the corresponding research impractical for real-world applications.

The formation of conjugated helical curved surfaces is based on the theorem of professor

A. M. Podkorytov [3, 4], which states that surfaces Σ_A and Σ_B are conjugated if each of them is generated by a corresponding relative motion Φ_A / Σ_A and Φ_B / Σ_B of congruent intermediaries $\Phi_A = \Phi_B$. The surface Σ_A and the intermediary surface Φ_A are enveloping with a line contact $l^1\left(l^1{}_2\right)$ [5].

Formulation of the research objective. The aim of this study is to develop a method for modeling the profile of the cutting tool of a multi-start worm milling cutter intended for machining helical gear engagements that are conjugated with the machined helical surface in conjugated kinematic pairs of mechanisms used in armament and military equipment. To achieve this goal, the Archimedean spiral, the logarithmic spiral, and a straight line will be considered.

Presentation of the core material. The foundation for accomplishing the task lies primarily in devising a solution for manufacturing cutting tools, which is precisely the focus of the proposed research. In practice, when modeling products with curved conjugating surfaces, issues frequently arise – a problem closely linked to the aviation, military, machine-building, tool-making, and instrumentation industries. With the emergence of advanced production technologies for military equipment and armaments – based on automated manufacturing complexes – and given the characteristics of modern computing hardware, designers face the necessity of developing new, more sophisticated methods for modeling conjugate surfaces without interference.

Such innovation will not only reduce design time, and improve reliability, durability, and accuracy of CAD processes, but will also enable technical modeling of examined components using innovative technological approaches via computer tools. This progress significantly elevates the computational and graphical capabilities of modern computing systems, as well as tools for design and analytical analysis. As a result, new prospects unfold for modeling cutting-tool profiles in the development of kinematic pairs used in military and defense applications allowing interference to be eliminated already at the design phase.

After studying various objective methods for modeling the profiles of cutting tools specifically multi-start worm milling cutters it was found that existing methods are not sufficiently practical for production. Therefore, to manufacture a multi-start worm milling cutter with the required precision, the parameters of the contact surface interaction are set under predetermined conditions, which effectively prevents interference during machining.

In every form of the production-technological process, the tool not only defines the technical sequence of actions but also determines the shape of the workpiece. Engineering improvements are impossible without due attention to tool quality. For instance, employing multi-start cutting tools particularly worm milling cutters not only optimizes technological operations but also ensures higher precision and productivity in part manufacturing.

In tool design practice, the most common and general case involves rotation of bodies about skew axes. The relative motion of such objects is known to be helical, characterized by axes and parameters of a screw line.

One of the key challenges in profiling cutting tools lies in accurately determining the geometry of the initial helical working surface of a multi-start worm milling cutter, which must match the machined helical surface. Worm milling cutters are among the most widely used tools in metalworking; no other tool demonstrates as much diversity in type, form, and application as cutters. Their significant advantage is the capability for precise part profiling.

As a basis for developing modeling techniques for the profile of a multi-start worm milling cutter, the Archimedean spiral theory was adopted, complemented by the logarithmic spiral and a straight line. However, in practice the Archimedean spiral is preferred. Each profile curve must ensure adequate clearance angles across all points of the cutting edge profile while remaining sufficiently large to meet the technical requirements of cutting even after multiple grinding iterations. In this respect, the Archimedean spiral produces satisfactory results (see Figure 1).

The equation of the Archimedean spiral in the polar coordinate system is given as follows (Figure 1):

$$\varsigma = b\Theta,$$

where ς and Θ are the radius vector and the polar angle in radians of a given point on the piral, b is the coefficient (proportionality factor) that characterizes the size of the spiral. From the equation, it is evident that the increment of the rotation angle is directly proportional to the increment of the radius vector. The pitch of the spiral (the increase in the radius vector per revolution) is a constant value.

For the angle $\Theta = \frac{\alpha}{2\pi}$, the radius vector $\varsigma = \alpha,$ then $b = \alpha / 2\pi$.

Accordingly, the equation of the spiral can be written:

$$\varsigma = \frac{\alpha}{2\pi}\Theta.$$

As for the cutter tooth, the equation of the Archimedean spiral along the tip can be written:

$$\varsigma_b = R - \frac{\alpha}{2\pi}\Theta_b,$$

where R is the outer diameter of the cutter.

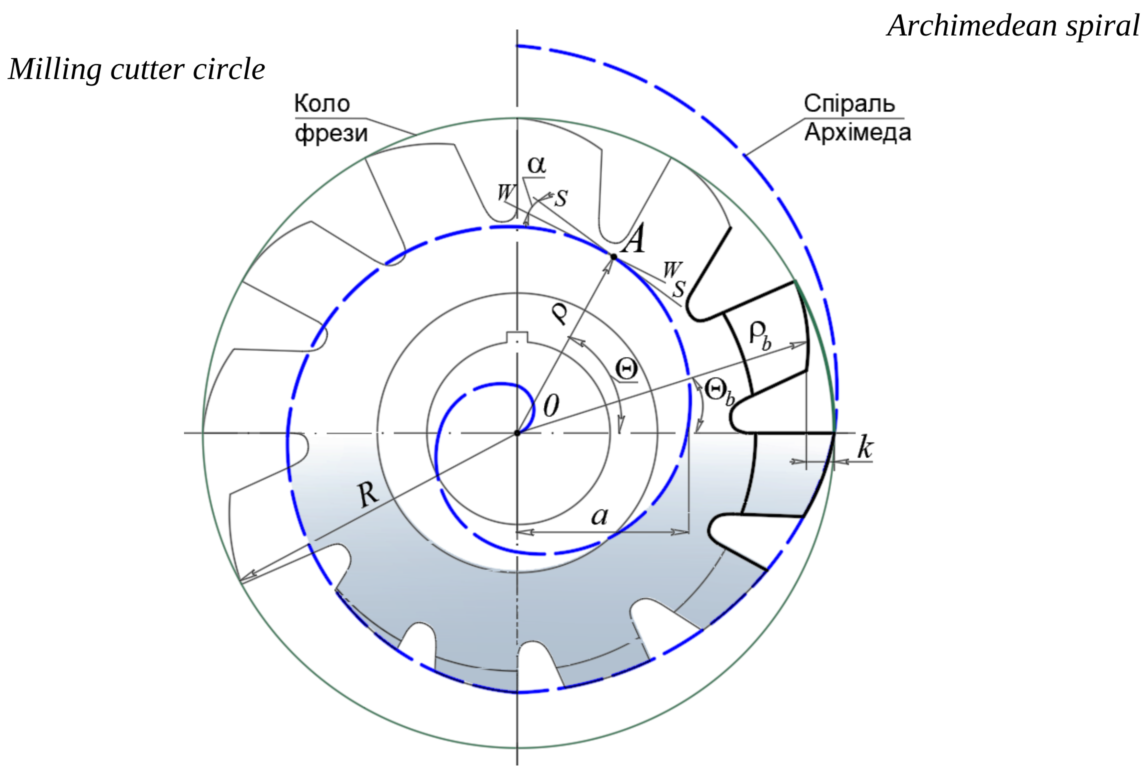

Figure 1. Archimedean spiral as a curve for a relieved tooth

The clearance angle lies between the tangent to the spiral $S - S_s$ and the tangent to the circle $W - W_s$, drawn at point A (Figure 2).

Using a formula from differential geometry, we can state the following:

$$tg\alpha = \frac{d\varsigma}{\varsigma d\Theta};\ \frac{d\varsigma}{d\Theta} = \frac{\alpha}{2\pi};\ tg\alpha = \frac{\alpha}{2\pi\varsigma} = \frac{1}{\Theta},$$

also

$$ctg\alpha = \Theta.$$

The pitch of the spiral is

$$a = kz,$$

where k – is the pitch of the spiral corresponding to the tooth lead, or the amount of back taper;

z – is the number of cutter teeth.

Thus,

$$tg\alpha = \frac{kz}{2\pi\varsigma}.$$

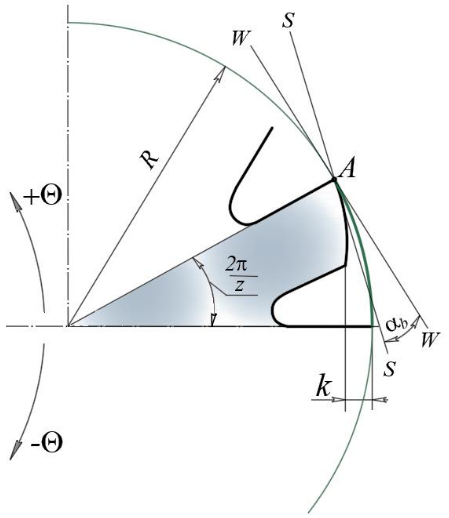

Figure 2. Determination of the clearance angle

Considering that $\varsigma = R,$ we find the dependence between the back angle at the tooth vertex α_B the radius, the number of teeth, and the amount of taper of the milling cutter.

$$tg\alpha_B = \frac{kz}{2\pi R},$$

Undercut amount determination:

$$k = \frac{\pi D}{z} tg\alpha_B,$$

D – the diameter of the milling cutter.

To prevent undercutting movements in the machine tool carriage, a cam is installed, the drop amount of which is equal to the undercut amount, related to the full rotation of the cam, and on the cutter – to the central angle of 360°/z. The drop amount is marked on each cam.

As knowns, the clearance angle in the measured plane is usually located between the plane tangent to the base surface of the tooth and the plane tangent to the surface formed by the rotation of the cutting edge (for example, the tooth tip). Both planes are tangents drawn to the same point, and the measured plane through this tangent can be extended infinitely.

However, we are only interested in three measurement planes (Figure 3):

a) *PP* – a plane perpendicular to the axis of the milling cutter hole;

b) *NN* – a plane perpendicular to the projection of the lateral cutting edge onto a plane perpendicular to the rake face;

c) *OO* – a plane parallel to the axis of the hole.

The tangent plane to the relieved surface can be defined by two tangents passing through the same point and lying in this plane. One of them is line *CE*, tangent to the Archimedean spiral; the other is line *CF*, tangent to the tooth profile curve.

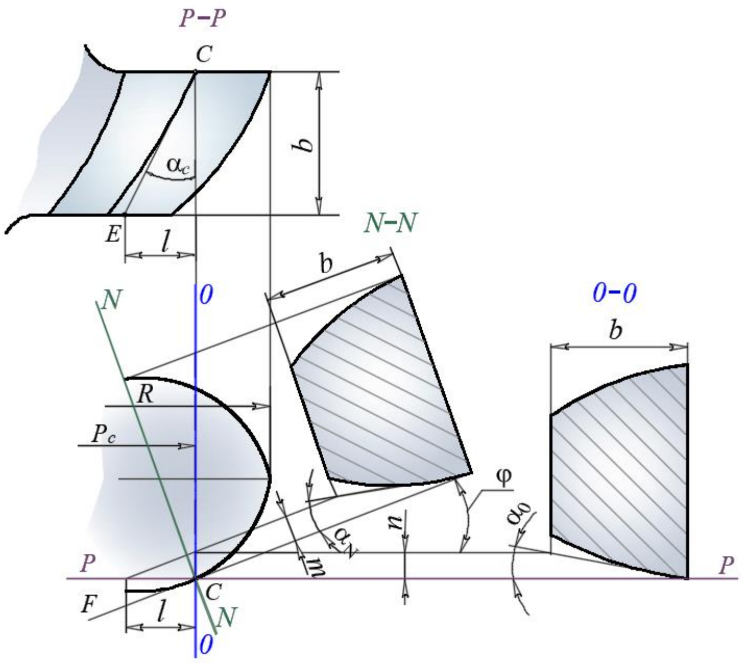

Figure 3. Determination of clearance angles in different planes for an arbitrary point of the milling cutter tooth

The tangent plane to the cylindrical surface can also be defined by two lines tangent at the same point *C* and lying in this plane. One of them is line *CH*, perpendicular to the radius vector (for example ςC at point *C*), and the other is line *CF*, tangent to the tooth profile curve.

Back angles marking: α_C – in the measurement plane *PP*, α_0 – in plane *OO*, α_N – in plane *NN*; in addition, α_B – the angle on a top.

The α_C angle determination (Figure 3):

$$tg\alpha_C = \frac{R}{\varsigma_C} tg\alpha_B.$$

The α_0 angle determination (Figure 3):

$$tg\alpha_0 = \frac{n}{b}; n = ltg\varphi; b = \frac{l}{tg\alpha_C}.$$

As a result

$$tg\alpha_0 = tg\alpha_C tg\varphi = \frac{R}{\varsigma_C} tg\alpha_B tg\varphi,$$

where φ – the angle between the tangent to the profile and the axis of the profile (i.e., the line perpendicular to the axis of the cutter).

The α_N angle determination:

$$tg\alpha_N = \frac{m}{b}; b = \frac{l}{tg\alpha_C}; m = l\sin\varphi.$$

As a result

$$tg\alpha_N = tg\alpha_C \sin\varphi = \frac{R}{\varsigma_C} tg\alpha_B \sin\varphi.$$

The last equation shows that the α_N angle is the minimal value compared to the back angle in other intersections. However, the difference between α_0 and α_N is practically small, and for the maximum value of $\alpha_B = 15^\circ$ we have $\alpha_N = 0,97\alpha_0$. Nevertheless, to calculate the α_B angle, we use the α_N value.

As the φ angle decreases, the α_N angle becomes smaller, and on the cutting edges with $\varphi = 0$ the α_N back angle is zero. During calculations, the minimum allowable α_N back angle on the side edges is usually set within the range of 2°–3°, and only in exceptional cases it can be reduced to 1°–1.5°.

Then, either analytically or graphically, the φ angle is determined for the most favorable point of the side edge, i.e., its minimum value. If this turns out to be less than 5°, which removes part of the involute, then for cutters with semi-round convex and concave profiles, slopes at an angle of 10° are provided.

Knowing φ and α_N, we find the back angle at the tip of the cutter tooth according to the following formula:

$$tg\alpha_B = \frac{\varsigma_C tg\alpha_N}{R\sin\varphi}.$$

After this, the amount of relief is determined, and the most suitable chuck size is selected from the available options, based on the rounded value of its taper.

To control the modeling of the profile of a multi-start worm cutter, in the case of template profiling, it is necessary to determine the intersection of the surface lying in a plane perpendicular to the helical parallel, on the reference cylinder with a specific diameter.

The template profile can be determined both graphically and analytically.

Currently, multi-start worm cutters are the most efficient; they are widely used in military equipment and weaponry for processing numerous parts in mass and serial production.

Conclusions. The proposed modeling method is based on the theory of conjugate surfaces, which allows for determining the configuration of the cutting edges of gear-cutting tools, ensuring the absence of interference.

For gear wheels, this means the elimination of undercutting within the required range of gear tooth counts, using non-standard module values that are specifically determined.

Modeling the cutting tool profile using the described method enables the identification of the curvature error of the cutting tool, allowing for the consideration of interference phenomena, the machining of new curved conjugate gear surfaces in production, and also the repair of military equipment in field conditions. This will contribute to the accelerated deployment of weapon system units.

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