

Modeling of shaping process and analysis of gear wheel cutting process by means of AUTOCAD and ANSYS software

A A Lyashkov, G E Murashev

Omsk State Technical University, 11 Mira ave., Omsk, 644050, Russia

Abstract. In the present paper methodology of computer aided geometric modeling of formation of workpieces with periodic teeth machined with centroid enveloping method is developed without involving complex mathematical apparatus. During its application, as opposed to already known methods, simultaneous modeling of two objects of formation – wraparound and removed contents – takes place. Analysis of configurations of solid models of cutaway layers and respective removed content volumes allows a design engineer to intentionally set the optimal values of tool advance parameter and number of passes. The key point of the present paper is to establish logical connection between geometric computer simulation of removed contents in CAD environment and analysis of chip formation in the process of cutting using ANSYS software. In the present paper AutoCAD 3D simulations rendering of cutaway layers is shown along with the corresponding realistic simulation of chips, created using metal cutting process finite element analysis software. Due to substantial difficulties of cutting process 3D simulation, it is considered reasonable to perform computer simulation of cutaway layers geometry generation on the first stage of problem solving. This will allow us to choose the optimal cutting parameters and consequently speed up the cutting process simulation.

Keywords: cutaway layers, geometry generation, solid modeling, cutting

1. Introduction

Formation of item surface is performed during its machining by cutting excess from a workpiece. The tool surface is generative and the obtained surface of the item is processed. A geometric model of the processed surface is an envelope of a family of generative surfaces. All the variety of methods of determination of envelope of family of lines and surfaces can be divided into three categories: graphic and graphic analytic, analytic, and numeric.

In the majority of practical item formation simulation problems the family of lines and surfaces is not reduced to an envelope, but also includes special points and lines. In this case it is necessary to determine discriminants of those families, i.e. envelope and special elements. The discriminant is the first object of lines and surfaces formation modeling. The discriminant determination is usually executed with analytic and numeric methods. Methods based on computer aided geometric modeling are also being intensively developed recently.

In theory of item formation by cutting, apart from the terms “envelope” and “discriminant”, a term “wraparound” is applied. A wraparound of a family of bodies is a boundary that envelopes the multitude of points belonging to at least one body of the family [1]. This concept was introduced due to the fact that the body of generative instrument, as a rule, is limited by segments of various surfaces. Therefore we need to determine the envelopes of several families of lines or surfaces and then to connect them. Moreover, the generative element in the process of real formation most often moves discretely, which means that the machined piece will differ from the envelope because of circularity deviation. The wraparound of a family of bodies is the second object in the process of formation.



In engineering practice, along with determination of discriminant and wraparound, it is often necessary to develop models of cutaway layers. Analysis of qualitative characteristics and quantitative parameters of those layers allows us to set optimal technological parameters of item formation by cutting tool. Therefore models of layers cut away in the process of formation are the third object in the process of formation.

A great amount of works is dedicated to modeling of the first and the second formation objects: [2, 3, 4] etc. The basics of modeling of the third object of formation in application to items machined by enveloping method are established in paper [5]. However, the proposed solution doesn't give us a clear idea of cutaway content volume. At the same time, the geometric characteristics of the removed content volume significantly impact cutting force [6], which affects tool life and quality of machining. In paper [7] an assumption is made that both shape and volume of cutaway layers affect cutting force. Yet there are not many papers in that field. Development of corresponding mathematical apparatus, that would allow cutaway layer simulations [8], might be a solution. Still, this approach is labor-intensive, lacks visual representation and doesn't allow us to simulate the cutting process.

The other approach to solution of the problem is development of mathematical model of formation of cutting scheme, which would allow us to determine the dimensions of cutaway layers with further implementation of this model on the basis of CAD software. Thus in paper [9] on the basis of developed mathematical model of cutting scheme a computer model of spiral groove formation by means of a straight section tool is obtained. The cutting scheme is visualized in flank profile of the spiral groove, which is used to analyse cutaway layer content volume. The proposed solution does not give us full data on shape or on content volume of cutaway layers and is fair only for certain type of tool.

Studies of cutaway layers and cutting process are currently concentrated in two directions. The first one is based on computer aided solid geometric simulation of item formation process using CAD systems [10, 11, 12], while the second one considers cutting process with the aid of CAE systems [13, 14, 15]. The studies in the second direction consider finite element models of workpiece-tool system, in which tool is represented as 2D solid body [16, 17]. It is pointed out that physical related to the item cutting process are very complicated [18], especially during 3D shaping, and demand refinement of already known solutions and development of new ones.

In general, no known literary source represents a complex consideration of the problem in both directions. It is therefore considered urgent to develop methodology of study of gear item formation on the basis of computer aided geometric modeling and finite element analysis software.

• II. Problem Definition

The objective of the present paper is development of methodology of computer aided geometric modeling of cutaway layers in the process of teeth formation on wheels without involving complex mathematical apparatus and with further use of the acquired models for cutting process analysis using ANSYS software.

In order to reach the mentioned objective, it is required to create an algorithm of computer aided geometric modeling of cutaway layers by means of AutoCAD software in application to gear wheel formation using rack tool, to test of the created algorithm and acquire computer aided geometric models of cutaway layers on their basis, to develop methodology of analysis of gear wheel cutting using rack tool on the basis of results of computer aided solid modeling of item formation using CAE software.

III. Theory

1. Gear wheel formation by means of a rack tool

Computer aided modeling of formation of cylindrical items with periodic profile is based on rack tool outline. Therefore the item profile constitutes an envelope of a family of rack profiles. This family is formed as a result of rolling action of the initial straight rack over the detail's circumference (figure 1).

In the process of relative movement, rack centroid rolls without sliding over wheel centroid. The rack movement can be divided into two components: rotation of the initial straight line around center O_1 of workpiece centroid on angle φ and shift of the rack along centroid tangent by distance $R \cdot \varphi$ (figure 1). As a

result, wheel teeth profile constitutes an envelope of a family of rack profiles. Equations of the family are of the following form [12]

$$\begin{aligned} x &= x_1(t) \cdot \cos \varphi + y_1(t) \cdot \sin \varphi + R \cdot (\sin \varphi - \varphi \cdot \cos \varphi), \\ y &= -x_1(t) \cdot \sin \varphi + y_1(t) \cdot \cos \varphi + R \cdot (\cos \varphi + \varphi \cdot \sin \varphi), \end{aligned} \quad (1)$$

where $x_1 = x_1(t)$, $y_1 = y_1(t)$ represent rack profile equations, φ represents family parameter, R represents wheel centroid radius. Equations (1) serve as basis for the development of envelope of family of congruent lines using analytic methods as well as for development of algorithm of computer aided solid modeling of envelope of family of profile models limited by these curves.

In the process of computer aided modeling relative movement of model of rack that defines kinematic formation scheme is determined by the following algorithm: a rack model turns on angle $\Delta\varphi$ around an axis, that goes through point O_1 and is normal to workpiece surface (figure 2), increment size of angle $\Delta\varphi$ being a cutting parameter set by design engineer in order to obtain a multitude of profiles; an object shifts along vector $\vec{m}(-R \cdot \cos \Delta\varphi, R \cdot \sin \Delta\varphi, 0)$ on distance $R \cdot \Delta\varphi$.

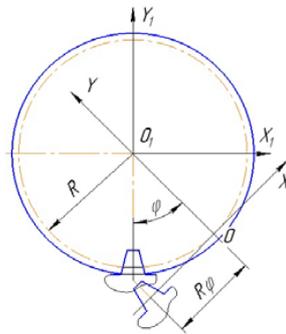


Figure 1. Kinematic formation scheme

After setting the limits of parameter φ variation and its increment size $\Delta\varphi$, formation modeling takes place. Interaction between solid models of rack and workpiece is implemented through boolean operations. An example of simulation is shown on figure 2. The obtained side surface of profile constitutes a wraparound surface. It closes in on envelope surface with reduction of $\Delta\varphi$ parameter upon fulfillment of formation terms.

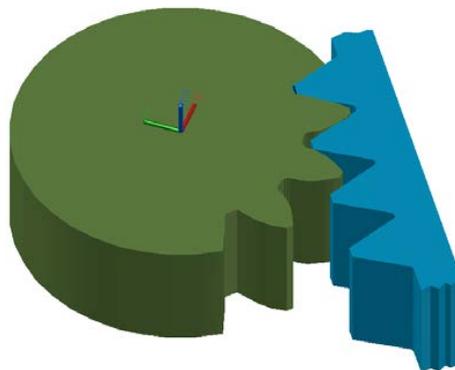


Figure 2. Models of tool and workpiece in the process of formation

2. Solid modeling of cutaway layers

The developed algorithms and programs of solid formation modeling along with mating profile [4, 11] acquisition allow us to follow through the process of sequential cutting of gashes between item teeth profiles, configuration of cutaway layer and load of segments of cutting edges. The proposed modeling allows us to acquire qualitative characteristics of cutting process as well as some quantitative parameters including cutaway layer content volume over double pass of the tool; content volume of layer removed by peripheral and side cutting edges; it also allows us to establish relationship between removed content volume and value of cutting parameter $\Delta\varphi$, etc. Analysis of these parameters on the very first stage of cutting process design allows one to establish optimal values of cutting parameter, number of passes and cutting depth for each pass.

The mentioned capabilities are illustrated with figures. Thus figure 3 depicts gear wheel workpiece model and models of layers cut with one tool pass. From this figure we can get qualitative characteristics of depth and shape of a cut that is made by peripheral and side cutting edges of tool teeth profile. It gives us an idea on change of shape and depth of cutaway layers in the process of cutting. In particular, configurations of profiles of cutaway layers are complex and vary in the process of cutting. Parts of tool teeth are unevenly loaded since they remove layers of different content volumes. At that, several tool teeth can simultaneously take part in formation process. Thus, figure 4 depicts formation of two gashes between item teeth by two tool teeth over one pass. Removed content volume consists of three fragments, two of which are cut with one tool tooth.

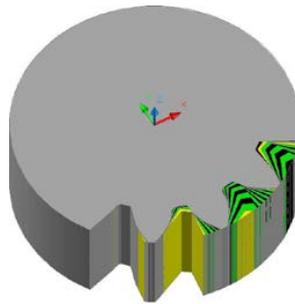


Figure 3. Wheel model and cutaway layers models

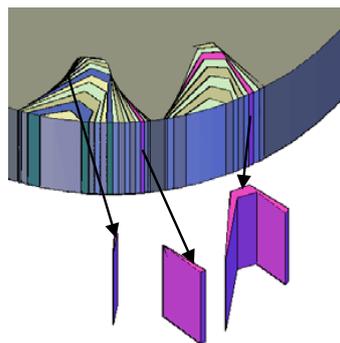


Figure 4. A fragment of wheel model and models of layers removed over one tool pass

In the majority of cases gear item manufacturing is performed not over a single pass, as shown on figure 4, but over several passes. Thus figure 5 depicts a gear wheel fragment after the first out of two passes. As follows from that figure, two tool teeth take part in the formation, but cutaway content volume consist of two fragments, as in previously considered case.

Therefore analysis of configurations of cutaway layers and their content volumes allows a design engineer to intentionally set the optimal values of tool advance parameter and number of passes in advance.

It is appropriate to make the final decision after cutting process study, methodology of which can be seen below.

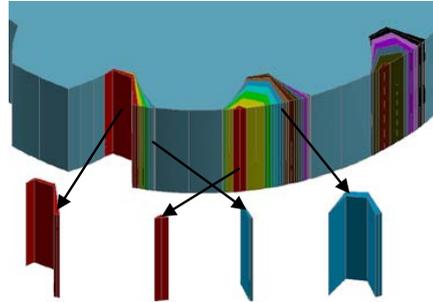


Figure 5. A fragment of wheel model and models of layers removed over two tool passes

4. Results of Experiments

In order to perform cutting analysis experiment in a given case, one tooth of rack tool is considered. It is situated in intermediate position of formation process, so that chips are removed by peripheral and side cutting edges of tool tooth. For cutting formation simulation it is proposed to use CAE system ANSYS. It is known that currently finite element method represents an essential instrument of cutting process simulation. It has several advantages [17, 18] including prediction of cutting forces and chip shape, study of contact between bodies, etc. In the majority of studies utilizing this method, a tool model is idealized as a 2D solid body [13, 15], i.e. a flat deformation problem is solved. In present paper three cutting edges simultaneously take place in cutting process. In this case the problem can be considered dimensionally with an opportunity of gaining new practical results.

On the first stage of modeling of the mentioned geometry in accordance with cutting modes, it is necessary to discretize the model (figure 6). Let us preset the main array of large elements in order to optimize and speed up calculations by setting element size of 1 mm. Additionally, let us preset the method of discretization of workpiece and tool as “MultiZone” with parameter Mapped Mesh Type – “Hexa”. This method of discretization divides unit into elements more rationally and, consequently, calculations are made faster and with higher precision. Since in the area of contact between tool and workpiece maximal precision of calculation and chip separation simulation is required, let us preset mesh element size in point of contact to be 0,15 mm. This results in an optimized mesh that allows us to conduct fast and precise calculations of cutting process.

Discrete workpiece and tool models and preset cutting modes are used for formation simulation, as shown on figure 7, where a tool is depicted in three positions in the process of sequential workpiece cutting. As follows from figure 7a, on the first stage chip gets divided into three parts after cutting material off the workpiece by three cutting edges of the tool. Notice chip crumbling in the beginning of cutting. On the second stage equivalent stresses distribution along the workpiece and chips can be thoroughly considered. Stress is distributed along the whole workpiece and decreases with distance from the cutting area; however, the highest stress takes place in chip separation area. On the third stage chip separation takes place and the largest zone of high stress can be observed. Therefore, upon such separation, a crack can spread unpredictably and result in certain deviations from the specified cutaway layer geometry.

Overall, in the cutting process we can observe the initial stage of simulation, during which chip formation is non-uniform and a pronounce chip division into three parts cut by three cutting edges of rack tooth can be observed. Equivalent stress is distributed from cutting area in the direction of tool movement; the highest stress is concentrated in the cutting area throughout the whole simulation. For more vivid representation of the result of chip modeling, it is dissected by longitudinal plane that runs along rack tooth symmetry plane and is shown as a separate geometric object (figure 8). The presented figures allow us to get a clear idea on chip shape and its transformations on different stages of tool movement. Thus profile analysis allows us to

make a conclusion on fairly smooth and even chip formation in its middle part and crumbling and tears in upper and lower parts.

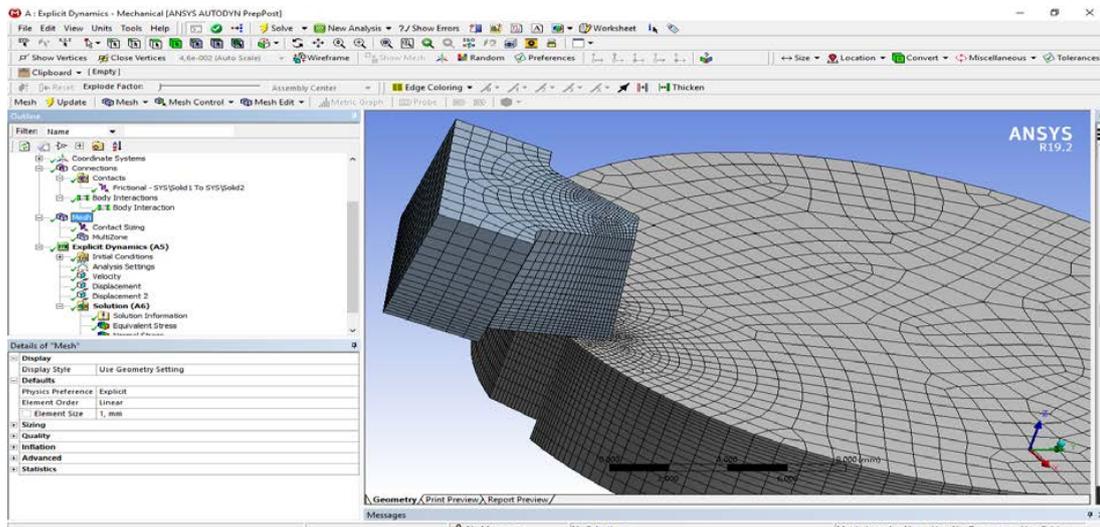
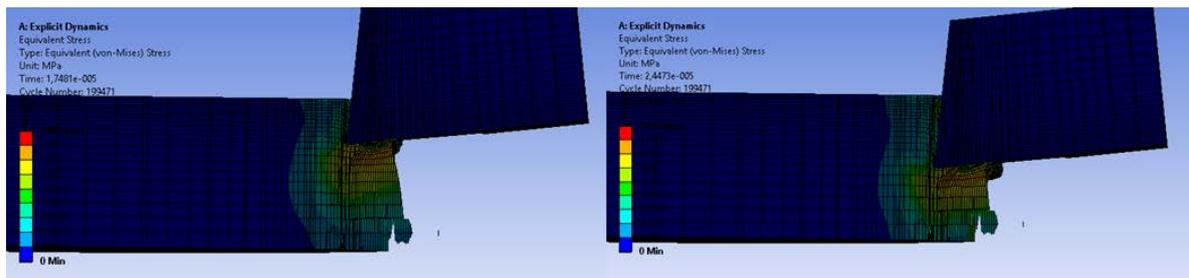
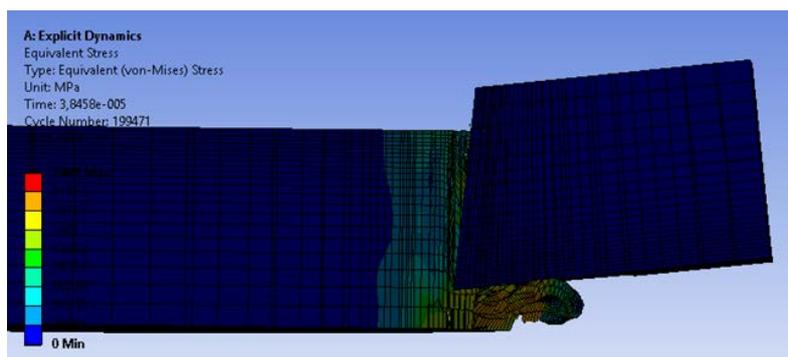


Figure 6. Workpiece and rack tool models discretized into elements



a) tool shift of 1,4 mm

b) tool shift of 2,1 mm



c) tool shift of 3,75 mm

Figure 7. Rendering of three stages of formation of 3D model of chips

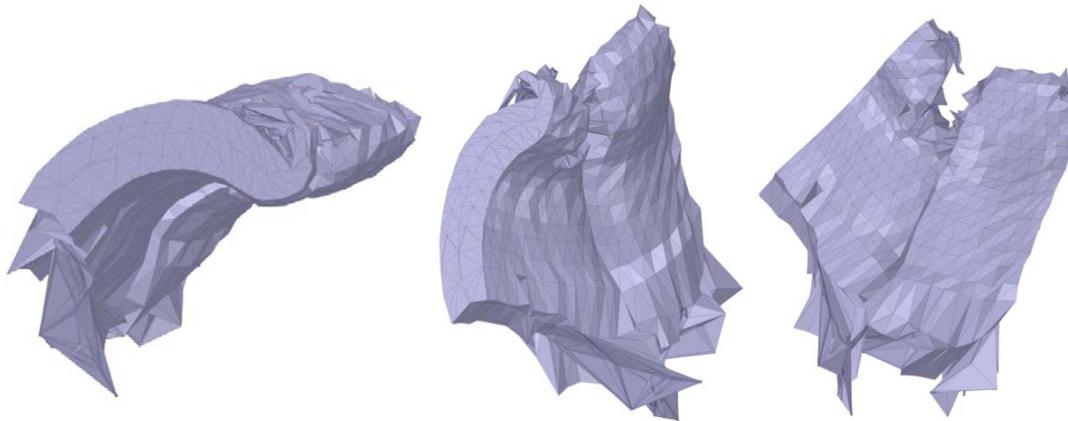


Figure 8. 3D models of chips in various projection directions

5. Consideration of Results

Gear item manufacturing involves solving a range of problems. One of them is associated with removed content volume modeling, which can be applied, for example, in order to set the optimal values of tool advance parameter and number of passes for processing by rolling. The authors propose to perform removed content modeling through CAD software and algorithms and software developed by researchers. The other problem is devoted to cutting simulation itself. In this case cutting process study with CAE systems allows us to set the optimal cutting parameters in order to develop cutting tool. In the literary sources known to the authors of the present paper the indicated problems get solved with no connection to each other and in different depth. In the present paper the interconnection of such problems in modeling of different stages of preparation and manufacturing of gear item with rack tool is considered. The authors plan on arranging further studies both on computer aided solid modeling of cutaway content volumes and on cutting process in their logical interconnection in machining of various gear items.

6. Conclusion

Methodology of computer aided geometric modeling of two objects of formation – wraparound and removed contents – in the process of formation of workpieces with periodic teeth machined with centroid enveloping method is developed without involving complex mathematical apparatus. Analysis of configurations of solid models of cutaway layers and respective removed content volumes allows a design engineer to intentionally set the optimal values of tool advance parameter and number of passes. Models of the acquired layers are subsequently applied in CAE analysis of the process of cutting of gear wheel with rack tool. Such double-stage study allows us to optimize not only formation parameters, but also cutting parameters, that facilitate development of cutting tool with effective parameters. In general, while computer aided modeling of removed content volumes for a range of problems is already highly developed, chip separation simulation technology is still at an early stage of practical use. In the future, the authors plan to continue studies on more effective use of results of simulation of both removed content volumes and chip separation.

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