Development of a sophisticated tool for processing parts with an involute profile

Alexander Ryazantsev\textsuperscript{1,2,*}, Anna Shirokozhuhova\textsuperscript{1,2} and Irina Evchenko\textsuperscript{2}

\textsuperscript{1}Voronezh State Technical University, Moskovsky Prospekt, 14, Voronezh, 394026, Russian Federation
\textsuperscript{2}JSC KBHA, Voroshilova Str., 20, Voronezh, 394006, Russian Federation

*ryazantsev86@rambler.ru

Abstract. The article presents main parts of a modern propulsion system with liquid rocket engines. The critical parameters that affect the turbo-pump unit performance, as well as main methods of manufacturing gears in mechanical engineering, are shown. Standard and complex-profile tools used for machining parts with an involute profile are considered. Features of designing and manufacturing of complex cutting tools are revealed. Problems in the design of gear cutter used for gear machining are shown. The dependence of the gear cutter external diameter on the profile of the manufactured part is revealed. The mechanism and mathematical calculation of the tool profile adjustment are presented, taking into account the actual geometric dimensions of the manufactured part. The tool parameters that provide the specified critical parameters of parts with an involute profile are indicated. The proposed method of adjusting the geometric dimensions of a complex-shaped tool allows you to adjust and modify the final made gear cutters, which eliminates material and labor resources for the new expensive tool production.

1. Introduction
Propulsion systems with liquid rocket engines are the most important element of space systems. Modern propulsion system is a complex system that uses chemical fuel, which are both a source of energy and a working body for the thrust generating. The main components and units of the liquid rocket engine include a chamber, a system for supplying components (fuel and oxidizer) from fuel tanks to the combustion chamber, a gas generator, fuel lines and automation units. The components in engines are supplied by turbo-pump units usually consisting of pumps (fuel and oxidizer) and a turbine that drives them. [1]
The dynamic load tests of the fuel pump are performed to confirm the turbo-pump unit performance. Tests are the main stage that confirms the correct product assembly. During testing gears are used to adjust the transmission speed of rotational motion on the shaft. Gears (fig. 1) are a particularly important element of the turbo-pump unit and are directly involved in the fuel pump tests. Gear connections must be smoothly rotated around the pump axis without jamming, so their manufacture is particularly responsible. Gear manufacturing is a labor-intensive process using high-precision complex-profile tools and specialized gear-cutting equipment. [2]

2. Methods of processing gears

Cutting teeth on gears can be carried out by milling, chiseling, grinding and other methods. [3] The tooth geometric dimensions can be obtained by copying the profile of the cutting tool (copying method) or by generation process (gear rolling method). The copying method is used for milling, stretching, planing, grinding teeth. The tool cutting edges profile has the form of depressions of the gear being cut. Disk or finger modular milling cutters are used as a tool, while processing is performed on universal milling, special and vertical milling machines. The depressions are formed sequentially, each separately in both cases. Division by one step with the help of a dividing head is made after cutting a single cavity. A set of 8 or 15 cutters is used for each module. Each mill is used for a certain range of tooth numbers. Disadvantages of the method: low productivity and accuracy of processing, the need to have tool kits depending on the module and the number of teeth of the gears being cut. The copying method is used in a single production.

The process of forming teeth using the gear rolling method is that the tool and the workpiece copy the gear engagement with their movements during the treatment. The tool can be shaped like a gear wheel, rack, etc. Chisels, worm cutters and combs are mainly used for cutting cylindrical gears by the gear rolling method. It is used in serial and mass production. The gear rolling method has the following advantages: high productivity and precision of processing, the automation possibility, the single tool usage for cutting the wheels of a single module with different teeth numbers with the same accuracy. [4]

The gear cutter is the most widely used tool in machine-building enterprises for processing gears. The use of this tool allows to obtain high-precision dimensions on the parts, since the processing is carried out by gear rolling.
Figure 2 shows the scheme of cutting a cylindrical wheel with a disk cutter. The billet is fixed on a mandrel rigidly connected to the table of the gear-cutting machine, from which it receives the movement of the roll A and the vertical feed – $S_b$. Gear cutter - T which is a hardened and ground gear wheel with an involute tooth profile, has the main thing-reciprocating motion (cutting speed - $V$) and circular feed - $S_k$. In contrast to the gear wheel, the gear cutter has teeth of great height. For the cutting process realization the front and back corners are executed on the cutting tool teeth. The cylindrical gear engagement is reproduced in the process of treatment the gear [5]. The gear cutter and the workpiece are kinematically connected, so that their linear velocities along the pitch circles are the same. Embedding the gear cutter into the workpiece at the tooth height is performed with a radial feed- $S_p$. Gears with a module $m \leq 2$ mm are cut in one pass, in order for the wheel to be completely cut, it must make one full turn. Gears with a module $m > 2$ mm are cut in several passes.

When designing a complex profile tool, labor-intensive calculations are performed using a large array of data, taking into account the geometry of the cutting elements and the law of involute engagement. This is one of the main reasons for the complexity of calculating a gear cutting tool.

Complex cutting tools manufacturing and implementation involves a long production cycle and requires large material and labor costs for production. The goal of this work is to improve and achieve optimal versatility in the use of standard special gear cutters, taking into account all the design features. [6]

3. Development and implementation of complex cutting tools for processing parts with an involute profile
For cutting of gear-wheels gear cutters, which is made in accordance with a state industry standard 6762-79, are used in aerospace industry. The use of standard complex-cutting tool not always allows providing treatment of details in accordance with the requirements of designer documentation on good. At this point, there is a need to design a special tool (gear cutter). The main parameters of the gear cutter are the module, the number of teeth, the angle of meshing, the seat diameter and the initial section offset. The tooth thickness and the outer circumference diameter of the complex-profile tool
ensure that gears are cut with the specified tooth thickness, while the diameter of the depressions is automatically maintained.

![Figure 3. The scheme of a gear cutter and a gear wheel engagement.](image)

In order to confirm the tool efficiency in the design process and correct the geometric dimensions of the manufactured tool, the machine-building enterprise has developed a method that allows reducing the cost of production technological preparation by mathematical modeling of the complex-profile tool treatment process and manufactured part (fig. 3). [7]

To calculate the external meshing of the gear cutter and pinion it is necessary to determine the value of the part internal diameter - $d_f$. Therefore, we need to calculate the value of the part center distance and the tool – $A_{i1}$, for a given size of the gear cutter diameter - $D_{gi}$. The inner diameter of the part is calculated using the formula:

$$e_i = D_{gi} - d_{fi}, \quad (1)$$

Center-to-center distance is calculated using the formula:

$$A_{i1} = \frac{m(z_1 + z_2) \cos \alpha_d}{2 \cos \alpha_{i1}}, \quad (2)$$

where $m$ - the module; $z_1$ - set number of the part teeth; $z_2$ - set number of gear cutter teeth; $\alpha_d$ - the specified angle of pressure of the part's tooth on the dividing circle; $\alpha_{i1}$ - the machine angle of meshing of a part with a gear cutter.
Figure 4. The pressure angle ($\alpha_d$) on the pitch circle.

When calculating the center distance ($A_{i1}$) you must take into account the influence of the gear cutter tooth thickness and the part. Since, as the tooth thickness increases, the machine meshing angle changes ($\alpha_{i1}$) shown on the figure 4.

The machine meshing angle of a part with a gear cutter ($\alpha_{i1}$) is found by the formula:

$$inv\alpha_{i1} = inv\alpha_d + \frac{S_{d1} + S_{d2} - \pi m}{m(z_1 + z_2)},$$

where $\alpha_d$ - the pressure angle of the part's tooth on the pitch circle; $S_{d1}$ - the specified part tooth thickness along the pitch circle arc; $S_{d2}$ - the specified gear cutter tooth thickness along the pitch circle arc; $m$ - the module; $z_1$ - the set number of the part teeth; $z_2$ - the set number of gear cutter teeth.

During the process of manufacturing gears, there are deviations as a mismatch in the tooth thickness. The discrepancy can be corrected by modifying the existing tool by adjusting the outer diameter of the gear cutter. This eliminates the need to manufacture a new expensive complex-profile tool [8].

In order to obtain parts with tothing, in accordance with the requirements of design documentation, the machine-building enterprise uses a technique that allows determining the amount of adjustment of the tool outer diameter, taking into account the tool angle of meshing (fig. 5).
The calculation of the adjustment value for the tool (fig. 6) outer diameter \( \Delta F \) is made using the formula:

\[
\Delta F = K \times \Delta W,
\]

where \( \Delta W \) - the specified length difference of the general normal, \( K \) – the adjustment coefficient.

The adjustment coefficient \( K \) is based on the formula:

\[
K = \frac{1}{\tan \alpha \times \cos \alpha_d},
\]

where \( \alpha_d \) - is the specified angle of pressure of the part's tooth on the dividing circle.

The gear cutter angle of meshing \( \alpha_i \) is calculated using the formula:

\[
\tan \alpha_i = \frac{\tan \alpha_d}{1 - \tan \gamma \times \tan \alpha_v}.
\]

where \( \gamma \) – the specified front corner shaping cutter, \( \alpha_v \) – the posed rear angle shaping cutter, \( \alpha_d \) - the given the pressure angle of the tooth parts on a pitch circle.

In order to adjust the geometric dimensions of cutting elements during the special tool design the technique has been developed at the machine-building enterprise, which allows determining the internal diameter of the processed gear wheel, taking into account the tool tooth actual thickness.
4. Conclusion
As a result of the analysis, the design features of complex-face tools designed for manufacturing parts with an involute profile are revealed. When changing the size of the tool outer diameter, using the calculations presented, it is possible to make adjustments and modifications to the final manufactured gear cutters, to ensure the critical parameters of the parts of liquid rocket engines with an involute profile, specified in the design documentation. The presented method of adjusting the complex-cutting tool geometric dimensions allows reducing the costs of technological preparation of production, in particular, the material and laboring resources of the enterprise for the new expensive tool production [9]. Therefore, the increase of production cycles of final manufactured parts and assembly units is excluded.

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