Engineering process automation to determine the required material hardness of a cylindrical gear in Autodesk Inventor

Ekaterina A Petrakova and Yuliya I Brovkina
Moscow Polytechnic University, 38, Bolshaya Semenovskaya street, Moscow, 107023, Russia

E-mail: eka_pet@mail.ru

Abstract. The article discusses the method of designing a cylindrical gear pair in Autodesk Inventor, which allows for its automated design and verification calculation within CAD software with the reconstruction of the geometry of the 3D model of the gear pair. The software product created by the authors makes it possible to obtain data on the required hardness of steel for the gear pair immediately after receiving the technical specifications for a wide range of operating torques, gear ratios and other parameters set in the technical specifications to select the best option from all possible. The paper presents the results of studies using the created software product: the values of the hardness of the material, the mass-dimensional parameters for the range of transmitted torques 250-710 Nm, gear ratios 2-5, and overall dimensions determined by the center distance of the gear transmission in the range 125-180 are obtained mm.

1. Introduction
In the early design stage, an engineer faces the question of the optimal choice of the hardness of material for the gear pair. It is known that an increase in the hardness of steel leads to a decrease in the overall dimensions of the gear train and, therefore, of the entire mechanism [1]. However, this increases the cost of the product [2]. The question of the relationship of overall dimensions with the hardness of material for gear pairs is relevant for enterprises engaged in the production of standard gears made of steels of various hardness, the choice of which is due to various customer requirements for the overall dimensions either or both cost of the product.

The parameterization of the 3D model of the gear train with the integration of the parameters obtained as a result of automated design and verification calculations of the parts according to the technical specifications using the internal functionality of the CAD software will allow one to quickly obtain data on the relationship of the hardness of the gear pair materials with its dimensions over a wide range initial parameters immediately after receiving technical specifications. In addition, computer-aided engineering through parametric design eliminates calculation errors and manual data transfer to the 3D model [3].

2. Problem statement, initial data and tools
The objective of the study is to automate the engineering processes on the optimal choice of steel hardness for the manufacture of a cylindrical gear transmission with the following initial data (with the possibility of their variation):
- main parameters: gear ratio U, transmitted torque at the output link (wheel) T2, center distance aw, module m.
- optional parameters:
  - ψa - the width coefficient (set depending on the location of the gear pair relative to the supports [4]);
  - Ka - center distance ratio (for spur gear pairs Ka=49.5, for helical-gear train– Ka=43);
  - Kβ - load concentration coefficient (for running-in wheels Kβ=1 [4]);
  - S_H - safety factor [5].

As the output, in addition to determining the value of the required hardness of the HB material, the physical and geometric parameters of the gear pair parts should be derived: overall dimensions – B and L (figure 1a), reference diameter d2 and gear mass mass.

To handle this task, the authors created a software product in Autodesk Inventor using the following tools and steps:

- a 3D model of a gear pair was created using standard Inventor tools (sketches, forming operations) [6];
- design and verification calculation of the gear pair [5] was compiled within the CAD software, written in iLogic as rules in a programming language Visual Basic [7];
- 3D parameterization of the gear pair was carried out by assigning geometric parameters depending on the calculation results to the parameter names specified in iLogic [3], [8];
- generators from the parametric parts library Inventor are used to parameterize individual elements of the gear wheel and gear: for gear rims - IGS; for key ways – iKPKeywayHub;
- creation of user interface for inputting the source data and outputting results using forms iLogic (figure 1b).

![Figure 1](image_url)

**Figure 1.** Gear pair design: a) 3D model; b) calculation fragment in iLogic.

The design and verification calculation of the gear pair is written in iLogic according to the classical methods [5]. The determination of permissible contact stresses of the gear pair and the required hardness of the material of the HB gear pair was carried out according to the formulas:

$$[\sigma]_H = \sqrt{\frac{K_H \cdot T_2 \cdot 10^3 \cdot (K_a \cdot (U + 1))^3}{\psi_a \cdot a_w^3 \cdot U^2}}$$

(1)

$$HB = 0.5 \cdot ([\sigma]_H \cdot S_H - 70)$$

(2)
Note that the HB hardness determined by Formula 2 corresponds to the hardness of the gear. The hardness of the material of the gear should be assigned higher by 20-30 HB for better grinding of teeth [5].

The internal diameter in the naye of the gear \(do\) (figure 1a) was determined depending on the transmitted torque \(T_2\) using the formula [4]:

\[
do = 8 \cdot \sqrt[3]{T_2}
\]

(3)

The keyway is automatically rebuilt in the 3D model by the iKPKeywayHub parametric element generator depending on the internal diameter \(do\) according to GOST 23360-78.

3. Research algorithm and results

For convenience of inputting the source data and outputting calculation results, the “Source data” and “Data output” forms were created (figure 2). The choice of torque values, gear ratios, axle distance and module is organized from the drop-down list of standard values according to GOST 25301-95 and GOST 9563-60. Creating an interface of interactive windows for source data entry and result output allows engineers who do not have the skills to create parametric models using iLogic in Autodesk Inventor to work with the created software product. iLogic rules run automatically in response to a change in the source data in the "Source data" window. After the rule is completed, iLogic automatically saves the changed values of the variables into a 3D model, which is also automatically rebuilt, while the results are displayed in the “Data output” window.

Using the software product created by the authors, studies were carried out to determine the hardness of the gear pair material for the following initial data: gear pair — cylindrical spur gear, gear location relative to the supports — symmetrical, safety factor \(S_H=1.1\) [5], transmitted torque \(T_2=250; 500\); 710 Nm, gear ration \(U=2; 2.5; 3.15; 4; 5\); module \(m=2\); center distance \(a_w=125; 140; 160; 180\).

As a result, the 3D gear model was automatically redesigned 60 times. For each 3D model, data were obtained on the required hardness HB (figure 3), basic geometric parameters (table 1), and the mass of the gear. Note that the reference diameter \(d_2\), and the overall dimensions of the gear pair - \(B\) and \(L\), presented in table 1 correspond for all three studied torques \(T_2\), while the hardness of the gear pair material is different in each case (figure 3).

In the future, when choosing a steel grade, it should be taken into account that obtaining the required hardness can be achieved by using both various steel grades and types of heat processing of a steel grade. For example, steel 40X, hardened at \(t=850^\circ C\) and drawing temperature \(t=700^\circ C\) will have hardness HB=226, and at drawing temperature \(t=300^\circ C\) the hardness will account for HB=498 [9].
Figure 3. The dependence of the hardness of the material for the gear pair on the gear ratio, center
distance and torque: a) $T_2=250$ Nm; b) $T_2=500$ Nm; c) $T_2=710$ Nm.

Table 1. The main parameters of the gear pair.

| aw  | U  | $d_2$ | B | L  |
|-----|----|------|---|----|
| 125 | 2  | 166  |   |    |
|     | 2.5| 178  |   |    |
| 3.15|    | 190  | 55| 254|
|     | 4  | 200  |   |    |
|     | 5  | 208  |   |    |
| 140 | 2  | 186  |   |    |
|     | 2.5| 200  |   |    |
| 3.15|    | 212  | 61| 284|
|     | 4  | 224  |   |    |
|     | 5  | 234  |   |    |
| 160 | 2  | 214  |   |    |
|     | 2.5| 228  |   |    |
| 3.15|    | 242  | 69| 324|
|     | 4  | 256  |   |    |
|     | 5  | 266  |   |    |
| 180 | 2  | 240  |   |    |
|     | 2.5| 258  |   |    |
| 3.15|    | 274  | 77| 364|
|     | 4  | 288  |   |    |
|     | 5  | 300  |   |    |
Figure 4. Dependence of gear mass on gear ratio and center distance for torque $T_2=710$ Nm.

The speed of rebuilding one parametric 3D model of the gear pair after the input of the initial data (taking into account the fact that the program performs all the necessary design and verification calculations) is no more than 2 seconds. Note that when parameterizing 3D assemblies with integration of calculation data from third-party programs (Mathcad, Excel) [10-12], it takes longer to obtain output data, and input-output of data in different programs causes some inconvenience of using the product.

4. Conclusion
The speed and convenience of working with the software package allows one to quickly and accurately receive data on the required hardness of the materials for the cylindrical gear pair and mass-dimensional parameters for the full range of transmitted torques, gear ratios, center distances regulated by GOST 25301-95. Such an approach to design makes it possible to make the optimal choice of gear pair material, taking into account customer requirements, already at the early stages of product design. Note that for the obtained 3D models of the gear pair, it is also possible to visualize and derive the parameters of all its elements, if necessary, for a more detailed analysis of the product with different initial data. In addition, the capabilities of modern CAD programs allow simultaneous automatic rebuilding of a parametric 3D model to receive 2D drawings of both assemblies and individual parts. For the enterprise, such engineering process automation means a reduction in the design and production time.

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