Analysis of the influence of the gear pair materials on the mass, dimensions and cost of a single stage cylindrical reducer for mass production

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Abstract. A study of single-stage reducers, made in a horizontal pattern, having the same technical characteristics and a similar configuration, but differing in the material hardness of the gear pair parts has been carried out. The design of reducers, the determination of the mass-dimensional parameters of the parts and the entire product assembly was carried out in one of the CAD programs of three-dimensional modelling. For identically designed reducers, a comparison of the mass and dimensions of all the parts was made. The data on the total masses and overall dimensions of the assembly items, as well as the results of the heat treatment time of gear wheels and toothed wheels are given. The parts dimensions of which undergo the greatest changes in size due to the replacement of gear and toothed wheel materials are identified. The paper gives the calculation of the machining time and the calculation of the cost for the production of a batch of 10 thousand pieces per unit of production, taking into account the cost of raw materials and materials, heat treatment, energy and technical needs, wages and social deductions, repair and maintenance of equipment, general production and selling expenses for these parts. As a result, data were obtained about the difference in the cost of production of a batch of reducers under study.

1. Introduction
Reducers are used in various areas of modern production. It is known that the overall dimensions of the reducers depend on the selected materials of the gear pair. The use of high-hard steels for the manufacture of gear wheels and toothed wheels leads to a decrease in the centre distance and diameters of the gears, and therefore, to the reduction of the size of body parts and the entire assembly product [1]. However, research on the degree of the gear pair material hardness influence on the overall mass parameters and the cost of the entire product is currently very small.

The authors decided to investigate the influence of the choice of a gear pair material on the dimensions, mass and cost of the reducer, having designed two horizontal single-stage cylindrical reducers with the same technical characteristics, choosing different materials for the manufacture of gear pairs.

2. Initial data and research instruments
Initial data: horizontal, single-stage, with a cylindrical spur gear reducer. The transmitted power is $P = 4$ kW, the rotational speed of the input shaft is $n_2 = 490$ min$^{-1}$, the torque on the output shaft is $T_2 = 250$ Nm, the gear ratio is $u = 4$. The service life of the gearbox is $L_h = 10500$ hours.

For the gear pair of the designed Reducer 1, the following materials and heat treatment were chosen [2]:

- a) gear wheel - carbon steel 45 (GOST 1050-88) with heat treatment: normalization at a temperature of 800° C, air, HB1 = 189-229;
- b) toothed wheel - steel 45 (GOST 8479-70) with heat treatment: normalization of 865-895° C, air, HB2 = 174-217.

For the gear pair of the designed Reducer 2, the following materials and heat treatment have been chosen [2]:

- a) gear - steel 40XH2MA (GOST 4543-71) with heat treatment: quenching 850-870° C oil, tempering 600-630° C, water, HB1 = 310-354.
- b) a gear wheel - steel 40XH2MA (GOST 8479-70) with heat treatment: quenching 860-870° C oil, tempering 650° C, water, HB2 = 277-321.

Research tools: PTC Mathcad program for creating integrated engineering calculations [3] and Autodesk Inventor program for three-dimensional modelling [4].

3. Researches and results

Design and verification calculations of gear, shafts, bearings, key and bolted connections, structural elements of the body were carried out according to classical methods [5-6].

The overall dimensions of the reducer are determined, first of all, by the centre distance, the value of which largely depends on the allowable contact voltage of the transmission [5]. The calculated permissible contact stress for the selected materials of Reducer 1 is 419 MPa, and for Reducer 2 it is 607 MPa. The overall dimensions of the reducer are influenced, first of all, by the centre distance, width and diameter of the toothed wheel (table 1).

| Parameter                               | Reducer 1 parameter value (mm) | Reducer 2 parameter value (mm) |
|-----------------------------------------|-------------------------------|-------------------------------|
| Centre distance                         | 160                           | 125                           |
| Toothed wheel width                     | 64                            | 50                            |
| The diameter of the toothed gear circle tops | 260                           | 204                           |

It should be noted that the results of the verification calculation showed that for both reducers the value of the contact and flexural strength of the teeth is almost the same. So, for both gears, the calculated contact voltages are lower than those allowed by 7-8%.

For objectivity of the study, all the details of both reducers must be absolutely identical in configuration. Calculation and design of the elements of the housing and reducer lid, bearing caps, oil dipstick, vent and other parts were made according to the calculations and recommendations [7].

When creating 3D models of reducer parts, non-standard parts were selected, the dimensions of which do not depend on the parameters of the gear pair and the body - the dipstick, drain plug, manhole lid, vent. These parts were designed as non-parametric 3D models of the same size for both reducers. 3D models of the housing and reducer lid, bearing caps were parameterized using the internal capabilities of the Autodesk Inventor software, as well as with the integration of external data into the CAD program [8-9]. The parameterization of the gear pair was carried out according to [10]. As a result, 3D-models of reducers with completely identical configuration of all parts were obtained (figure 1: a - Reducer 1; b - Reducer 2).
Analysis of the designs of 3D-models showed that Reducer 2 is more compact than Reducer 1 in each of the three parameters - length, width, height (figure 2). The mass of parts and the entire reducer was determined by the Autodesk Inventor program, taking into account the selected materials of all parts that are included in its composition. The total mass of Reducer 1 is 47.6 kg, Reducer 2 - 36.9 kg.

To calculate the cost of materials of the reducer designed parts, data on the masses of blanks for the manufacture of these parts are necessary. In the mass production of reducers, blanks for shafts and gears are produced by hot stamping, body parts, and bearing caps - by casting into a metal mold. To determine the mass of the workpieces and analyse the percentage of metal to shavings during machining, 3D-models of the reducer workpiece parts with machining allowances were recreated in Autodesk Inventor [11].

The results of comparing the mass of parts before and after machining allow us to state that, on average, about 20% of the material goes into chips when machining parts, which fully agrees with the data of [12]. When machining castings, the percentage of chip yield is 7-10% [12].

![Figure 2. Comparative assessment of the dimensions of Reducer 1 and Reducer 2.](image)
Table 2 shows the masses of the workpieces and the masses of the parts of the reducers, determined using the Autodesk Inventor program.

| Name                          | Workpiece mass (kg) | Part mass (kg) |
|-------------------------------|---------------------|----------------|
|                               | Reducer 1 | Reducer 2 | Reducer 1 | Reducer 2 |
| Shaft-gear                    | 3.33      | 2.41      | 2.70      | 1.93      |
| Toothed gear                  | 13.19     | 7.51      | 10.89     | 6.24      |
| Reducer housing and lid       | 26.63     | 19.82     | 24.54     | 18.02     |

In assessing the cost of heat treatment of the shaft gears and gears of both reducers, the quenching and normalization times were determined [13]. The heat treatment time of the gear shaft for Reducer 1 is 111 minutes, for Reducer 2 it is 190 minutes. Heat treatment time of gears: for Reducer 1 - 342 minutes, for Reducer 2 - 550 minutes. Taking into account the fact that 20 parts with dimensions of 200-250 mm can be simultaneously in furnaces for normalization and quenching, we obtained that the total heat treatment time for a batch of 10 thousand gear wheels and 10 thousand gear shafts is for Reducer 1 - 3775 hours and for the Reducer 2 - 6167 hours. Heat treatment cost for Reducer 1 is 4.79 million rubles, for Reducer 2 it is 15.02 million rubles.

For a comparative assessment of the cost of reducers, parts were identified that have different sizes and, therefore, cause a difference in the cost of reducers. These parts are the gear shaft, toothed wheel, gearbox housing and lid. The remaining parts of the reducers, as noted above, are the same in all parameters and physical properties, therefore, to estimate the difference in the cost of manufacturing reducers, they are not taken into account. Thus, for parts - gear shaft, gear wheel, reducer housing and lid - the cost of materials for blanks was determined taking into account prices obtained from official sources of companies engaged in the wholesale sale of ferrous and non-ferrous metals.

We will note that for the manufacture of reducer body parts cast iron of brand SCh20 was chosen. For Reducer 1 and Reducer 2, the cost per unit of production was: for gears - 793 rubles and 622 rubles, for gear shaft - 143.2 rubles and 163.56 rubles, for housing and reducer lid - 802 rubles and 596.4 rubles, respectively.

Further, to estimate the cost of manufacturing Reducer 1 and Reducer 2, the cutting conditions were calculated for the manufacturing operation of manufacturing the gear shaft, gear wheel, reducer housing and lid [11]. The processing time of a batch of parts of 10 thousand pieces is shown in figure 3.

Figure 3. Calculation results of manufacturing time.

To determine the cost of production of these parts, the cost of production was calculated by calculation cost items (table 3). The calculation of the cost of raw materials and basic materials produced taking into account the cost of realized waste.
Table 3. The cost estimates.

| Costing item                                               | The cost of manufacturing parts: gear shaft, gear wheel, reducer housing and lid. |
|-----------------------------------------------------------|----------------------------------------------------------------------------------|
|                                                           | Per unit, rub.                     | Per batch of 10 thos. items, rub.     |
| Raw and basic materials                                   | Reducer 1 | Reducer 2 | Reducer 1 | Reducer 2 | Reducer 1 | Reducer 2 |
| Heat treatment                                            | 1795.18  | 1426.320 | 17951750 | 14263200 |
| Energy for technological needs                            | 479.010  | 1502.020 | 4790100  | 15020200 |
| Salary (basic and supplementary) and social contributions  | 30.600   | 26.530   | 306000   | 265300   |
| Repair and maintenance of equipment                       | 117.820  | 102.336  | 1178200  | 1023360  |
| Overhead costs                                            | 26.100   | 26.100   | 261000   | 261000   |
| Manufacturing costs                                       | 118.875  | 103.215  | 1188750  | 1032150  |
| Total: production cost                                    | 39.625   | 34.405   | 396250   | 344050   |
| Selling expenses                                          | 85.124   | 68.750   | 851240   | 687500   |
| Total: total cost                                         | 2692.329 | 3289.676 | 2692390  | 32896760 |

4. Conclusions

Taking into account the fact that the cost of assembling Reducer 1 and Reducer 2 is the same, and also taking into account the same cost of parts of the same name that do not differ in size and materials for their manufacture, it can be stated that for the reducers under study:

- For the party of Reducer 1 and 2 for 10 thousand pieces for each one: the total time of heat treatment of the parts of the Reducer 2 is longer by 2380 hours ($\approx$99 days); the total time of machining the parts of the Reducer 2 is less by 25,800 minutes ($\approx$18 days);
- The cost of production of the batch of 10 thousand units of Reducer 2 is more by 5.973 million rubles, which is 22.19%.

According to the sum of the overall dimensions, Reducer 2 is more compact than Reducer 1 by 14.3%; its weight is less by 10.7 kg, which is 22.5%.

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