Design, research, and production of gear wheels for mining machines

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Abstract. The current state of the Ukrainian fuel and energy complex requires a continuous increase in coal production. As part of concept implementation for the coal industry development now created and introduced into serial production a new generation of mining machines. The most loaded element of mining machine is its gear wheels of cutting part. Calculations for the strength and durability of gearings have been carried out. The modelling of the teeth stress-strain state by the finite element method has also been carried out.

Works were carried out on the processing of parts of gearboxes of mining machines.

Investigations of the processes of blade processing of gears and shafts of gearboxes of coal combines were carried out. The state of the surface layer, the quality and accuracy of processing these parts with a blade tool made of superhard materials are determined. Researches of grinding of an involute profile of gear wheels of gearboxes of mining machines are carried out. A study was made of the surface quality and accuracy of gears after grinding with special abrasive wheels.

The influence of processing processes with a tool made of superhard materials on the strength and durability of gear drives of mining machines is determined.

1 The actuality of the task

The current state of the Ukrainian fuel and energy complex requires a continuous increase in coal production. Currently, 80% of coal deposits are in thin seams. To solve this problem Ukrainian plants created and introduced into serial production a new generation of coal shearsers.

An example of a new design is UKD200-500 coal shearer. It is designed for mechanized coal extraction as part of mining complexes, in longwalls of shallow and inclined seams 0.85–1.5 m thickness, moving along strike with inclination angles up to 35°, as well as rise and fall with angles up to 10°, with coal cutting resistance up to 480 kN/m. Its technical characteristics are at the level of modern foreign counterparts.

UKD200-500 coal shearer is a cutting action machine equipped with auger executive bodies for destruction and loading of coal onto a conveyor – Fig. 1. Moving the shearer with a scraper conveyor is carried out by means of an external feed system.

The most important and loaded element of the shearer is its cutting part – Fig. 2. It is a three-stage spur gearbox with an electric motor:

- 1st stage is three in-line cylindrical gears;
- 2nd stage is planetary single-stage with fixed ring gear;
- 3rd stage is four in-line cylindrical gears.

Fig. 1. The UKD200-500 coal shearer.

- Darnel K4-16-233 electric motor, rated power 250 kW, rated speed 1470 rpm, asynchronous three-phase with squirrel-cage rotor.

The cutting part of the UKD200-500 coal shearer is unified. This allows it to be installed on either the left or right side of the frame. Each gearbox stage is located in a separate sealed chamber, protected from the penetration of abrasive particles.

The material of external gears is Steel 20Ch2N4ASh, with heat treatment – carburizing followed by quenching and low tempering. Material of the planetary ring gear – Steel 40 ChN, with heat treatment – improvement for hardness 270–300HB.
2 Problem statement

Reliability and durability of the shearer as a whole depend on the reliability and durability of the cutting part, mainly its gears. It is necessary to take into account that coal mining equipment operates in especially difficult conditions. These are elevated temperatures, a wide range of shock loads and extremely high dust levels. In this case, it is required to ensure the high durability of gears and bearings – at least 15000 hours. Based on this, during the design process, as well as in the future, taking into account the operating experience, calculations for contact and bending durability and static strength of gearings was performed.

The reliability and durability of gears also depend on the accuracy of their manufacture. Therefore, when organizing production, it was necessary to increase the accuracy of the teeth. To do this, we carried out work on the study of the processing of large-module gears for gearboxes of mining machines with the use of modern abrasive and cutting tools.

Compared to other processing methods, this technology allows to significantly increase wear resistance, reduce the coefficient of friction, increase the accuracy of processing and reduce the height parameters of the roughness of gear wheels and, thereby, increase the reliability and service life of gears.

Next, we will consider the methods, approaches and results of calculations and experimental studies of cutting processing and profile grinding.

3 Materials and methods

3.1 The basic initial data

The design load was taken as follows:
- rated torque $T_r = 1624$ N·m;
- the maximum long-term operating torque for calculating the durability $T_{LM} = 3090$ N·m;
- the maximum short-term torque for calculating the static strength $T_M = 5740$ N·m.

The total estimated resource of the combine is 15000 hours. We assume that each of the two cutting parts works for half of the calculated resource with nominal loads. Therefore, the estimated life for the cutting part is 7500 hours.

3.2 Calculations of the gear’s geometry, contact and bending stresses

The calculation of the gearing geometry, contact and bending stresses in them was carried out based on standard techniques [1–4]. Also, the permissible stresses were refined based on mathematical modeling for fatigue processes in the teeth [5].

The assessment of durability was carried out using the recommendations of GOST 21354–87 [4]: the slight slope of the right branch of the contact fatigue curve was taken into account at the total numbers of load cycles $N_L > N_{lim}$. Here $N_{lim}$ is the base numbers of cycles corresponding to the allowable contact stress number $\sigma_{lim}$ – Fig. 3.

![Fig. 3. Contact fatigue curve of active tooth surfaces: zone of limited (I) and long-term fatigue (II).](image)

The resource calculation was carried out in the next sequence.

1. The equivalent numbers of load cycles were determined for calculating the contact and bending fatigue $N_{HE}$ and $N_{FE}$ according to the next formulas [6]:

$$N_{HE} = \sum_{i=1}^{i_n} \left( \frac{T_{Li}}{T_{1H}} \right)^{0.5q_i} N_{Li} ;$$

$$N_{FE} = \sum_{i=1}^{i_n} \left( \frac{T_{Li}}{T_{1F}} \right)^{q_i} N_{Li} \leq N_{F_{lim}} ,$$

where $i = 1; \ldots; i_n$ – accepted for calculation bin of the load spectrum; $T_{Li}$ and $N_{Li} = 60n_i t_i$ – corresponding values of torque and load cycles on the pinion; $N_{F_{lim}}$ – base number of cycles corresponding to the allowable bending stress number $\sigma_{lim}$; $q_i = 9$ for the case of surface chemo-heat treatment of teeth and an unpolished tooth root; $q_{x} = 6$ for other variants of heat treatment or polished tooth root.
Additionally, for case \( N_L > N_{lim} \), steps with loads that create stresses below the modified allowable stress number \( \sigma_{H0} = a_{H0} \sigma_{lim} \) were excluded from the cyclosrama. Recommendations \( a_{H0} = 0.75 \) [4].

2. The total number of cycles to failure was calculated.

2.1. Bending fatigue:

\[
N_{F\Sigma,1,2} = N_{FE(2)} \left( \frac{\sigma_{FP1,2}}{\sigma_{F1,2}} \right)^{\eta_F} \quad \text{if} \quad N_{F\Sigma,1,2} \leq N_{F\lim,1,2};
\]

\[
N_{F\Sigma,1,2} = \infty \quad \text{if} \quad N_{F\Sigma,1,2} > N_{F\lim,1,2}.
\]

2.2. Contact fatigue:

\[
N_{HE} = N_{HE} \left( \frac{\sigma_{HP}}{\sigma_H} \right)^6 \quad \text{if} \quad N_{HE} \leq N_{H\lim};
\]

\[
N_{HE} = N_{HE} \left( \frac{\sigma_{HP}}{\sigma_H} \right)^{20} \quad \text{if} \quad N_{HE} > N_{H\lim}.
\]

3. The calculated durability of the teeth was determined by contact and bending fatigue in hours, \( L_{H0} \) and \( L_{FH} \):

\[
L_{H0} = \frac{N_{H\Sigma,1,2}}{N_{HE}}; \quad L_{FH} = \min \left( \frac{N_{F\Sigma,1,2}}{N_{FE1}}, \frac{N_{F\Sigma,2}}{N_{FE2}} \right),
\]

where \( t \) – required resource of gears.

The minimum of \( L_{H0} \) and \( L_{FH} \) was taken as the final value of the durability \( L_h \) for each gear pair.

Also, modeling of the stress-strain state for gears by the finite element method has been carried out. Finite element analysis was carried out in specialized software ANSYS. Gears, carrier of the planetary stage, gearbox housing, shafts, spline parts, etc. were research.

3.3 Experimental research of milling and profile grinding of teeth

The increase in productivity, accuracy and quality of processing of hardened gear wheels of gearboxes of mining machines is ensured by the improvement of the technology and kinematics of tooth milling and tooth grinding, the development of instrumental and technological equipment for the processing process. The main allowance after heat treatment for tooth grinding up to 90% should be performed with a blade tool due to high-speed tooth processing with special cutters [7].

The load capacity of gears in terms of contact strength increases with an increase in the surface hardness of the teeth. However, the high complexity of manufacturing hardened large-module gears limits their use due to significant allowances.

Milling cutters can be equipped with cutting plates made of hard alloy, ceramics, superhard materials to obtain the necessary accuracy and quality of surface treatment of gear wheels. Due to the intensification of cutting modes when using cubic boron nitride (CBN) plates, productivity increases by 2–5 times without reducing the quality and accuracy of processing. The use of CBN cutters makes it possible to significantly increase the reliability and durability of gear wheels due to the high quality of processing [8].

Tests of the process of profile grinding of gears were carried out on a tooth grinding machine with a CNC mod. "HÖFLER RAPID 1250" – Fig. 4.

During the study of the process, the gear grinding power and all other measurements of the precision parameters of the processed gears were recorded [9]. Gear wheels of the same standard size made of hardened steel with a hardness of up to HRC 60 were ground. The outer diameter of the gear wheel \( d = 233.4 \) mm; number of teeth \( z = 29 \); module \( m = 7 \) mm; tooth helix angle \( \beta = -18^\circ \); crown width \( b = 60 \) mm.

The following highly porous abrasive wheels were tested:

400-32-127 WG946 Hs12 Vs – monocrundum;
400-32-127 3SG46Hs 12 Vs – zol-gel monocrundum;
400-32-127 A9946Hs 12 Vs – white corundum;
400-32-127 A8960K9V – chrome corundum;
400-32-127 25AF46L6V – white corundum with normal porosity.

4 Results and discussion

4.1 Calculation results of gears

Calculation results of strength and durability for gearings of the gearbox cutting part are presented in Tables 1–3. Analysis of the data in these tables shows that the strength and durability for all gears of the cutting part are ensured.

Also, we will give an example of modeling the stress-strain state for gears using the finite element method.

Fig. 5 shows Finite Element model of gear pair – her general view and area in the contact of teeth.
Fig. 6 shows the distribution of equivalent stress by von Mises, MPa, in contact of first pair of the gearbox cutting part. Fig. 7 shows the distribution of bending stress, MPa, for pinion of their pair.

**Table 1.** Calculation results of gears strength and durability for 1st stage.

<table>
<thead>
<tr>
<th>Gear</th>
<th>$Z_1$</th>
<th>$Z_2$</th>
<th>$Z_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of teeth</td>
<td>23</td>
<td>43</td>
<td>50</td>
</tr>
<tr>
<td>Module $m$, mm</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Factor of safety from pitting $S_t$ ($S_{t, min} = 1.2$)</td>
<td>1.45</td>
<td>1.74</td>
<td>1.90</td>
</tr>
<tr>
<td>Factor of safety from tooth breakage $S_r$ ($S_{r, min} = 1.55$)</td>
<td>2.72</td>
<td>2.12</td>
<td>2.97</td>
</tr>
<tr>
<td>Factor of safety from static contact strength $S_h$ ($S_{h, min} = 1$)</td>
<td>1.93</td>
<td>1.93</td>
<td>2.32</td>
</tr>
<tr>
<td>Factor of safety from static tooth breakage $S_{f,t}$ ($S_{f,t, min} = 1.75$)</td>
<td>3.62</td>
<td>3.50</td>
<td>3.59</td>
</tr>
<tr>
<td>Calculated service life of teeth $t$, hours</td>
<td>330200</td>
<td>12.7·10$^6$</td>
<td>73.5·10$^6$</td>
</tr>
</tbody>
</table>

**Table 2.** Calculation results of gears strength and durability for 2nd (planetary) stage.

<table>
<thead>
<tr>
<th>Gear</th>
<th>$Z_1$</th>
<th>$Z_2$</th>
<th>$Z_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of teeth</td>
<td>15</td>
<td>23</td>
<td>60</td>
</tr>
<tr>
<td>Module $m$, mm</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Factor of safety from pitting $S_t$ ($S_{t, min} = 1.2$)</td>
<td>1.24</td>
<td>1.72</td>
<td>1.42</td>
</tr>
<tr>
<td>$S_{h, min}=1.1$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Factor of safety from tooth breakage $S_r$ ($S_{r, min} = 1.55$)</td>
<td>2.83</td>
<td>2.45</td>
<td>3.19</td>
</tr>
<tr>
<td>$S_{h, min}=1.7$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Factor of safety from static contact strength $S_h$ ($S_{h, min} = 1$)</td>
<td>1.71</td>
<td>1.71</td>
<td>1.69</td>
</tr>
<tr>
<td>Factor of safety from static tooth breakage $S_{f,t}$ ($S_{f,t, min} = 1.75$)</td>
<td>3.79</td>
<td>3.69</td>
<td>4.74</td>
</tr>
<tr>
<td>Calculated service life of teeth $t$, hours</td>
<td>14400</td>
<td>810500</td>
<td>1.2·10$^6$</td>
</tr>
</tbody>
</table>

**Table 3.** Calculation results of gears strength and durability for 3d stage.

<table>
<thead>
<tr>
<th>Gear</th>
<th>$Z_4$</th>
<th>$Z_5$</th>
<th>$Z_6$</th>
<th>$Z_7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of teeth</td>
<td>14</td>
<td>20</td>
<td>20</td>
<td>24</td>
</tr>
<tr>
<td>Module $m$, mm</td>
<td>16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Factor of safety from pitting $S_t$ ($S_{t, min} = 1.2$)</td>
<td>1.66</td>
<td>1.98</td>
<td>2.19</td>
<td>2.01</td>
</tr>
<tr>
<td>Factor of safety from tooth breakage $S_r$ ($S_{r, min} = 1.55$)</td>
<td>2.92</td>
<td>2.78</td>
<td>2.78</td>
<td>3.05</td>
</tr>
<tr>
<td>Factor of safety from static contact strength $S_h$ ($S_{h, min} = 1$)</td>
<td>1.50</td>
<td>1.50</td>
<td>1.65</td>
<td>1.65</td>
</tr>
<tr>
<td>Factor of safety from static tooth breakage $S_{f,t}$ ($S_{f,t, min} = 1.75$)</td>
<td>2.89</td>
<td>3.52</td>
<td>3.87</td>
<td>2.77</td>
</tr>
<tr>
<td>Calculated service life of teeth $t$, hours</td>
<td>52500</td>
<td>151300</td>
<td>277100</td>
<td>165600</td>
</tr>
</tbody>
</table>
4.2 Results of experimental research for profile grinding

The test results of grinding wheels made of monocrystalline and zol-gel corundum showed their high efficiency in comparison with wheels made of white electrocorundum. These wheels provide a reduction in grinding power and better indicators in terms of accuracy and quality of processing.

Research on the tooth grinding process was carried out when grinding two gears of the same size. Allowance for processing \( t = 0.51 \) mm. The number of processing stages is 3 (rough \( t = 0.24 \) mm, semi-finished \( t = 0.24 \) mm, finished \( t = 0.03 \) mm).

The results of the wheel grinding process from the zol-gel wheel showed that the tooth grinding power is, on average, \( P = 566.5 \) W at the semi-clean (2) stage and \( P = 400 \) W at the clean (3) stage. The accuracy of gear wheel processing corresponds to 2 degrees of accuracy (according to DIN 3962).

The results of research into the grinding process of gear wheels with a circle made of monocrondum showed that the power of tooth grinding is on average \( P = 900 \) W at semi-clean (2) stages and \( P = 800 \) W at clean (3) stages. The accuracy of gear wheel processing corresponds to 2 degrees of accuracy (according to DIN 3962).

The results of research into the process of grinding gear wheels with a circle made of chrome corundum (ruby corundum) showed that the power of tooth grinding is, on average, \( P = 1100 \) W at semi-pure (2) stages and \( P = 900 \) W at pure (3) stages (Fig. 8). The processing accuracy of the gear wheel also corresponds to 2 degrees of accuracy.

The use of grinding wheels made of monocrystalline corundum (monocrondum and zol-gel corundum) allows you to reduce the effective tooth grinding power 3 times lower than with white corundum wheels and 1.5 times lower than with chrome corundum wheels. Grinding of monocrondum and chrome corundum wheels was carried out through 7–8 depressions of the workpiece, while straightening of regular wheels of white corundum was carried out through 4–5 depressions.

The study of the surface roughness of gear wheels showed that the roughness when grinding with cubic boron nitride (CBN) wheels provides a \( R_a \) value of 1.00–1.10. It depends on the strength of CBN grains, which are much higher than ordinary abrasive materials. When using ordinary abrasive materials, for example, white corundum, \( R_a \) 0.50–0.60.

And for example, when using monocrystalline corundum and chrome corundum \( R_a \) 0.60–0.70. In all processing modes, an increase in surface roughness is ensured while reducing the processing time of gear wheels. The depth of grinding did not show a significant increase in the surface roughness of the gears.

In the case of complex metallographic and X-ray analysis of the surface layer of gears, it was established that grinding with a cutting depth of \( t = 0.1 \) mm and more is impractical, because the depth of the defective layer exceeds the allowance for processing and is 200 \( \mu \)m, which cannot be removed during the following finishing processing operations (Fig. 9).

In practice, grinding gears with a depth greater than \( t = 0.05 \) mm is not advisable, because the defective layer
may coalesce after processing. Finishing is appropriate for a grinding depth of up to \( t = 0.01–0.015 \) mm, floor finishing with a depth of \( t = 0.03 \) mm. With this gear grinding technology, the defective layer is 20–30 microns, which can be removed during the following finishing operations.

Simultaneously with metallographic and X-ray studies, the distribution of final stresses to the depth of the surface layer of gears was studied. It was established that at a depth of 5–8 \( \mu \)m, compressive final stresses turn into ultimate tensile stresses, and at a depth of 20 \( \mu \)m they are equal to 100–400±10 MPa. The depth of final tensile stress distribution is 70–100 \( \mu \)m.

The maximum final tensile stresses in the surface layer of gears occur when processing with a tool made of white corundum, and the minimum when processing with a tool made of CBN. During final grinding \( t = 0.01 \) mm, cubic boron nitride circles are formed by compressing final stresses of up to 200±10 MPa.

It was established that after grinding with CNB wheels, the wear resistance of gear wheels increases by up to 10% compared to grinding with corundum, thereby confirming that due to high-quality processing, it is possible to increase the durability of gear wheels.

## 5 Conclusion

A detailed assessment of the strength and durability of the main parts and components of the cutting part of the new generation coal shearer was carried out. Created and put into serial production of coal shears at a prominent machine-building enterprise of Ukraine [10].

Practical recommendations for the use of tooth grinding technologies with the purpose and provision of parameters of the surface layer of hardened large-module gear wheels have been developed.

Thus, it can be concluded that the developed design of the gearbox for the cutting part of the combine provides the necessary durability of 15 000 hours and an average resource before overhaul.

## References

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