Crushing of abrasive particles in gearbox oil of tractors operating in dusty environmental conditions

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Abstract. This paper investigates the factors affecting the strength of abrasive particles in tractor gearbox oil operating in dusty conditions. The study focuses on gearboxes with constant mesh gears, categorized into two types based on torque transmission. The research aims to determine the degree of activity of abrasive particles influencing gear teeth wear resistance. A methodology for calculating the possibility of crushing abrasive particles based on their concentration, size, and strength is proposed. The influence of normal force arising from friction torque, rolling bearings, and oil agitation on abrasive particles is also examined. The findings indicate that when gear transmission does not transmit torque, the normal force does not lead to abrasive particle crushing, resulting in high wear capacity in the gearbox oil. However, under the influence of normal force from the torque transmitted by the internal combustion engine, abrasive particles in the tooth contact zone are crushed, reducing their wear capacity. The study's results contribute to understanding the factors affecting abrasive particle strength in tractor gearboxes operating in dusty conditions, providing insights into improving system design and operation for enhanced durability and efficiency.

1 Introduction

Agricultural machinery, such as tractors, harvester combines, seeders, grain cleaning machines, choppers, and grinders, rely heavily on gears for their operation. Gearboxes in these machines can be categorized into two types: constant mesh gears and sliding gears. Constant mesh gears transmit torque through sliding on the center part of the secondary shaft by the clutch or sliding gears [1-2].

The strength of abrasive particles in tractor gearbox oil is affected by various factors, especially in dusty environmental conditions. Abrasive particles in the oil of gearboxes with constant mesh gears or sliding gears on the secondary shaft play a significant role in gear wear [3].

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A methodology for determining the degree of activity of abrasive particles based on their concentration, size, and strength is proposed. This methodology aims to calculate the possibility of crushing abrasive particles in the contact zone of teeth. Experimental results show that the normal force arising from friction torque, rolling bearings, and oil agitation influences abrasive particles. When the gear transmission does not transmit torque, the normal force does not lead to the crushing of abrasive particles, resulting in the highest wear capacity of abrasive particles in the gearbox oil. However, under the influence of normal force arising from the torque transmitted from the internal combustion engine, abrasive particles in the contact zone of the teeth are crushed, causing these particles to lose their wear capacity [4-5].

Understanding the factors affecting the strength of abrasive particles in tractor gearboxes operating in dusty conditions can provide insights into enhancing the durability and efficiency of agricultural machinery. By optimizing gearbox design and operation, agricultural machinery can better withstand the challenging environmental conditions they often encounter, ultimately contributing to more sustainable and productive farming practices [6-7].

2 Methods

In existing tractor gearbox designs, only two pairs of gears are loaded with torque. In a constant mesh gearbox, torque transmission by constant mesh gears is carried out by a pair of gears. The master gear is mounted on the primary (drive) shaft. The other pairs of gears do not transmit torque. They are loaded only by the torque formed from the force of friction arising in the gears, rolling bearings and resistance to agitation of the oil found in the gearbox crankcase.

In another design of transmission gearbox torque delivery to the secondary shaft of the gearbox is carried out by displacement of the sliding (idler) gear on the centers of the idler shaft to obtain full meshing on the length of the tooth of the tooth of the drive pinion of the corresponding gear. Here, the transfer of torque to the intermediate shaft is made by the pinion of the primary shaft and the pinion of the intermediate shaft; in the second pair of gears of the corresponding gear of the intermediate shaft coincides with the corresponding to it pinion of the secondary shaft.

3 Results and discussion

The load on the intermediate shaft depends on the engine torque. The torque transmitted from the drive (primary) shaft to the intermediate shaft of the gearbox depends on the engine crankshaft torque $M_\text{do}$, gear efficiency of the gear train $\eta_m$ and gear ratio $i_m$.

Then the torque transmitted from the drive shaft to the intermediate shaft of the gearbox is equal to:

$$M_m = M_\text{do} \cdot \eta_m \cdot i_m, \text{Nm}$$

If the drive shaft of the gearbox is not loaded by the torque transmitted by the internal combustion engine, it is loaded by the torque arising from the friction forces in the gears, rolling bearings and resistance to agitation of the oil in the gearbox crankcase. In the gearbox, the gears transmitting torque for forward travel are engaged by means of clutches sliding on the centers of the secondary shaft. [8]. When the gearbox does not transmit torque, the sliding clutch is in neutral position, then the bottom gear is not loaded with torque, while the secondary shaft is loaded with resistance torque. In this case, the moment of resistance arising on the driven shaft of the gearbox is determined by the expression:

$$M_w = M_o \cdot (1 - \eta_c) \cdot i_c, \text{Nm}$$
where $Mv$ – torque on the transmission drive shaft, Nm; $\eta_c$ - is the coefficient of efficiency of the considered spur gear; $i_i$ - is the gear ratio of the gear train under consideration.

### Table 1. Number of gear teeth on the intermediate and driven shafts of the gear box.

<table>
<thead>
<tr>
<th>Gear indicators</th>
<th>Drive and transmission intermediate shaft</th>
<th>Transmissions of the tractor gearbox</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gear ratio</td>
<td>1.29</td>
<td>1  2  3  4  5  6</td>
</tr>
<tr>
<td>Number of teeth meshing gears</td>
<td>Number of gear teeth on the intermediate shaft of the gearbox</td>
<td></td>
</tr>
<tr>
<td></td>
<td>28  52  50  48  46  39  32</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Number of gear teeth on the transmission drive shaft</td>
<td></td>
</tr>
<tr>
<td></td>
<td>36  12  14  16  18  25  32</td>
<td></td>
</tr>
</tbody>
</table>

In the further calculation of factors affecting the strength of abrasive particles in the oil gear box with constant mesh gears were made for all (six) available gears (gear ratio and the number of teeth of the driving and driven gears) front stroke are shown in Table 1, the results of the calculation (calculated parameters affecting the strength of abrasive particles) are shown in Table 2. The radius of the dividing circle of the cylindrical gears is equal to:

$$ r_i = \frac{m \cdot z_i}{2}, \text{ mm} $$

where $m$ - modulus of meshing, mm; $z_i$ - number of teeth of the gear under consideration.

The scientific work [9, 10] is devoted to the calculation of the contact area of closed gears with constant meshing; they calculated the contact width of gear teeth in the rolling zone. According to which the calculated width of the contact area at a load of 55 N on the gear was 2.25 mm at a tooth length of 41.5 mm. At the same time, the calculated value of the contact area was:

$$ F_x = L_m \cdot B, \text{ mm}^2 $$

where $L_m$ - tooth contact length, mm; $B$ - contact width, mm.

The magnitude of the normal force acting on the gear is determined by the torque used to break the frictional resistance expended during the operation of the gear:

$$ P = \frac{M_m}{r_i \cdot \varepsilon_a}, \text{ N} $$

where $M_m$ - torque spent on selling the friction resistance on the gearbox drive shaft, Nm; $\varepsilon_a$ - the coefficient of mutual overlap of the teeth of the gears being in meshing, the value of which is determined by the following expression:

$$ \varepsilon_a = 1.88 - 3.2 \left( \frac{1}{z_1} + \frac{1}{z_2} \right) $$

where $z_1$ and $z_2$ – number of teeth of the driving and driven gears in meshing.

The calculated value of the coefficient of mutual overlap of teeth not korigirovanovannyh gears, depending on the number of teeth gears are in the range of $\varepsilon_a = 1.55 – 1.80$.

To calculate the average size of abrasive particles, which are in the gearbox oil and participate in the process of wear of gear teeth, an analytical dependence is proposed, taking into account the maximum and minimum size of abrasive particles [10, 11]. The minimum size of abrasive particles is established taking into account the height of roughness roughness of friction surfaces and the thickness of the oil film between the friction surfaces of the gear teeth are accepted particles of size not exceeding $d_{min} = 4 \mu m$. The maximum size of the abrasive particles is based on the coefficient of friction between the abrasive particle and the friction surface of the gear teeth. The maximum size of abrasive particles determined
according to this condition is as follows \( d_{\text{max}} = 48 \ \mu m \). Then the average size of abrasive particles is obtained dependence:

\[
d_{cp} = \sqrt{d_{\text{max}} \cdot d_{\text{min}}} \ \mu m
\]  \( (7) \)

The calculated value of the average size of abrasive particles amounted to \( d_{cp} = 15.5 \ \mu m \).

The calculated value of the oil volume per contact area with a thickness equal to the average abrasive particle size of 15.5 \( \mu m \) is:

\[
V_{\text{min}} = F_k \cdot d_{cp}, \ mm^3
\]  \( (8) \)

Analysis of tractor gearbox oil working in dusty conditions show that when changing the oil in the aggregate accumulate solid mechanical impurities of soil origin with a concentration of up to 1.3% by mass. Mineralogical study, mechanical impurities show in their composition mainly consist of wear products on the basis of iron, consisting of particles of size not more than 4 microns and silicon oxide with a direct size more than 20 \( \mu m \). The determined mechanical impurities are distributed in equal proportions of 50% by mass[14]. Due to the fact that wear products have particles of size not exceeding the sum of the oil film thickness and roughness protrusion do not participate in the process of wear, particles consisting of silicon oxide have larger size and they intensively participate in the process of deformation of contact surfaces as a result of which there is wear of surfaces and crushing occurs [12, 13].

The volume of abrasive particles in the oil layer with a height equal to the average size of abrasive particles involved in the process of wear of gear teeth located on the area of their contact:

\[
V_a = V_{\text{min}} \cdot \varepsilon_k \ mm^3
\]  \( (9) \)

where \( \varepsilon_k \) - concentration (by mass) of abrasive particles in gearbox oil.

The volume of a single abrasive particle having a medium size,

\[
V_{1a} = \frac{\pi \cdot d_{cp}^3}{6} = 0.5236 \cdot d_{cp}^3, \ mm^3
\]

The number of evenly spaced abrasive particles located on the contact area of gear teeth is calculated to be 4826 pieces.

\[
n_{ma} = \frac{V_a}{V_{1a}}
\]  \( (10) \)

Compressive strength of medium-sized abrasive particles in the contact area for non-torque transmitting gears,

\[
\sigma_a = \frac{4 \cdot P \cdot \pi \cdot d_{cp}^2}{n_{ma} \cdot \pi \cdot d_{cp}^2}, \ MPa
\]  \( (11) \)

According to the research conducted by M. M. Tenenbaum [14 ] to calculate the compression load \( P \), leading to crushing of abrasive particles depending on their size, the following empirical dependence was obtained:

\[
P = 10^{-8} \cdot Y \cdot d_{cp}^3, \ MN
\]  \( (12) \)

where \( P \) - load leading to destruction of abrasive particles, MN; \( Y \) и \( x \) – empirical coefficients.

In this expression, the average size of abrasive particles were taken in micrometers.

In the conducted studies as compressive abrasive particles used plates made of Steel 45 and Steel 45X, subjected to volume hardening, in the expression for calculating the value of compressive load taken values of \( Y= 16.03 \) и \( x=0.82 \).

Then the permissible stress leading to crushing of abrasive particles located on the contact area, for gears transmitting torque is as follows

\[
[\sigma_a] = \frac{4 \cdot P}{\pi \cdot d_{cp}^2}, \ MPa
\]  \( (13) \)
### Table 2. Calculation parameters affecting the strength of abrasive particles in the oil of tractor gearboxes operating in dusty operating conditions.

<table>
<thead>
<tr>
<th>Tractor gearbox operation under operating conditions</th>
<th>Forward gears of the tractor gearbox</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Transmission gear ratios</td>
<td>4.33</td>
</tr>
<tr>
<td>Friction torque on transmission drive shaft, Nm</td>
<td>30.6</td>
</tr>
<tr>
<td>Radius of curvature of teeth of intermediate shaft gears, mm</td>
<td>30.0</td>
</tr>
<tr>
<td>Contact area of teeth of meshing gears, mm²</td>
<td>103.75</td>
</tr>
<tr>
<td>Normal force acting on the gear, N</td>
<td>56.9</td>
</tr>
<tr>
<td>Overlap coefficient of meshing gear teeth</td>
<td>1.55</td>
</tr>
<tr>
<td>Volume of oil on the contact area of meshing gear teeth, mm³</td>
<td>1.608</td>
</tr>
<tr>
<td>Volume of abrasive particles on the contact area of the meshing gear teeth, mm³</td>
<td>0.0105</td>
</tr>
<tr>
<td>Amount of abrasive particles on the tooth contact area of the meshed gears, mm³</td>
<td>5384</td>
</tr>
<tr>
<td>Actual compressive strength of abrasive particles on the contact area of the teeth not transmitting torque, MPa</td>
<td>36.00</td>
</tr>
<tr>
<td>Permissible compression stress leading to crushing of abrasive particles located on the contact area of teeth transmitting torque, MPa</td>
<td>90.27</td>
</tr>
<tr>
<td>Ratio of compressive strength of abrasive particles for torque transmitting and non-torque transmitting gears</td>
<td>2.51</td>
</tr>
</tbody>
</table>

Thus, according to the calculation data given in Table 2, in case when gears of constant mesh gearbox installed on the intermediate and idler shafts are not connected to the gears, because of which they do not transmit torque to the rear axle, these gears of constant mesh are loaded only by the moment of resistance arising from the force of friction in the gears, in the rolling bearings and resistance to agitation of oil in the tractor gearbox crankcase.
4 Conclusion

Based on the research carried out on the crushing of abrasive particles in tractor gearbox oil, the following conclusions can be drawn:

- when the gear transmission does not transmit torque, the normal force arising from the friction torque in the gear transmission, rolling bearings and from the agitation of oil in the unit, acting on abrasive particles does not lead to their crushing and as a result of which the wearing capacity of abrasive particles in the gearbox oil has the highest value;
- in the gear transmission of the gearbox, under the influence of the normal force arising from the torque transmitted from the internal combustion engine, the abrasive particles in the contact zone of the teeth are crushed, causing these particles to lose their wear capacity.

References

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