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SHAPING THE SERVICE LIFE OF GEAR DRIVE SYSTEMS OF WORKING MACHINES

Abstract. The paper presents a generalized summary of the effects of basic geometrical, material, construction and technological and operational parameters on the durability of gear drives of machines and special vehicles. The issue of gear meshing durability is examined, indicating the significance of the impact of these parameters on: immediate and fatigue strength of gear teeth and resistance of surface layer to tribological failure. In addition, the important role of lubrication engineering in the shaping of bearings durability is demonstrated. The paper aims to enrich the knowledge of design engineers which is necessary at the stage of concept development and making decisions on the optimization of innovative drive systems of working machines designed for military use.

Keywords: gears, bearings, lubrication, drive systems, durability.

1. INTRODUCTION

Gears are an integral part of virtually all working machines: both civilian and military. In many cases their durability determines their operational reliability. Experiments and operational tests [5] show that a significant proportion (approximately 30%) in premature loss of durability of these gears is due to tribological failure of gear meshing and bearings, directly or indirectly related to improper lubrication and/or ineffective sealing of drive and driven shafts and body (Fig. 1). Therefore, tribological wear and thermal state [4], in addition to fatigue and immediate strength of structural elements and units, is the key issue in ensuring the required durability of the mentioned group of gears.

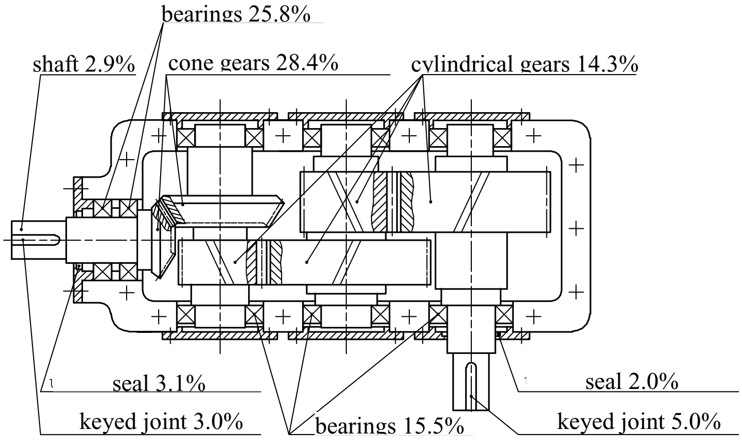

Fig. 1. Structure of damage in components of a helical-bevel gearbox of a mining scraper conveyor drive

The same phenomena determine the durability of gears in power transmission systems of military vehicles – tracked vehicles in particular. These issues were treated as those of

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primary importance throughout the history of OBRUM. Typical examples include work on a global analysis of power losses in the drive system of the T-72 tank in the aspect of its modernization [12], investigated more closely by studying the effect of design parameters on the losses generated in gear meshing [13], and works discussing the fundamentals of selecting lubricating oils for the side transmission of a tracked vehicle [11] and its effect on the durability of gear meshing [10]. This paper fills a gap in terms of a global approach to the shaping and evaluation of the durability of the main kinematic joints in gearboxes at different stages of the process of technological "existence", i.e. in the process of design, manufacture and use.

2. MAIN PARAMETERS AFFECTING THE DURABILITY OF GEAR TRANSMISSION

In general, the working (operating) life of gears follows from the general rules of machine design [6] and is shaped during subsequent stages of its existence, that is in the design, manufacture and use phases. In short, durability results from the taking into consideration of the design, technological and operating parameters that create a synergistic system of shaping the resultant durability of a transmission.

2.1. Effect of the design, technological and operating parameters on the durability of gear meshing

The effect of the design, technological and operating parameters should be discussed in relation to possible meshing failures which include (Fig. 2):

- immediate fractures, resulting from exceeding the static strength limit, which is characteristic of the strong random overloads and extreme starting loads (e.g. in drive systems of tracked vehicles);
- fatigue fractures, resulting from exceeding the fatigue strength limit, characteristic of variable working load, which is almost always present;
- fatigue chipping of the surface layer of gear teeth (pitting) which causes disruptions in the smoothness of transmission operation, increased dynamic forces in gear meshing, and ultimately leads to a volumic fracture of gear teeth;
- excessive abrasive wear due to the abrasive action of hard contaminant particles in the lubricating oil on the mating surfaces of the teeth, causing their wear (microcutting);
- seize damage on active faces of teeth, characteristic of transmission with insufficient lubrication, especially with oil without anti-seize additives and as a result of higher operating temperature [11].

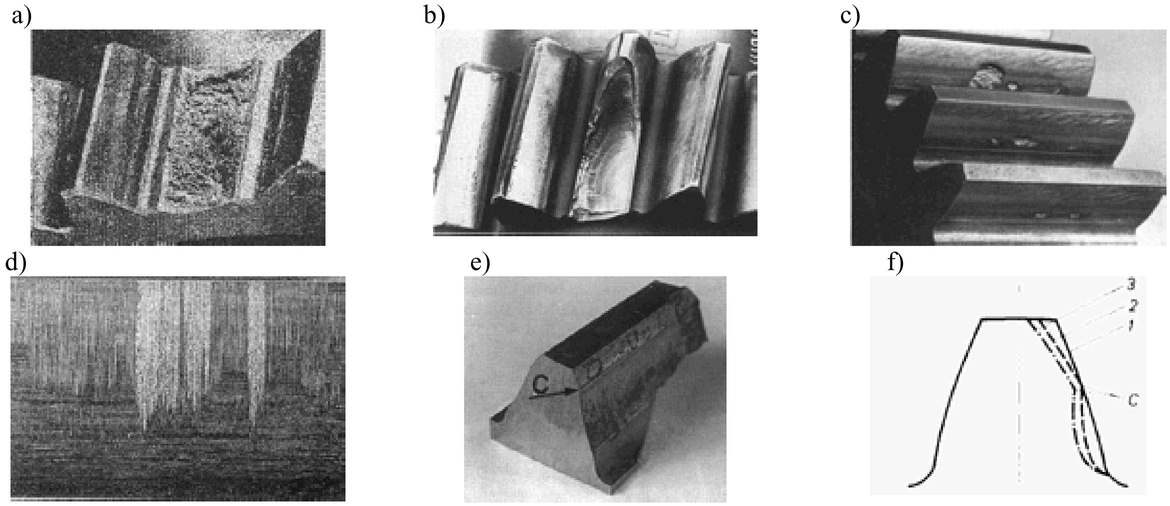

Fig. 2. Examples of operating failures of gear teeth:
a) instant fracture, b) fatigue fracture, c) pitting, d) seize damage, e) fracture due to excessive abrasive wear, f) phases of abrasive wear (1, 2, 3),
where: c – pitch (central) point

Among the mentioned types of wear occurring in gears of mobile machines (of civilian or military use), the most frequent causes of elimination from use include instant fatigue fracture of teeth, and other that often lead to them as a result of tribological wear in the form of chipping of the surface layer or of excessive wear.

Table 1 illustrates the effect of material of the gears, of design and operating parameters and of lubrication. An "X" in the table means a decisive impact, an "(X)" indicates impact that is possible under extreme operating conditions, especially with insufficient lubrication.

Table 1. Illustrative representation of the effect of material , design and operating factors and of lubrication on teeth damage

Type of damage	**Factors affecting damage**		
	Material	Design and operating factors	Lubrication
Instant and fatigue strength	X	X	-
Contact strength (pitting)	X	X	(X)
Resistance to seize damage	(X)	X	X
Overheating	-	X	X

As mentioned before, durability of meshing is determined at the stages of design, of manufacture and assembly, and in the process of usage [9]. Damage in the form of fatigue failure of teeth is affected mainly by material and technological factors, as shown in Table 2.

Table 2 shows that the most important (dominant) effect on the volumetric strength of teeth is produced by the value of the module, the strengthening of the surface layer of teeth and positive addendum modification coefficient, and therefore by features resulting from the process of design, material selection and gear manufacture.

Table 2. Relative (estimated) effect of selected parameters on the fatigue strength of gear teeth [1]

A. Material, fabrication process and shape features of surface layer	
– manufacturing processes:	
quenching and tempering : nitriding : hardening	1 : 1.2 : 1.4
– surface roughness of quenched and tempered steel:	
$R_z = 4\ \mu m : 10\ \mu m : 40\ \mu m$	1 : 0.9 : 0.9
– surface roughness of teeth made of hardened steel:	
$R_z = 4\ \mu m : 10\ \mu m : 40\ \mu m$	1.05 : 1 : 0.95
– damage from grinding:	
no damage : damage present (micronotches)	1 : 0.5
– condition of surface layer:	
no strengthening : mechanical strengthening (e.g. by shot blasting)	1 : 1.3
– gear manufacturing process:	
casting : rolling : forging	0.8 : 1 : 1.3
B. Geometric features	
– 2-fold increased tooth module	1 : 2
– toothing modification:	
for teeth number in pinion $z_1 \leq 20$	1 : 2
for teeth number in pinion $z_1 > 40$	1 : 1.1
– pressure angle: $\alpha_t=20^\circ$: $\alpha_t=28^\circ$	
for teeth number in pinion $z_1 \leq 20$	1 : 1.25
for teeth number in pinion $z_1 > 40$	1 : 1.15
– cylindrical gears:	
spur gears : helical gears ($\beta=17^\circ$)	1 : 1.2
– relative tooth fillet radius:	
$\rho/m = 0.25 : 0.4$	1 : 1.1

In the case of factors that affect the durability of meshing for reasons of fatigue chipping of the surface layer (pitting), the significant effect of lubrication is demonstrated, as shown in Table 3.

Table 3. Factors affecting meshing durability due to pitting [1]

A. Material and manufacturing processes	
– manufacturing processes:	
quenching and tempering : nitriding : surface hardening	1 : 2 : 2.5
– machining of teeth made of quenched and tempered steel:	
milling : milling+grinding	1 : 1.4
grinding : grinding+copperizing	1 : 1.2
– machining of teeth made of alloyed steel in the form of:	
grinding : grinding+copperizing	1 : 1.1
low hardness : high hardness after quenching	1 : 1.1
cast gears : rolled (forged) gear	1 : 1.15
B. Lubrication and lubrication parameters	
– 2-fold higher operating viscosity:	
for wheels of quenched and tempered steel	1 : 1.1
for wheels of quenched steel	1 : 1.05
– decrease of operating viscosity during use by 20 mm^2/s:	1 : 0.8
– lubricant type for wheels of quenched and tempered steel:	
mineral oil : synthetic oil (for quenched and tempered steel)	1 : 2
mineral oil : synthetic oil (for quenched steel)	1 : 1.3
base oil : oil with EP additives	1 : 1
Note: An interesting fact is that it has been experimentally found that modern EP additives in oil have no significant effect on the occurrence and development of pitting [1].	
C. Toothing geometry	
– no modification : positive modification:	
for teeth number in pinion $z_1 \leq 20$	1 : 1.3
for teeth number in pinion $z_1 > 40$	1 : 1.1
– pressure angle at pitch diameter: $\alpha_t = 20°$: $\alpha_t = 28°$	1 : 1.3
– tooth height:	
normal : high	1 : 1,3[1]
– tooth helix angle:	
spur gears : helical gears ($\beta = 30°$)	1 : 1.4
– addendum:	
nominal height : short	1 : 1.2
[1] Thermal state issue appears, suitable synthetic oils should be used.	

As shown in Table 3, in relation to pitting wear, the effects of design and technological parameters, especially the technological properties of the surface layer of the teeth and, above all, the impact of the type of oil and its viscosity are more distinct than in the case of fatigue strength of the teeth. It should be noted here that the role of anti-seize EP additives in the oil is disputable. These additives have an effect in the case of increased seizure resistance and of the less studied tribological damage in the form of the so-called micropitting [15], which subsequently develops into the ordinary form of pitting.

2.2. The issue of bearing durability in gears in the power transmission systems of working machines

Durability of rolling bearing arrangements, used almost exclusively in the gear transmissions of working machines, is shaped, as in the case of gearing, at the stages of design, manufacture and usage. The difference is that the bearings are selectable components, and therefore the service life thereof depends heavily on the quality of the bearing mounting and on the quality of lubrication. The graph in Fig. 3 shows the underlying causes of failures of rolling bearings in the process of their use.

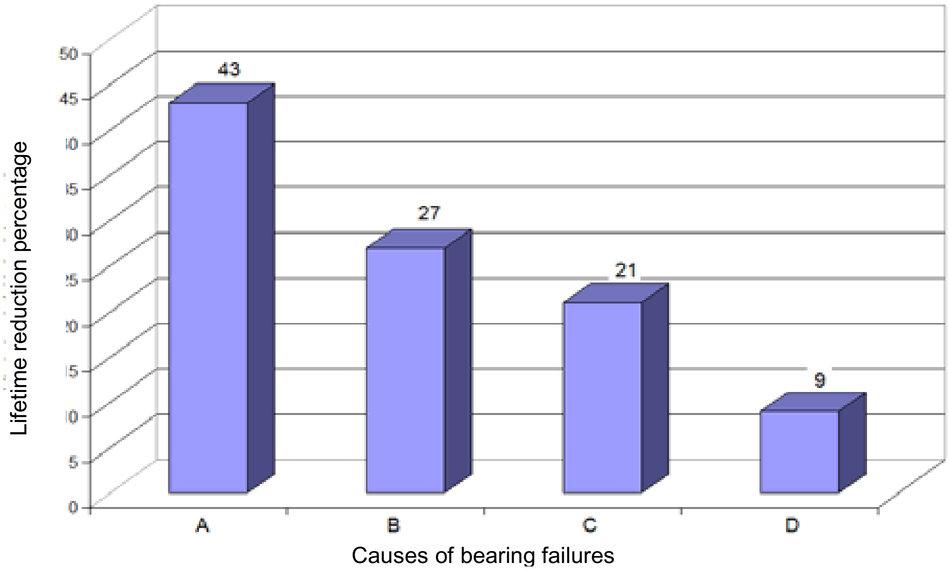

Fig. 3. Basic causes of failures (elimination from use) of rolling bearings [1]:
A - inappropriate lubrication, B - incorrect installation (fit on the shaft and prevention against movements relative to the mounting), C - random fracture of bearing cage or race, D - loss of contact life, i.e. pitting of rolling elements and raceways

It is worth mentioning here [2, 3, 8, 14], that rolling bearings are an example of those standardized machine components, the life of which is determined in the form of a mathematical formula that takes into account the main factors of design, materials and operation (mainly the quality of lubrication in the process of use). The relationship defining the service life of a rolling bearing is as follows:

$$L_e = a_1 \cdot a_2 \cdot a_3 \cdot L_{10} \tag{1}$$

where:

L_{10} - rated lifetime of a bearing determined experimentally for a risk (failure) level $r = 10\%$. The value of L_{10} can be calculated using the following formula:

$$L_{10} = \left(\frac{C}{F_z} \right)^q \tag{1a}$$

where:

C - dynamic load rating (in units of kN) of bearing at precisely defined radial load. At this value of C, contact fatigue of rolling elements and/or raceway occurs after 10^6 revolutions (with the probability of p = 90%),

F_z - equivalent load (kN). Manner of calculating F_z is defined by bearing manufacturers for the various types of bearings,

q - exponent determined experimentally; $q = 3$ for ball bearings, $q = 10/3$ for roller bearings,

a_1 - reliability factor, depends on the adopted level of risk, determined as follows

Risk of preserving durability r, %	10	5	3	2	1
Value of a_1	1.00	0.62	0.53	0.33	0.21

a_2 - factor for bearing steel manufacturing process; for ordinary steel $a_2 = 1.0$, for vacuum degassed steel $a_2 > 1.0$,

a_3 - factor for operating conditions, i.e.: type of lubricant, its cleanliness and operating temperature of bearing.

In accordance with DIN 281 standard:

$$a_3 = f\left(e_c, \frac{C_u}{F_z}, \kappa \right) \tag{2}$$

where:

e_c - factor of oil contamination with solid abrasive particles (see Table 4),

κ - lubricant viscosity ratio [9], wherein:

$\kappa = \upsilon_{op}/\upsilon_w$, where:

υ_{op} - operating viscosity at operating temperature (mm^2/s),

υ_w - theoretical required viscosity),

$\frac{C_u}{F_z}$ - relative load that causes contact fatigue of the surface layer.

Determining the function of a_3 defined with formula (2) requires a complex procedure implemented with the use of a computer program or the classical method of nomograms defined in bearing manufacturers' catalogues. In general, if bearing operation within permanent contact strength range ($F_z/C_u \leq 1$) and oil viscosity ratio $\kappa = 1.0$ are adopted, it can be assumed that a_3 is equivalent to the oil contamination factor e_c, as shown in Table 4.

Table 4. Lubricant contamination factor e_c

Oil contamination degree	Value of e_c
Laboratory conditions	1.0
High cleanliness, fine filtering of oil and no contamination of grease	0.8 ... 0.6
Standard (most common) cleanliness	0.6 ... 0.5
Slight contamination of lubricant	0.5 ... 0.3
Typical contamination in dust-laden environment and abraded material in oil	0.3 ... 0.1
Strong contamination of lubricant	0.1 ... 0.01

Table 4 shows that in the case of gear operation under the conditions of dusty environment and lubricant strongly contaminated with solid mineral particles and products of abrasive wear, the actual service life of bearings is in the order of 5 to 10 times lower than the calculated lifetime, if the impact of oil contamination on its lowering is not taken into account.

It is noteworthy that despite the abundant statistical data on the failure rate in the use of bearing arrangements in gear transmissions, many problems still remain unresolved. This refers particularly to precise qualitative and quantitative procedures that determine the impact of operating loads in specific groups of mobile working machines, especially tanks, on the service life of bearing arrangements. There is a quite substantial amount of laboratory research results, which indicate how important is the effect of lubrication (Fig. 4) or of water content in lubricating oil (Fig. 5).

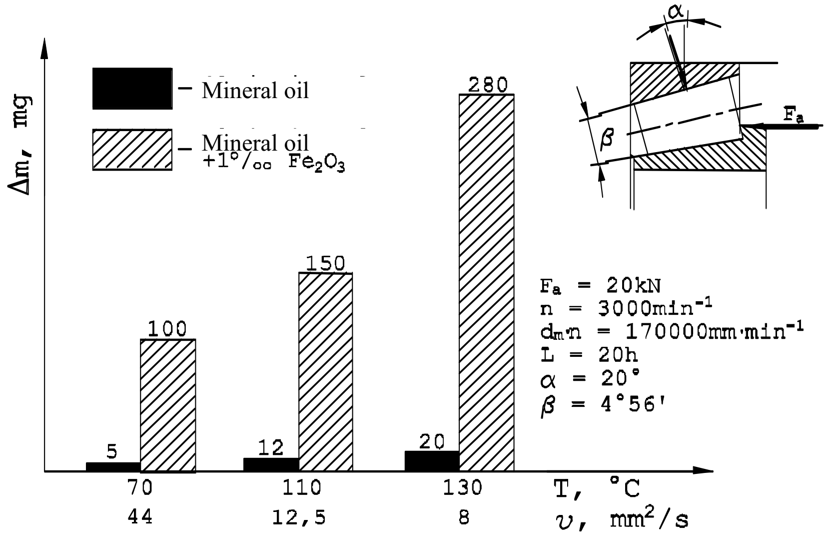

Fig. 4. Cone bearing wear vs. viscosity and temperature of lubricating oil [1]

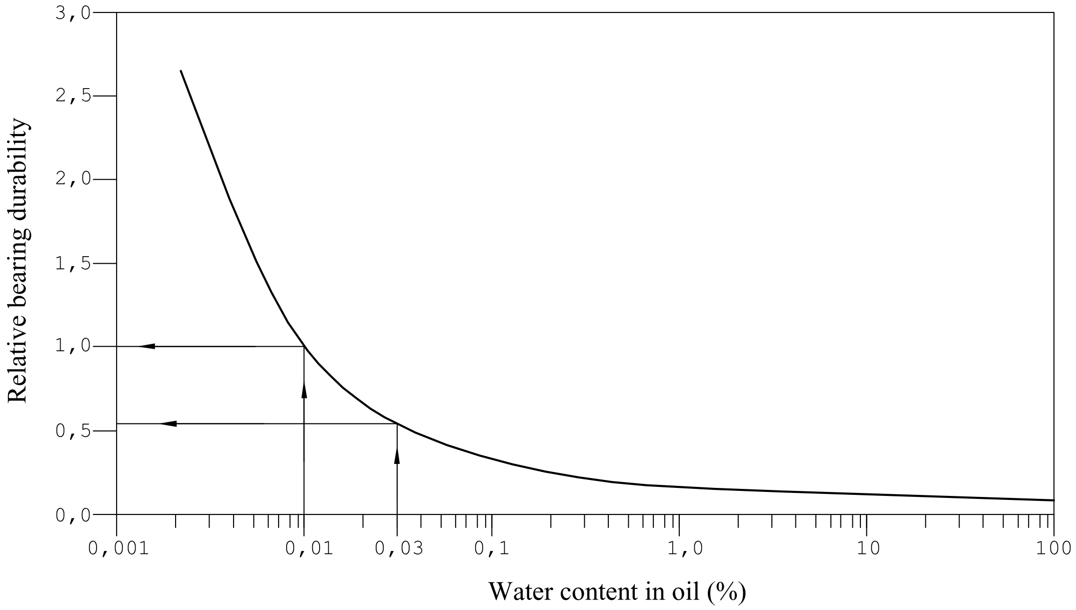

Fig. 5. Effect of water content in oil on durability of cone bearings (acc. to FAG) [14]

These data indicate that in the process of design it is important to take into account the tightness of the transmission and oil filtration, but in many cases these data are not sufficient to show how to design the structure of the transmission to avoid premature failure. That requires carrying out additional studies and field tests for special purpose mobile machines.

3. SUMMARY

Actions to extend the service life of gears in power transmission systems of special vehicles must be consistently implemented during the stages of both design and use. Due to the fact that a significant portion of gear failures results from progressive operating tribological wear, especially of bearings and gear meshing, it is important to fully understand the importance of lubrication engineering.

The selected results of experimental research and theoretical considerations presented in this paper (the problem is broad) indicate that there are already practical reasons for such integrated proceeding to extend the service life of gear transmissions during all stages of transmission existence, i.e. design, manufacture, installation and use.

The key issue during transmission operation is to ensure tightness of the transmission in an aggressive environment (sealing efficiency), to monitor its technical condition and to provide an integrated lubricating oil filtration system.

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