

Study on the wear of cylindrical gears of transmission mechanisms

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ABSTRACT

Gears are the main elements of transmission mechanisms such as reducers for general industrial applications, gearboxes of land transport vehicles and railway reduction gearboxes. They all are subjected to substantial dynamic loading and wear during operation. This paper analyses the materials used to produce various types of reducers. The main wear processes are examined in compliance to DIN 50320. The presented heat treatment technologies are aimed to achieve the best indicators determining the workability, contact strength and bending strength of materials. Measurements of gear profiles made of different materials and intended for a railway vehicle (electric locomotive) have been done. A formula for predicting the wear of gear profiles has been worked out in a probabilistic aspect. Optimised approaches to extend the service life of gears are suggested. It is also proposed what type of materials and technologies to choose for heat treatment of the selected reducer gears.

KEYWORDS

Reducer, Gears, Materials for gears, Gear profile, Gear wear, Electric locomotive

1. INTRODUCTION

Wear is a destructive action, with gradual removal or deformation of material on solid surfaces. The causes for wear can be mechanical or chemical. The study on wear and processes related to it is known as tribology. The examinations are focused on the types of wear phenomena observed in industries (such as abrasive wear, adhesive wear, frictional wear, fatigue wear, erosive wear and corrosive wear), their mechanisms, application of surface coating to protect the surface from industrial wear, types of surface coatings, thermal spray coating and its application in industry to protect the surface against wear [1, 2]. Detailed information on wear phenomena is presented in DIN 50320 [3] and ISO 10825 [4] that help industries to minimize the costs maintenance the parts. The mechanisms of gear wear can be generally classified into four categories [5]: abrasive wear, adhesive wear, erosive wear and corrosive wear

2. ESSENCE OF THE PROBLEM

The Bulgarian machine-building companies have long-year traditions in machine manufacturing and, more precisely, in reducer manufacturing. However, the Bulgarian reducers are not competitive under current economic conditions and with great competition with world-known companies, such as SEW, Lenze, Nord, Flender, Rossi, etc. Therefore, it is necessary to optimise certain parameters. The optimization criteria are determined based on a thorough analysis of advantages and disadvantages of competitive products made in the country and abroad.

The reducer quality depends on the reliable operation of all its elements. Gears, being the main reducer element, are subjected to heavy loading, so it is necessary to ensure their load-bearing capacity and extend their life by developing new tooth shapes and, above all, choosing new materials and new manufacturing processes [6, 7]. For the last fifty years, the Bulgarian reducer manufacturing companies have used only certain grades of steel to produce gears, the most widely applied being: steel 45, 40X, 18XGT, 30XGT, 12XH3A, etc. [8]. These grades comply with the БДС292 standard [9] and have the following classification:

- High-quality carbon steels, which have increased strength and ductility properties and are used for non-critical and medium-loaded gears for operation in non-corrosive environments – grade 40, 45, 50, etc.

- Structural alloy steels, which are used for operation in corrosive environments, for medium and heavy-loaded gears. The use of several alloying elements greatly improves the structural properties of steels – grades 40X, 40XH, 18XГТ, 30XГТ, 12XH3A, 40XM, etc.

The choice of material lies in the base of technological process development and heat treatment. It determines the durability and energy consumption of processes in manufacturing finished products. Therefore, it is necessary to analyze the factors determining these costs.

3. MATERIALS AND REQUIREMENTS FOR GEAR MANUFACTURING

The materials used for gear production are metallic and non-metallic. Metallic materials, in turn, are divided into ferrous and non-ferrous alloys [12]. Non-metallic materials, such as thermoplastics and duroplastics, are not applied in vehicle reducers. The application of forged steels is the most common in production of gears with surface or volume hardening.

Surface hardened steels (by chemical heat treatment):

- The carburizing or nitriding steels are used to obtain maximum *wear resistance* of contact surfaces.
- The cementation gears are suitable for heavy duty applications, e.g. in gearboxes, and have high resistance to wear, pitting, and fatigue. The cementation gear provides maximum surface hardness, wear resistance, and bulk impact toughness.
- The surface hardened gears (by chemical heat treatment - CHT) can withstand higher loads than the bulk hardened gears, although the latter are cheaper due to easier heat treatment.

The study presented in [10] has found that surface coating improves the segment life and reduces replacement costs. The motivation for surface innovation in the surface area is to provide practically attractive surfaces. The wide range of coatings can reduce the consumption, degradation and provide wear protection of materials. As for the main disadvantages of surface carburizing (cementation) as a hardening method, they are *the deformations of parts and their cost*.

Volume-hardened steels:

- Volume-hardened steels have higher core strength than cementation steels.
- Compared to surface hardened steels (by CHT), some volume-hardened steels reach comparable hardness values.

However, the volume-hardened parts such as gears *cannot transmit the same force load as cementation wheels*. With volume hardening, *the residual stresses are much more unpredictable*.

Volume-hardened steels with high hardness show *insufficient impact toughness*. To obtain compressive residual stresses of sufficient depth in the volume-hardened steel, it is necessary to implement local thermal hardening such as induction hardening or chemical heat treatment such as nitriding.

Steels must meet two groups of basic requirements: technological requirements in their production (machinability, deformability and thermal susceptibility) and operational requirements (fatigue strength, heat resistance and wear resistance) [8].

Standard ISO 6336-5 [11] defines the boundary material parameters (including requirements of quality control throughout all phases of production). This standard covers both surface and volume hardened gears and gives details about the requirements for the gears of three different quality classes.

The European standard EN 10084 [12] offers a wide variety of steel grades, both with maximum permissible sulfur content and with controlled sulphur content for easier and smoother machining.

The high-strength steels such as DIN 20NiCrMo2, DIN 17CrNiMo6 and DIN 15NiCrMo16-5 are preferred for manufacturing medium-sized and large-sized gears, while DIN 16MnCr5 steel is recommended for small-sized gears.

Having studied the western manufacturers of reducers, it was found that some of the main used materials are steels with the following designations: 20MnCr5, 31CrMoV9, 42CrMo4, etc.

The analysis in [7, 8] shows the newest materials used to manufacture gears – air-hardened steels OvatecTM277 and OvatecTM 677 (self-hardening, martensitic steels).

Table 1 presents the chemical composition of steel grades: 40X, 45XH, 12XH2, 18XГТ, 20MnCr5, 31CrMoV9, 42CrMo4, OvatecTM277 and OvatecTM 677.

Table 1: Chemical Composition of Steels Used to Manufacture Gears

Designation	Standard	Equivalent	C, %	Si, %	Mn, %	P, %	S, %	Cr, %	Mo, %	V, %
40X	GOST 4543	DIN 37Cr4/41	0,36-0,44	0,17-0,37	0,5-0,8	max 0,035	max 0,035	0,8-1,1	-	-
45XH	БДЦ6354-82	EN10083-	0,41 -	0,17 -	0,5 -	max	msx	0,45 -	-	-

		1/A1	0,49	0,37	0,8	0,035	0,035	0,75		
12XH2	БДC6354-82	EN10083-1/A1	0,09 - 0,16	0,17 - 0,37	0,3 - 0,6	max 0,035	max 0,035	0,6 - 0,9	-	-
18XГТ	GOST 4543-71	DIN 20MnCr5	0,17-0,22	0,17-0,37	max 0,3	max 0,035	max 0,035	1-1,3	-	-
20MnCr5	EN10084	GOST 18XГТ	0,17-0,22	max 0,4	1,1-1,4	max 0,025	max 0,035	1-1,3	-	-
31CrMoV9	EN10085	GOST 30H3MΦ	0,27-0,34	max 0,4	0,4-0,7	max 0,025	max 0,035	2,3-2,7	0,15-0,25	0,1-0,2
42CrMo4	EN10083-3	GOST 40HГM	0,38-0,45	max 0,4	0,6-0,9	max 0,025	max 0,035	0,9-1,2	0,15-0,3	
Ovatec TM 277	EN16CrMnNi Mo9-5-2F	-	0,155	0,15	1,3	0,02	0,015	2,2	0,5	0,2
Ovatec TM 677	DIN 100Cr6	-	0,675	1,525	1,45	0,025	0,015	1,1	0,25	0,20

The presence of alloying elements improves the material features in the following way:

- Cr (X-chromium) – improves the mechanical properties, wear resistance, acid resistance and heat resistance of steel.
- Mo (M-molybdenum) – increases the strength properties at high temperatures.
- Mn (G-manganese) – if more than 1%, it increases the strength properties of steel. Being up to 10-15% in austenitic steels, it improves impact toughness and wears resistance.

The main characteristics of specified steels are:

- Structural alloy steel 40X is used in heavy-duty components (shafts, axles, gears, pistons, rods, crankshafts and camshafts, rings, spindles, pins, slats, gears, bolts, half-axles, bushings, screws, etc.). Chromium steel 40X is also used in forged, cold and hot stamped components, and steel products are used to manufacture pipes, tanks, etc. Steel 40X is difficult to weld. The EU equivalents are 37Cr4, 37Cr4KD, 41Cr4, 41Cr4KD, 41CrS, complying with GOST 4543 standard [13].
- Steel 45XH is a structural alloy steel (substitute: 40XH) used to manufacture crankshafts, gears, couplings, bolts, etc. It complies with GOST 4543 standard.
- Steel 12XH2 is a structural alloy steel (substitutes: 20XHP, 20XГHP, 12XH3A, 18XГT, 20XГP) and is used to manufacture shafts, gears and other parts that require high strength, ductility and high surface hardness. It complies with GOST 4543 standard. According to the EU, 15NiCr6 is the equivalent of steel 12XH2.
- Steel 18XГIII is applied to produce improved and cement able parts with a responsible purpose, which require increased strength and viscosity of the core, as well as high surface hardness, operating under the influence of shock loads. The steel is a high-quality structural chromium-manganese steel and meets the standards GOST 4543-71 and TY 14-1-3238-81.
- Steel grade 20MnCr5 is a structural alloy steel, subjected to surface hardening and meeting the requirements of standards ISO 683-3 / EN 10084 [12, 14].
- Grade 42CrMo4 is alloy steel, subjected to quenching and tempering. Rolled steel grade 42CrMo4 is popular in mechanical engineering, used to produce responsible high-strength parts of compressors, turbines, working elements of heavy ground and underground equipment, parts for agricultural machinery produced in compliance with the requirements of DIN EN ISO 683-2 standard [15] (previously - EN 10083-3 [16]). Steel grade 42CrMo4 has low weld ability due to its high sensitivity to cracking.
- The OvatecTM family of steels are designed to provide a strong, easy heat-treatable, with high performance alternatives to the low alloy steels, which nowadays are used for component manufacturing. There are two grades available: OvatecTM277 and OvatecTM677.

- OvatecTM277 is a steel that, after cementing, can be cooled directly from the cementation hardening temperature, avoiding quenching baths and reducing quench deformation and subsequent necessity of machining. OvatecTM277 is of standard quality for bearings but 277T is of the premium bearing grade. OvatecTM277 is a self-hardening (martensitic) steel used for applications with high requirements and is designed for surface hardening (by chemical heat treatment - CHT). It is hardened and easily tempered due to its composition and can replace large part of steels for various engineering applications. The new grade of steel OvatecTM277 [17] is produced according to an innovative metallurgical technology and is widely used by European companies. OvatecTM277 steel is used for responsible gears (gears for wind turbines) [7, 8].

- OvatecTM677 steel is intended for bearings and gears for powerful transmissions. Due to the reduced content of supplied inclusions and fine distribution of oxide inclusions, OvatecTM677 is steel with excellent fatigue strength (especially suitable for gears). By using gas or air hardening, it is possible to reduce deformations, hence: to reduce production costs and improve lab our safety and environment. With its high carbon content, OvatecTM677 enables manufacturing of parts using technologies that are highly competitive to those for production of surface hardened parts (by CHT)

and able to achieve comparable mechanical features (e.g. high hardness comparable to that of surface hardened steels – by CTT) and especially fatigue resistance.

When comparing the chemical composition, it is noted that some steels used according to standards EN, DIN and GOST correspond completely to each other (18XIT and 20MnCr5), while others use identical alloying elements (chromium, manganese, molybdenum, etc.), with a minimal difference in percentage content. Particular attention could be paid to steels OvatecTM277 and OvatecTM677, which are self-hardening (martensitic) steels, used for high-load applications.

The chemical composition of steels determines their mechanical performance and the type of used heat treatments. The indicators, which are important for mechanical strength, are: boundary of yield strength (Re, MPa), tensile strength (Rm, MPa), and relative elongation (A, %). [7, 8].

Table 2 presents the parameters used for comparison.

Table 2: Mechanical characteristics of steels

№	Designation	Re, MPa	Rm, MPa	A, %	Impact toughness, J/cm	HB
1	40X	784	980	10	59	217
2	45XH	640	785	13	59	248-293
3	12XH2	590	780	12	69 - 88	229 - 249
4	18XIT	833	980	9	79	240
5	20MnCr5	690	min800	9	min20	217
6	31CrMoV9	800	1000-1200	10	25-40	248
7	42CrMo4	650	800-1100	12-13	63	241
8	Ovatec TM 277	850	1200	15		190
9	Ovatec TM 677	1450	1550	20	63	220

OvatecTM677 steel shows lower fatigue strength. Additional surface treatment is necessary to increase fatigue life in order to be comparable to cementation steels.

The data in Table 2 (without OvatecTM677 steel) makes possible to establish that there are no major differences in the mechanical strength of materials used. Their mechanical properties are close and it cannot be said that certain grades are much better or recommendable for gear manufacturing.

4. HEAT TREATMENT OF STEELS FOR GEARS

Heat treatment (number, type and duration) determines up to 30% of the cost of manufactured gears. Therefore, it is very important to analyze the differences in technologies, used equipment and peculiarities of heat treatment of different steel grades. [17, 19, 20, 21].

Steels with grades 1 ÷ 7 in Table 1 are heat treated at appropriate temperature and conditions in compliance to БДC EN 10825 [22] and pr БДC EN ISO 683-3:2022/prA1:2024 [14].

The heat treatment peculiarity of steel grade OvatecTM277 is that it is completely hardened and acquires a purely martensitic structure when cooled in air, which reduces deformations due to hardening compared to traditional surface-hardened steels. This allows saving funds from technological operations to remove deformations of hardening. The use of hardening environments such as oils and salts is avoided, thus improving safety and reducing environmental pollution. Carburizing time can be reduced compared to that of traditional surface-hardened steels, since steel OvatecTM277 has an increased carbon content in the base material.

OvatecTM677 can be hardened directly at hot deformation temperatures, which results in new achievements with cold machining, opening up the possibility to create completely new technologies for manufacturing different parts.

Comparing the heat treatment modes, the following important features can be noted:

- the operating temperatures in heating modes of different steel grades overlap and there are none with values that require special furnaces;
- the hardness of gear teeth working surfaces varies in the range of HRC 52-64. High hardness is a major factor for greater efficiency and contact strength of teeth and less wear;
- the steel grade 18XIT is distinguished by very good mechanical performance and hardness of HRC 55-63, but the heat treatment technology requires several cycles to complete the finished part (normalization, carburization, hardening, tempering). This determines a longer cycle of heat treatment and, accordingly, greater energy consumption of the process;
- the type of heat treatment is of great importance. Surface-hardened gears can withstand higher loads than volume-hardened ones, although the latter are cheaper due to easier heat treatment. The main disadvantages of surface carburization (carburization) as a hardening method are the part deformations and the cost. Deformations are controlled as much as possible during heat treatment and finally corrected by fine grinding. The higher product cost is justified from the view point of obtaining a high power-to-weight ratio and high durability;

- attention should be paid to the indicated advantages of OvatecTM277 and OvatecTM677.

5. MEASURING THE WEAR OF GEAR WHEELS IN TRANSMISSION MECHANISM OF ELECTRIC LOCOMOTIVES IN BULGARIA

The transmission mechanism of electric locomotives of series 43/44 and 42/45 has low operational reliability. That problem has been existing for a long time and is related to certain damage to electric locomotives and implementation of their repairs. The damage is mainly reduced to: damage in the cardan coupling, gears, reducer lubrication, noise, vibrations, etc.

Vibrations have an exceptional influence on the occurrence of damage in reducers [22, 24, 25]. They have been studied experimentally, and it has been established that the obtained spectra are close in configuration and can be presented in a generalized case. The amplitudes located in the frequency range of about 4500 Hz belong to the reducer housing. All main types of damage in gears lead to dynamic loading on gears and bearings, and to vibrations in the reduction gearbox, respectively, as 45% of rolling bearings are not repairable [26, 27].

The largest amount of damage was found in the parts related to: the reducer box, the square, the bearings of the driving pinion and the driven large gear wheel [28]. They are the main transmission mechanism components subjected to dynamic load and wear in operation.

The results obtained are useful for assessment of risk and consequences of failures both for improving the quality of repairs and for the operation of transmission mechanism of electric locomotives.

The gears of electric locomotive reducer go out of service mainly due to wear, damage to teeth and destruction of the gear ring [29].

To classify the characteristic damage that occurs in the pinions (driving) and in the large gear wheel (driven) of the reducers, it is necessary to study the defects in three series of electric locomotives. From the observations conducted so far, according to the requirements of БДC ISO 10825 - 43/44, 45, 46 and ZFN 201, the damage of reducer gears [28] have been classified by the following features: surface damage of teeth (wear and peeling); residual deformations (nick-ing); surface fatigue damage (pitting); tears and cracks (hardening cracks or fatigue cracks); tooth breakage (overload fracture or fatigue fracture).

The most common surface damage to pinions and the gear large wheel is the wear of their involute profiles. The amount of this type of damage to pinions is about 3 times greater than to large gear wheels, which confirms the theoretical hypothesis of wear.

It has been experimentally determined that the linear wear of involute tooth profile of a worn pinion and a large gear wheel it is twice as high as the permissible standard values. The maximum error of tooth direction has increased 7 times for a pinion and twice for a large gear wheel. The tooth profile has worn more intensively on one side due to the geometric deviations in rolling bearings, dynamic loading, etc. The grounds for such interpretations are given by the new methods used to calculate rolling bearings, as a result of which it is possible to increase gear efficiency [30].

Another surface damage of teeth, although being less common, is peeling of a pinion [29], which has become obsolete due to peeling on the tooth surface layer. It is caused by: heat stresses, insufficient depth of the hardened surface layer or low strength of the basic metal. Damage may also occur as a result of residual deformations such as chipping. It is characterized by depressions on teeth lateral surfaces, sometimes caused by an unknown body passing in the time of meshing.

One of the most common failures occurring as a result of surface fatigue of wheelset reducer gears is the appearance of pitting. The largest pits are located near the dividing circle, while the smaller ones appear on the surface immediately next to the tooth base. The reasons for progressive pitting are complex, such as errors in the tooth profile, surface roughness and peripheral speed, which are prerequisites for its appearance.

The tears and cracks in gears are due to improper thermal treatment, overstressing or defects in the material. During the manufacturing process of gear blanks by forging, slag or other non-metallic inclusions often appear. That defect is due to improper hardening or structural changes occurring in the core-hardened layer zone of alloyed steels.

Sometimes fatigue cracks also appear, especially in the wheelset reducer large gear wheel.

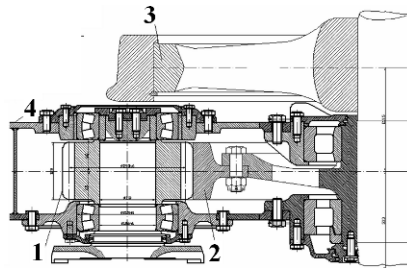
The fracture at the end of pinion and large gear wheel teeth of wheelset reducer is due to load concentration at one of the teeth ends, and sometimes it is caused by intensive pitting formation.

Besides the considered failures of reducer of electric locomotives, damage might also appear during operation as described in БДC ISO 10825 and in the company standard ZFN 201.

The change of tooth profile shape results in deterioration of reducer kinematics. In its turn, that leads to dynamic load increasing, losses due to friction and decrease of efficiency and durability of gears.

5.1. Parameters of Studied Gears

The object of study is a transmission mechanism gear of electric locomotives series 44 and 45, shown in Figure 1.



1 - pinion (driving); 2 - large gear wheel (driven); 3 - wheel axle; 4 – reducer box

Figure 1: The transmission mechanism gear of electric locomotives series 44 and 45

The main geometric parameters, material features and accuracy indicators of transmission mechanism gears of electric locomotives series 44 and 45 are given in Table 3.

Table 3: Parameters of the transmission mechanism gears of electric locomotives series 44 and 45

Parameters	Dimension	Gear for transmission ratio - u			
		u = 3,348		u = 3,591	
		Z ₁ = 23	Z ₂ = 77	Z ₁ = 20	Z ₂ = 79
Module (standard), m	mm	12	12	12	12
Execution module, m _v	mm	12,12	12,12	12,24242	12,24242
Profile angle, α	°	20	20	20	20
Output contour	-	Corrected +9,52	Corrected MAAG-3,3	Involute БДC3296-79	Involute БДC3296-79
Center distance, a _w	mm	606+0,05 47E14-14 Lo 84396	606+0,1 64E16-15 Lo 86116	606±0,05 47E14-2 Lo 83099/b	606 76E16-7 Lo 204256
Width of the tooth crown, b _w	mm	120	120	120	120
Diameter of the pitch circle, d _f	mm	265	887,4	224	933,72
Diameter of the dividing circle, d	mm	276	924	244,85	967,15
Diameter of the apex circle, d _a , d _a	mm	318,6	941,4	274,28	984
Output contour displacement coefficient, x	mm	+0,793	-0,275	+0,5	+0,5
Tolerance of tooth profile error, f _f	μm	16	34	16	34
Tolerance of tooth direction error, F _β	μm	21	40	21	40
Length of the common normal, W _m (number of teeth/length – tolerance)	mm	3/98,94 -0,08/-0,15	9/311,8 -0,15/-0,30	3/96,03 -0,09/-0,17	10/354,51 -0,14/-0,28
Tooth height, h	mm	26,8	27	25,14	25,14
Roundness at the base, R	mm	4	4	4	4
Accuracy level and type of meshing	-	6-6-6B БДC3296-79	7 – C БДC3296-79	6-6-6B БДC3296-79	7 – C БДC3296-79
Material	-	12XH2 БДC6354-82	45XH БДC6354-82	12XH2 БДC6354-82	45XH БДC6354-82
Tensile strength, R _m	MPa	784÷1079	802÷904	784÷1130	802÷904
Yield strength, R _s	MPa	min 539	min 657	min 538	min 657
Relative elongation, A	%	min 8	min 10	min 8	min 10
Minimum shrinkage	%	min 30	min 30	min 30	min 30
Impact toughness KCU2	J/sm ²	39	29	39	29
Surface layer hardness	HRC	56÷60	48÷52	56÷61	48÷52

5.2. Measured Parameters of the Transmission Mechanism Teeth Profile of Electric Locomotives Series 44 and 45

To assess the wear of a transmission mechanism teeth profile, several parameters are usually used, such as tooth thickness S_b, length of the common normal W_m and the hardened layer depth. The assessment of teeth profile wear is carried out by determining the corresponding tooth geometric profile, consisting of a part of involute and transition curve.

The tooth profile image construction is automatically done, using the obtained values of coordinates of the points on it, according to БДC1526-78, by the method described in [31]. The tooth profile geometric structuring and drawing is performed using splines of AutoCAD software. The profile geometry determination is based on software modeling on the principle of cutting teeth with a tooth comb using the centroid rolling method.

The measurements of gear wheel teeth profiles of reducers of electric locomotives series 44 and 45 were made in Sofia Locomotive Depot (Poduene Electric Depot) in the period 01.01.2024-30.06.2025. The results showed that the profile wear was more intense in the sections on the side of electric motor driving the pinion.

The methodology of obtaining a real operating gear tooth profile is based on measuring the thickness of teeth using a caliper with accuracy of 20-50 μm in 12-15 different sections along the teeth height. The deviation of thickness of the measured tooth can be determined measuring a new tooth by a caliper or calculating the thickness with a given section radius using the formula:

$$S_i = m \cdot (d_i / d) \cdot (\pi / 2 + 2\xi \cdot \text{tg} \alpha_0) + d_i (\text{inv} \alpha_0 - \text{inv} \alpha_i) \quad (1)$$

where: m - module; d_i - current diameter, mm; d - diameter of the dividing circle; ξ - overlap coefficient; α_0 - angle of meshing; α_i - current angle of involutes.

Figure 2 shows the change of tooth profile wear of reducer gear wheels of the studied electric locomotives series 44 and 45.

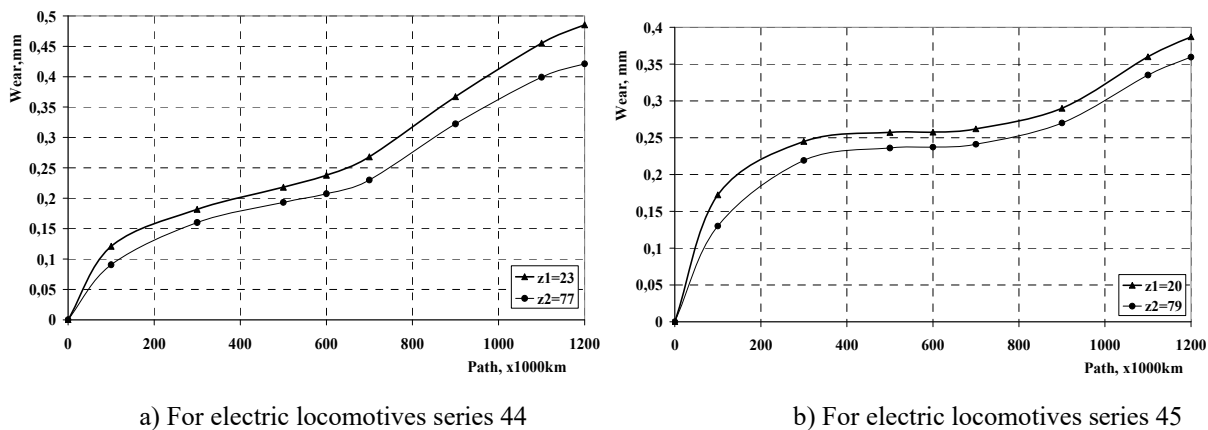


Figure 2: Change of the tooth profile wear of reduction gearbox of the studied electric locomotives

Figure 2 makes possible to draw the following conclusions:

1. The wear of the pinions and large gears of the wheel (LGW) system reducer, as a function of time and mileage, has a practically identical character with a clearly pronounced zone of initial wear during the combined operation of the wheels, a zone of low wear and a zone with a sharp increase in wear.
2. The process of slight wear of the wheel reducer of an electric locomotive series 44 begins at a mileage of 200-300 to 600 thousand km. At a mileage of more than 600 thousand km, wear increases sharply.
3. The nature of the wear of the reduction gears of an electric locomotive series 45 (Fig. 2b) allows us to conclude that the gear has a zone of very low wear at a mileage of 400-800 thousand km, after which it increases sharply.

The average 24-hour mileage of electric locomotives is 400 km and if the estimated work days in a month are 25, then the mileage per month is 10,000 km. Vectors X (time in months or mileage in thousand km) and Y (wear in mm) appear as output data for the MathCad 2000 software product in which the function "submatrix" is used, to construct a polynomial regression at different degrees of the polynomial, used as a regression prediction, with the following data:

$X := \text{data}^{<0>}; Y := \text{data}^{<1>}; n := \text{rows}(\text{data}); n := 5$

Polynomial degree $k := 2$

$z := \text{regress}(X, Y, k); \text{fit} := \text{interp}(z, X, Y, x);$

$\text{coeffs} := \text{submatrix}(z, 3, \text{length}(z) - 1, 0, 0)$

Relative error:

$$R := \frac{\sum \left[\left(\text{fit}(X) - \text{mean}(Y) \right)^2 \right]}{\sum \left[\left(Y - \text{mean}(Y) \right)^2 \right]} \quad R = 0.996$$

$$i := 0 \dots n-1; j := 0.49; tx_i := \min(X) + j \cdot \frac{\max(X) - \min(X)}{50}$$

➤ For electric locomotives series 44

➤ For electric locomotives series 45

data :=	100	0.121
	300	0.181
	600	0.238
	900	0.367
	1100	0.455
coeffs ^T = [1.114 3.359·10 ⁻⁴ 2.897·10 ⁻⁵]		
data :=	100	0.172
	300	0.244
	600	0.258
	900	0.290
	1100	0.360
coeffs ^T = [-0.044 5.905·10 ⁻³ -1.913·10 ⁻⁵]		

The processing of statistical data on wear of gears of electric locomotives series 44 and 45 makes possible to determine the parameters of wear equation:

$$\delta = (\delta_1 + h) \cdot 10^{t/12xA} - h \quad (2)$$

where: δ - wear, mm; δ_1 - mean wear (mileage) t; h - displacement coefficient; A - durability coefficient; t - current mileage. The parameters of equation (2) for electric locomotives series 44 and 45 are given in Table 4.

Table 4: Parameters of the equation for wearing the gears of electric locomotives series 44 and 45

Electric locomotives	Parameters of pinions ($z_1 = 23/20$)			Parameters of large gear wheels ($z_2 = 77/79$)		
	δ_1 , mm	h	A	δ_1 , mm	h	A
Series 44	0.72	0.3	20	0.65	-0.14	6.9
Series 45	0.008	-0.35	-10.9	0.112	0.11	18.742

Formulas (1) and (2) are used to predict the wear of tooth profile of the respective wheel with desired accuracy of results obtained.

The wear equation of pinions ($z_1 = 23$) of an electric locomotive series 44 is:

$$\delta = (0.72 + 0.3) \cdot 10^{t/12 \cdot x^{20}} - 0.3 \quad (3)$$

The wear equation of large gear wheels ($z_2 = 77$) of an electric locomotive series 44 is:

$$\delta = (0.65 - 0.14) \cdot 10^{t/12 \cdot x^{6.9}} + 0.14 \quad (4)$$

The wear equation of pinions ($z_1 = 20$) of an electric locomotive series 45 is:

$$\delta = (0.008 - 0.35) \cdot 10^{t/12 \cdot x^{(-10.9)}} + 0.35 \quad (5)$$

The wear equation of large gear wheels ($z_2 = 79$) of an electric locomotive series 45 is:

$$\delta = (0.112 + 0.11) \cdot 10^{t/12 \cdot x^{18.742}} - 0.11 \quad (6)$$

Figure 3 and 4 shows wear changes of the reducer gear tooth profile of studied electric locomotives with using steels 12XH2 for pinions according to БДЦ6354-82 and 18ХГТ according to GOST 4543-71, and steel grade 45XH for LGW according to БДЦ6354-82. The dependences of gear tooth profile wear as a function of the locomotive mileage are as follows:

- for material steel grade 12XH2 according to БДЦ6354-82 (pinions) and 45XH according to БДЦ6354-82 (LGW)

$$\delta = -2E - 07p^2 + 0.0004p + 0.1483 \quad \text{for } z_1 = 20; \quad \delta = -2E - 07p^2 + 0.0006p + 0.0478 \quad \text{for } z_1 = 23 \quad (7)$$

$$\delta = -1E - 07p^2 + 0.0004p + 0.1206 \quad \text{for } z_2 = 77; \quad \delta = -1E - 07p^2 + 0.0004p + 0.1453 \quad \text{for } z_2 = 79 \quad (8)$$

where: δ - wear, mm and p – locomotive mileage, thousand km.

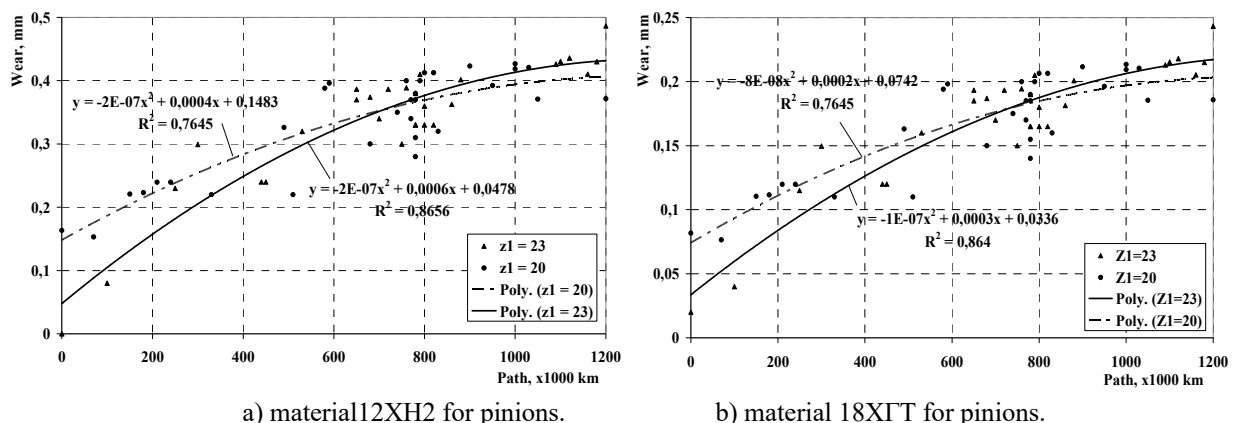


Figure 3: Change of the wear of pinions at a certain locomotive mileage

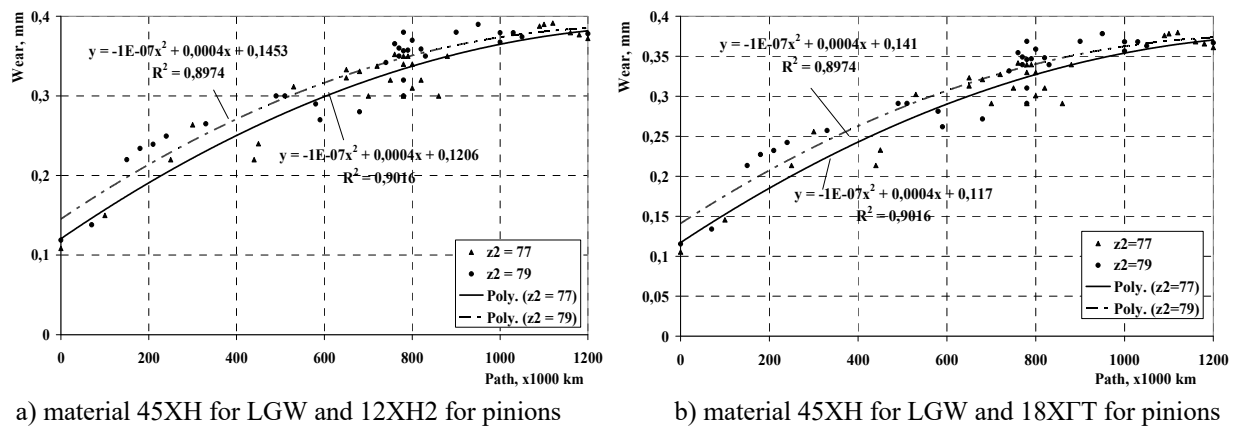


Figure 4: Change of the wear of LGW at a certain locomotive mileage

- for material steel grade 18XIT according to GOST 4543-71 (pinions) and 45XH according to БДC6354-82 (LGW)

$$\delta = -8E - 08p^2 + 0.0002p + 0.0742 \quad \text{за } z_1 = 20; \quad \delta = -1E - 07p^2 + 0.0003p + 0.0336 \quad \text{за } z_1 = 23 \quad (9)$$

$$\delta = -1E - 07p^2 + 0.0004p + 0.117 \quad \text{за } z_2 = 77; \quad \delta = -1E - 07p^2 + 0.0004p + 0.141 \quad \text{за } z_2 = 79 \quad (10)$$

From the obtained dependences (7) ÷ (10) of measured wear of gears, it has been established that the wear of pinions and LGW manufactured from steel grades 18XIT according to GOST 4543-71 (pinions) and 45XH according to БДC6354-82 (LGW), respectively, is two times less than the wear of wheels manufactured of steel grades 12XH2 according to БДC6354-82 (pinions) and 45XH according to БДC6354-82 (LGW). That gives grounds to use 18XHT steel for pinions. The wear of LGW from material 45XH, associated with pinions made of 18XIT steel, decreases by 5%. To increase the reliable operation of gears, in addition to the choice of material and heat treatment, it should be paid attention also to the choice of lubricant [32, 33].

6. CONCLUSION AND RECOMMENDATIONS

The analysis of chemical composition and mechanical features of steels, as well as of technologies for gear processing applied in various types of reducers, has shown that the Bulgarian mechanical engineering companies should keep the following guidelines for manufacturing gears:

Option 1 – to use traditional materials, as for this purpose should change technologies and part of equipment (through modernization) in order to reduce the energy consumption for heat treatments and mechanical processing;

Option 2 – to master the application of new materials and technologies.

It is a good solution to use steel grade 18XIT as main material for gears for general machine-building reducers due to its proven qualities and mastered technologies of mechanical processing and heat treatment. It is necessary to invest in modernization of machines and installations to reduce the production costs and make products more competitive on the market. From measuring the transmission mechanism gear profile of electric locomotives operated in Bulgaria, it was established that the gears of wheelset reducers go out of use mainly due to wear, teeth damage and gear ring destruction.

The analytical dependencies for wear prediction have been obtained as a function of mileage of the respective locomotive. The derived formulas (7) ÷ (10) are recommended to apply for predicting the wear of tooth profile in a probabilistic aspect. To increase the reliability of traction reducers of electric locomotives, the following recommendations for design and production can be given:

- To develop new materials, starting from new self-hardening (martensitic) and air-hardening steels, advanced sintered steels and Nan powders.
- To develop new processes that combine advanced achievements in the field of materials, tools (as design and material), automation, thermal and mechanical processing, innovative additional processing and application of various powder metallurgy methods.

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