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Analysis and recommendations for the minimisation of
material failures

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Abstract

This report has been written with the sole purpose of describing and analyzing the damage of the gears used in the maritime industry as a gear train for an overhead crane. The paper presents examples of materials used in the production of gears, their mechanical and physical properties and the exact justification of their choice. The production process of gears from casting to heat treatment and finishing as well as their design are described. The work is mainly focused on describing the damage in the gears caused by surface fatigue, called pitting. The definition, description and effects of this phenomenon have also been included. Performed non-destructive testing showed the degree of damage to the WD200 gears teeth. Further, the causes and consequences of the failure are described. Finally, recommendations for minimizing material damage caused by pitting are presented, along with an example of one of the tests to see if there is a tooth chip during the operation of the gear.

Introduction

The mechanical transmission/gear train is a mechanical drive used to transfer the rotational motion from the active (driving) shaft to the passive (driven) shaft. The main task of mechanical transmission is to transfer energy from the active shaft to the passive shaft and to change the values of the torque, speed and forces. Gear trains are used in all industries. They are designed to reduce the speed of the propeller shaft and at the same time increase the torque. They were (and still are) used in steam, gas, electric and diesel engines. The gears are the basis of the gear design. The most common are cylindrical gears of various tooth shapes with straight, helical or spherical teeth. Straight toothed helical gears are easier to manufacture. One pair of teeth remains in mesh during operation. Thus, the power transmitted by such transmission is limited.

As Łazarz (2011) wrote in his article about gear trains the gears and bearings are the most susceptible to damage. Modern methods of diagnosing gears are aimed at detecting the early stages of the development of damage such as chipping the top of the tooth, cracking the tooth at the base, fatigue chipping of the surface layer, seizure of mating surfaces and other. In diagnosing rolling bearings, it is very important to detect the initial stages of damage to the raceways and rolling elements. A heavily loaded transmission should be temporarily or continuously monitored to ensure safe operation.

Material selection for gear trains

The selection of the type of material used in the construction of gear trains has a decisive influence on its dimensions, durability, weight and price.

In the process of designing a gear train, it is necessary to choose between two aspects: technical and economic and find a solution that meets the assumed criteria.

By using more expensive, but more durable materials, also improved by thermal or thermo-chemical treatment, it is possible to reduce the overall dimensions and weight of the device and significantly increase its durability. However, this results in a significant increase in the production costs of individual components.

Making the gears cheaper means a component with large dimensions, weight and relatively lower durability.

From the point of view of production companies, the most advantageous solution is a compact structure with low weight, with adequate strength, durability and affordable price.

One of the most popular materials used in the production of gear wheels are alloy steels. The table below shows the properties of a few alloy steels used for gears (O Stali Metalach, 2019).

Table 1 Material properties (Phuciennik and Maciejczyk, 2017)

		C45	17CrMoV5	30CrV9	37Cr4
Tensile strength limit	S_u	640 MPa	800 MPa	800 MPa	1570 MPa
Yield point	S_y	390 MPa	500 MPa	600 MPa	1350 MPa
Modulus of elasticity	E	206000 MPa	206000 MPa	206000 MPa	206000 MPa
Poisson factor	μ	0,300	0,300	0,300	0,300
Fatigue strength in bending	σ_{Flim}	410,0 MPa	414,0 MPa	705,0 MPa	740,0 MPa
Fatigue strength in contact	σ_{Hlim}	520,0 MPa	615,0 MPa	1180,0 MPa	1288,0 MPa
Hardness in the tooth core	JHV	210	210	210	210
Hardness on the side of the tooth	VHV	800	615	800	615
The basic number of cycles in bending	N_{Flim}	3000000	3000000	3000000	3000000
The basic number of cycles in contact	N_{Hlim}	50000000	50000000	100000000	100000000

Calculations made by Płuciennik and Maciejczyk (2017) show that when materials with better mechanical properties are used, the mass drops significantly. For extreme values, there is a difference of over 20 kg (Table 2). It means that e.g. a wheel made of 37Cr4 material is over 3 times lighter than that made of 17CrMoV5 material.

Table 2 Basic (calculated) transmission parameters (Płuciennik and Maciejczyk, 2017)

		C45		17CrMoV5		30CrV9		37Cr4	
Gear ratio	-	4,353		4,4		4,4		4,4	
Axis distance	[mm]	250		224		224		224	
Working pressure angle	[°]	19,842		20,861		20,681		20,861	
Contact ratio	-	1,6719		1,6016		1,6016		1,6016	
X-axis parallelism boundary deviation	[mm]	0,014		0,012		0,0095		0,0095	
Y-axis parallelism boundary deviation	[mm]	0,007		0,006		0,0047		0,0047	
Number of teeth	-	17	74	15	66	15	66	15	66
Unit correction	[mm]	0	-0,045	0	0,232	0	0,232	0	0,232
Tooth length	[mm]	50	50	40	40	10	10	10	10
Beheading of the tooth	[mm]	0,00 02	0,0002	0,0047	0,0047	0,0047	0,0047	0,0047	0,0047
Vertex pressure angle	[°]	32,7 7	23,64	33,94	25,04	33,94	25,04	33,94	25,04
Gear weight	[kg]	29,671		27,553		8,47		7,85	

As the materials change, the dimensions of the gears, and thus the entire transmission, also change. When a material with better properties is used, the tooth length (rim width) is reduced. For C45 material, the tooth length is 50 mm, for 17CrMoV5 - 40 mm, and for 30CrV9 and 37Cr4 materials, only 10 mm.

The choice of material also affects the operating time of the gearbox. In this respect, the 30CrV9 and 37Cr4 materials perform best, for which the basic number of load cycles in the contact is 10 million. Heat treatment is essential for the quality of the gears made. C45 structural steel and 17CrMoV5 steel are heat-hardened steels, 30CrV9 steel is nitrided steel, while 37Cr4 steel is nitrocarbonated steel.

Heat treatment has a positive effect on the workpiece, increases its hardness and strength, but at the same time increases the costs of manufacturing the gear.

For devices such as gear trains, weight and dimensions are not always decisive parameters. From the point of view of design assumptions and operating conditions, the most optimal material of the above for the production of gears is the heat-hardened 17CrMoV5 steel alloy, combining good strength and durability, reduced dimensions and a compromise price.

Gear manufacturing process

Gears for general use are commonly mass-produced by die casting. Then by hobbing are produced smooth and accurate gear teeth. Shaving and hardening are finishing operations carried out to improve dimensional accuracy, surface finish and hardness. Shaving uses high precision tools to remove small amounts of material to correct profile errors. Finally, the grinding operation produces a high surface finish, correcting any distortion following heat treatment. The grinding method is determined by the shape and the module of the gear (Norton Saint-Gobain Abrasives). Continuous gear generation, profile grinding, bevel gear grinding, and power honing are the most common grinding processes in gear grinding.

Power-honing is an increasingly popular process in the production of gears and shafts for gear trains. Power honing is a final process where gears are finished after hobbing and heat-treating. Gear flanks are ground in the internal diameter of a honing ring, generating a typical surface structure, improving lubrication, and resulting in quieter gear transmission (Norton Saint-Gobain Abrasives).

Surface roughness is one of the most important factors affecting the lubrication of gears (Lundberg, 1995). In the contact areas of the tooth flanks, poor surface roughness contributes to friction and can cause pitting fatigue. A poor tooth surface finish can deteriorate the lubrication resulting in the welding and seizing of the teeth. Reducing the surface roughness reduces the amount of damage (Evans, Snidle and Sharif, 2009), because less unevenness will penetrate the lubricating film. In the non-contact area of the root, the surface roughness contributes to the risk of cracks initiating bending fatigue damage.

Analysis of the damage to the gear train

This work focuses on the analysis and recommendations for the minimization of material failure of gear train WD200 (Figure 1), which is widely used in the maritime and agricultural industries (all the WD200 gear train data are included in the appendix).

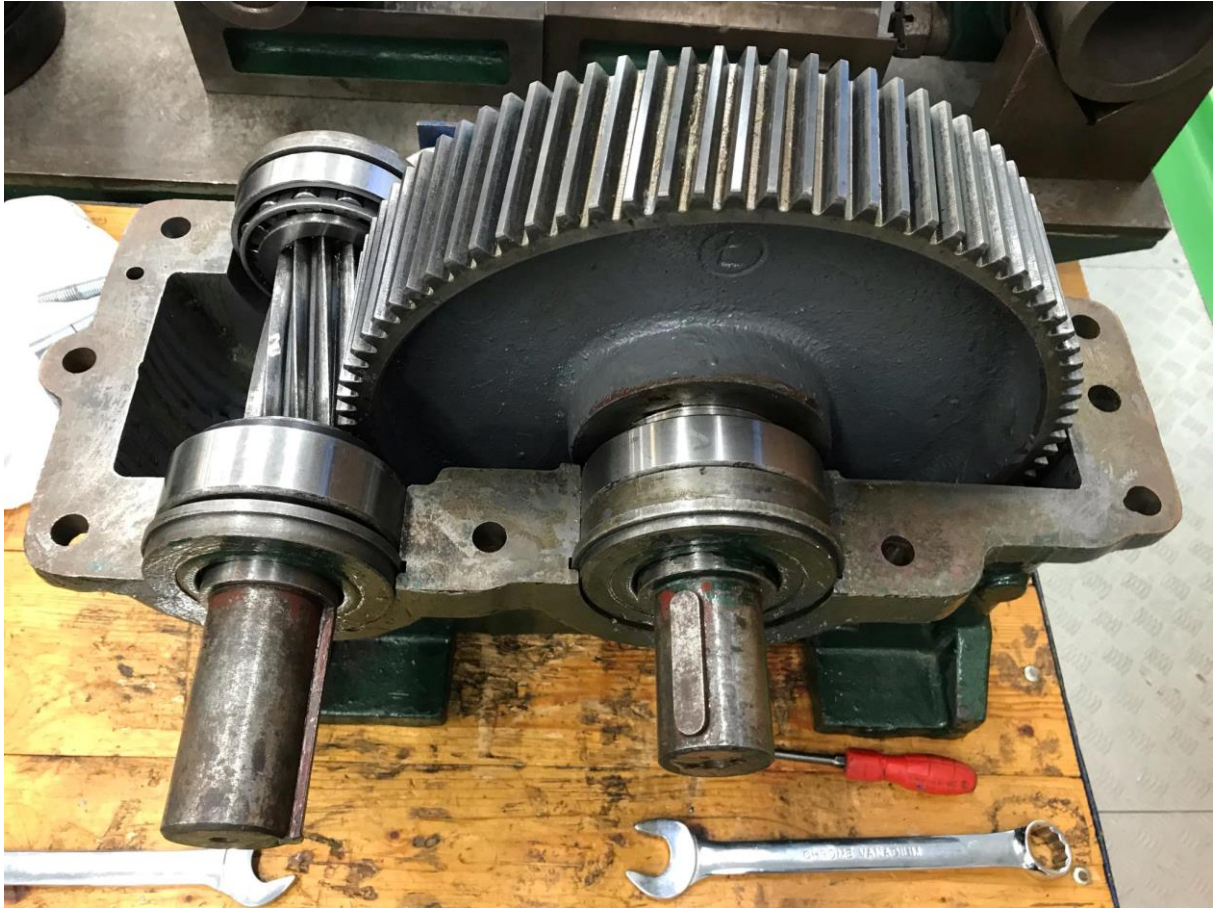


Figure 1 Gear train WD200

The analysed gear train comes from an overhead crane operating in the Gdańsk shipyard. The transmission was driven by a 100 kW electric motor connected via a gear clutch. Thanks to the appropriate transmission of the output shaft with a clutch, it set the crane wheel in motion.

The WD200 series helical gear train consists of a divided, rigid closed housing, in which gears are mounted in rolling bearings. The housing is also an oil reservoir. The gears and bearings are lubricated with oil splashed by the rotating parts of the gearbox. The gearbox is cast from 17CrMoV5 steel and finished with tooth grinding in indexing form, like on Figure 2.

The reason for the uncertainty related to the operation of the transmission was the increased noise of the entire device.

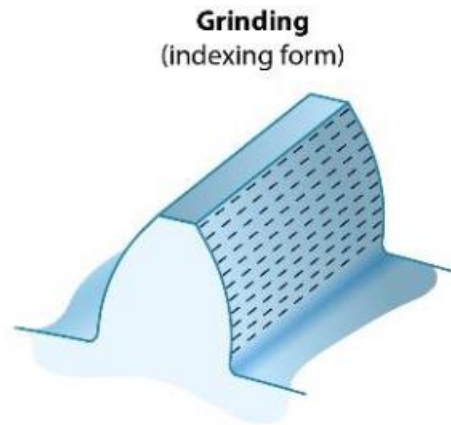


Figure 2 Grinding in indexing form (Sun, Lancaster and Giusca, 2017)

Analysing and diagnosing gear failures is all about recognizing the visual and audible signs associated with typical failure modes.

The first step is therefore to perform a careful inspection of the failed gear pair and their associated bearings.

Care must be taken to ensure the real root cause is found as more than one failure mechanism can sometimes lead to superficially similar damage. It is important to note that nearly 50% of all gear failures are a result of their bearings and supporting arrangement (Neale Consulting Engineers, 2016).

The first test after disassembling the cover was to check the bearing clearances. Slight backlashes were detected in the bearings of the shafts of both wheels. Then the penetrant test was used to test the surface damage of the teeth. Small cavities were observed on the surface of the teeth as shown in Figure 2. Another study was measurements made using a lathe and a dial indicator. The measurements did not show any disturbing results, all dimensions were within the acceptable limits. Measurements and results are included in the appendix.

Such defects were likely due to fatigue damage to the surface due to cyclic contact stress carried by a lubricating film that is in or near the elastohydrodynamic (EHL) regime (Machine Design, 2007). Such a phenomenon is called pitting or, in the case of smaller defects - micropitting (as Sun (2017) presented in his work with a depth of about $10\mu\text{m}$ - $20\mu\text{m}$).

Pitting is one of the most common causes of gear failure. It also affects antifriction bearings, cams and other machine components where surfaces undergo rolling/sliding contact under heavy load. When the mating gears are of the same material and heat-treated, pitting is expected

first on the gear with fewer teeth (small wheel- Figure 4) because it sees a greater number of load cycles (Machine Design, 2007).

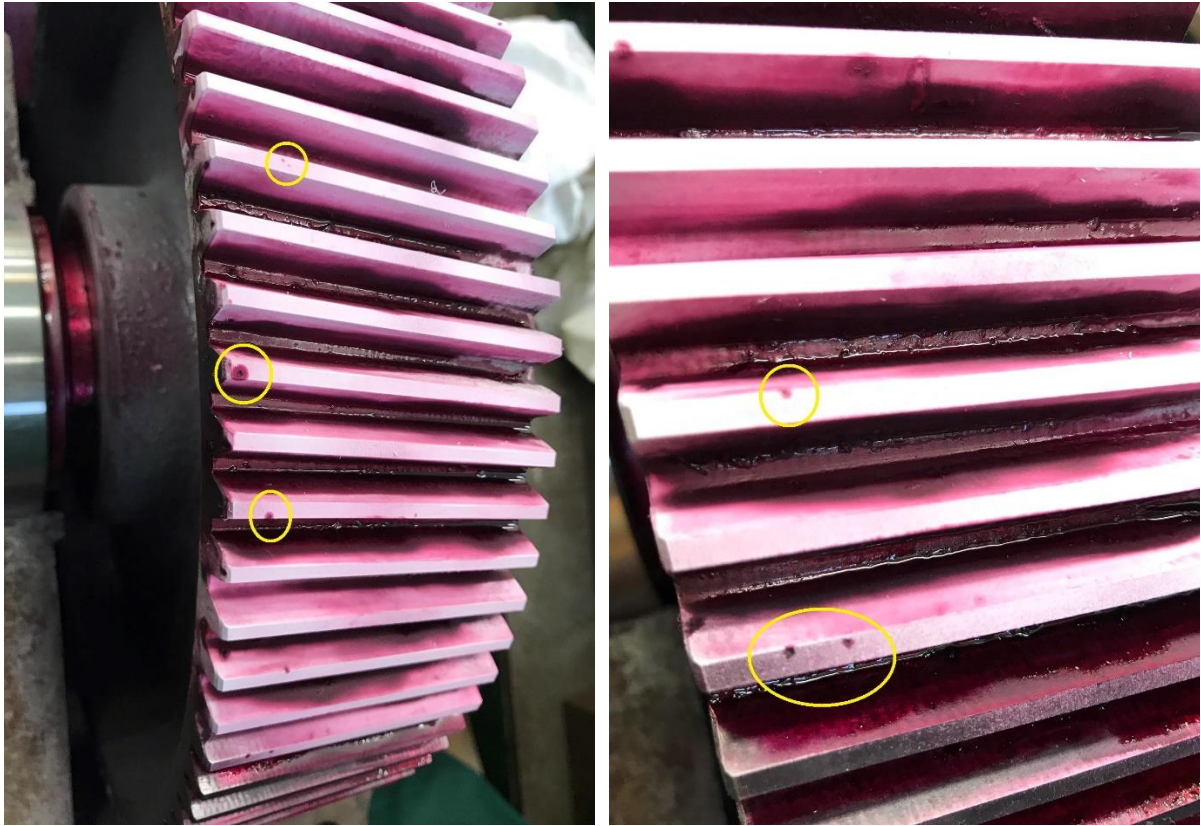


Figure 3 Pitting on WD200 driven gear

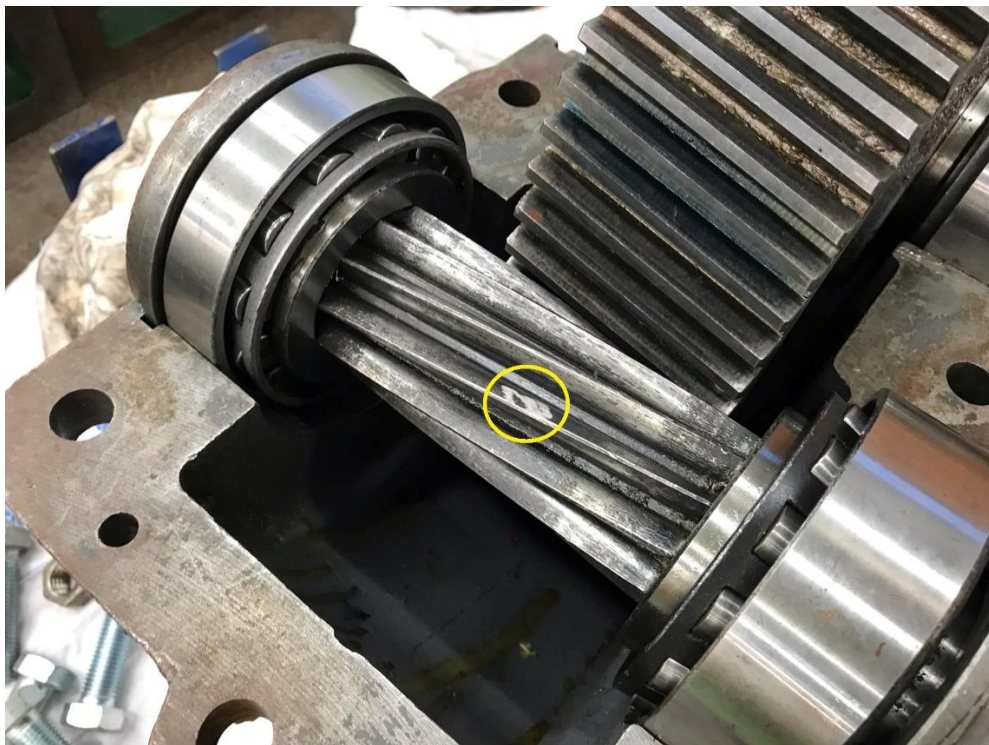


Figure 4 Expanded pitting on WD200 driving gear

Pitting starts with the nucleation of subsurface or surface-breaking cracks, then propagates under repeated contact loading. Eventually, a crack grows large enough to become unstable and reach the tooth surface. There, a small volume of material separates, leaving a pit about 250 μm deep (Machine Design, 2007). A large pitting-damaged area (Figure 5) can modify the tooth profile, an excessive increase in temperature at the gear device, an increase of smear by lubricant, an increase of backlash, trigger vibrations and audible noise (KHK Stock Gears). This type of failure happens in both through-hardened and surface-hardened gears, though the latter often exhibit micropitting.

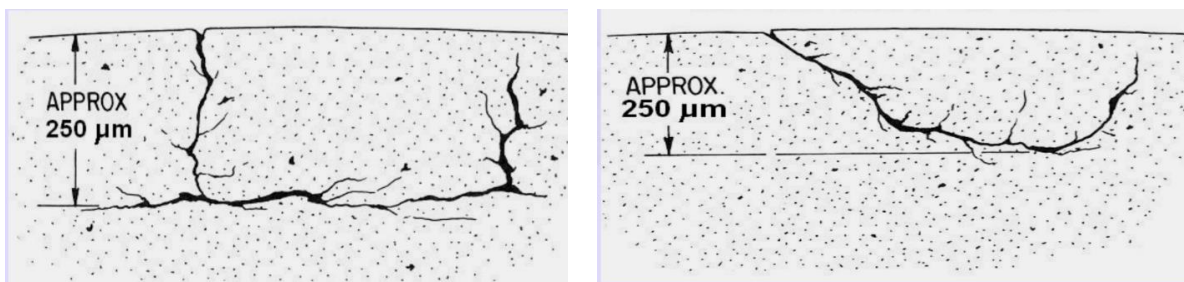


Figure 5 Pitting-Surface origin failure (Gearsmechon, 2018)

Since both gears were made of the same material, the pitting started first on the smallest gear wheel which has the greater friction work of the teeth per unit time and extends to the tooth as shown in Figure 5. Then propagation on the large wheel began, as observed the defects were not very large and were only on the tooth's forehead, so they probably did not affect the operation of the system yet.

On the other hand, the spreading pits of the small wheel overbalanced the entire shaft-gear system, which caused runout, resulting in bearing failure. Therefore, the noise was generated by pitting and, in addition, bearing failure. Both wheels were made of 17CrMoV5 alloy steel, the basic number of cycles in contact for this material is 50'000'000 as given in Table 1.

The gearbox worked at its stand for many years without failures. Therefore, surface fatigue occurred as a result of exceeding the permissible number of cycles for a given material. The damage will propagate, removing the metal that will thin the teeth and disrupt the load sharing between the teeth, greatly increasing noise and vibration. Additionally, macro-pitting all over the teeth with considerable grosspitting. The teeth will be so thinned by the wear that the tips will become sharp as a knife (Liang, 2017).

Such gears, unfortunately, are not suitable for further work. In the next section, methods are presented to reduce pitting and extend the duty cycle of the transmission.

Recommendations for the minimisation of material failures

WC/C Coating

The use of coatings on gears gives many benefits, including an increase in seizure resistance, a drop in gear temperature, or an increase in gear efficiency (Michalczewski et al. 2004). In the conditions of friction of highly loaded machine elements, it is possible to replace the tribological functions of lubricants. With the use of a suitably selected thin PVD coating with a thickness falling within the dimensional tolerance of these elements (Michalczewski, 2002). The latest results of model studies prove that only in the case of low-friction coatings (WC/C) the fatigue life of friction junctions can be similar to that of uncoated junctions (Piekoszewski, 2011). At the same time, it has been observed that when coatings are used, it is not always advantageous to apply the coating to both cooperating elements (Michalczewski, 2002).

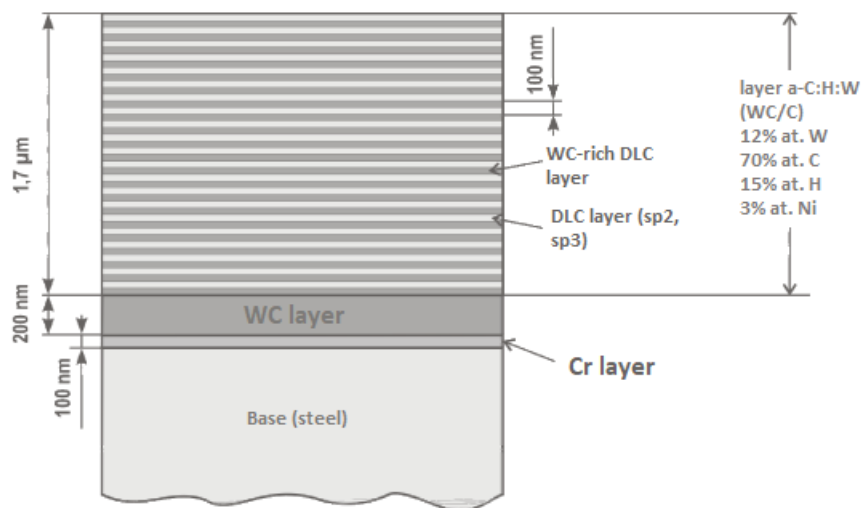


Figure 6 Design of the WC/C coating (Michalczewski et al. 2007)

The WC/C coating consists of three layers (Figure 5). A layer of Cr with a thickness of 100 nm is deposited on the steel base. It is an interlayer that improves the adhesion of the WC to the steel substrate (Kalin and Vižintin, 2005). Hard tungsten carbide WC (approx. 200 nm thick) is responsible for transferring high pressures and, if the outer layer is rubbed, protects the substrate against abrasion. The external layer is responsible for interaction with the cooperating element. Its atomic composition measured by secondary ion mass spectrometry (SIMS) is 12% W, 70% C, 15% H, 3% Ni (Mercer et al. 2003). It is a multilayer, cyclically repeated (every 100 nm) structure (commonly known as WC/C), which includes a WC-rich DLC layer and a DLC layer. WC occurs in the form of nanocrystals with a diameter of approx. 2 nm, randomly distributed

in the DLC layer (Jiang et al. 2003). The presence of nickel is due to the technological process. The outer layer of the WC/C coating in the process of friction with the steel element shows a low coefficient of friction. Good anti-friction properties are due to the high content of amorphous carbon (sp^2). The internal stress of the coating is compressive and amounts to 900 MPa (Krantz et al. 2003).

Research conducted by Michalczewski et al. (2007) for four variants of material combinations of gears proves the influence of the coating on the service life of the gear, depending on the configuration.

The test consisted in running the test gear under the same conditions, at a constant rotational speed, constant load and at a constant, controlled temperature of the tested oil, until the fatigue cracking was found, visually assessed by measuring the surface area of the breakage on the most damaged small wheel tooth. The research was carried out until pitting occurred.

The results of gear tests for the applied material configurations of wheels with WC/C coating are presented in Figure 6, and the working surface of gear teeth for the tested material configurations of wheels with WC/C coating is presented in Figure 7.

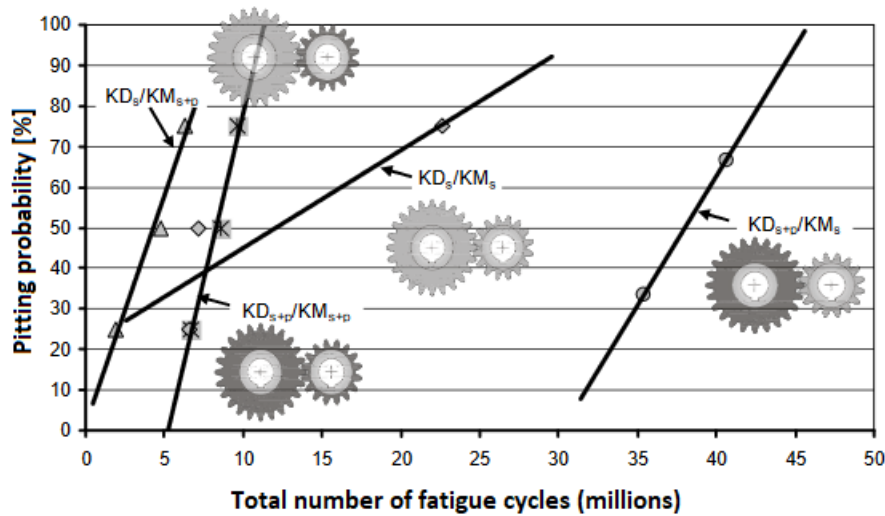


Figure 7 The probability of pitting failure for investigated gears with WC/C coating (Michalczewski et al. 2007)

Where:

KD_s – Big wheel not coated,

KD_{s+D} – Big wheel coated,

KM_s – Small wheel not coated,

KM_{s+D} - Small wheel coated,

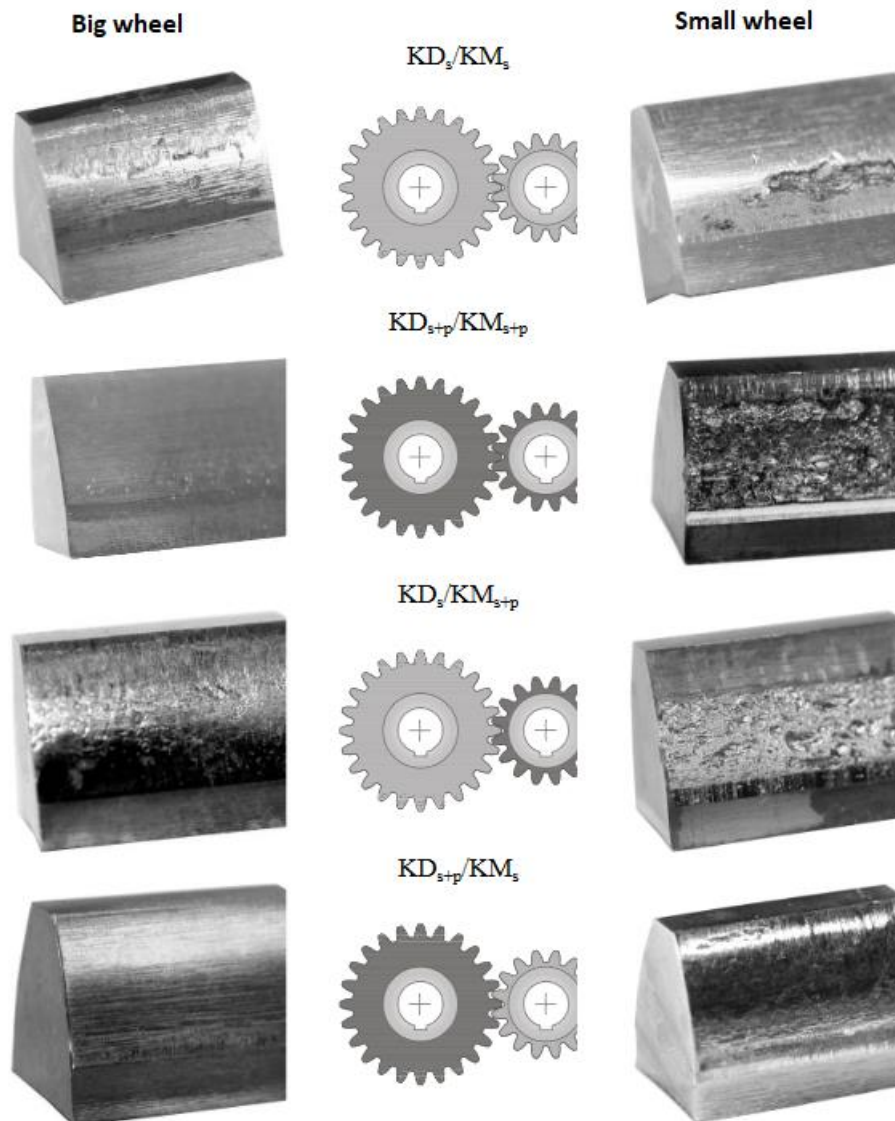


Figure 8 The surface of teeth for investigated gears with WC/C coating (Michalczewski et al. 2007)

The conducted tests clearly show that the pitting resistance of the coated gear elements depends not only on the type of coating but also on the choice of the coated element. Many unsuccessful attempts to apply thin anti-wear coatings to highly loaded lubricated friction junctions may have failed due to the coating of both mating elements, which significantly improved the seizing resistance, but was the worst choice in terms of pitting resistance. Also, coating a wheel with a greater tooth friction work per unit time (large wheel) in relation to the obtained results is incorrect.

The obtained test results indicate that to increase the pitting resistance of the gear wheels, the coating should be applied only to the gear for which the tooth friction work per unit of gear operation time is smaller (large gear). Overcoming the barrier of insufficient pitting resistance of combinations with coatings is of great practical importance, as it allows to obtain better technical effects than in the case of classic solutions, while significantly reducing the negative impact of toxic lubricating additives on the natural environment, as well as obtaining, thanks to the increased durability of machines, significant economic effects (Michalczewski et al. 2008).

Superfinishing

Superfinishing is another material finishing process commonly used to finish the surface of gears, transmission gears and shafts, bearings, cams and followers, journals and seal faces (Curtis-Wright). This process uses small polishing stones that are suspended in the medium and vibrate in the bath with the workpiece (gears) to remove any sanding marks. Typically, this process is accelerated by the use of chemicals and must be tailored to each application to optimize the time needed and media volume. The shape of the involute means that the effect of the superfinishing process varies in both the profile and the width of the face of each tooth and may not be consistent between the teeth (Sun, Lancaster and Giusca, 2017). The Figure below shows superfinished tooth surface.

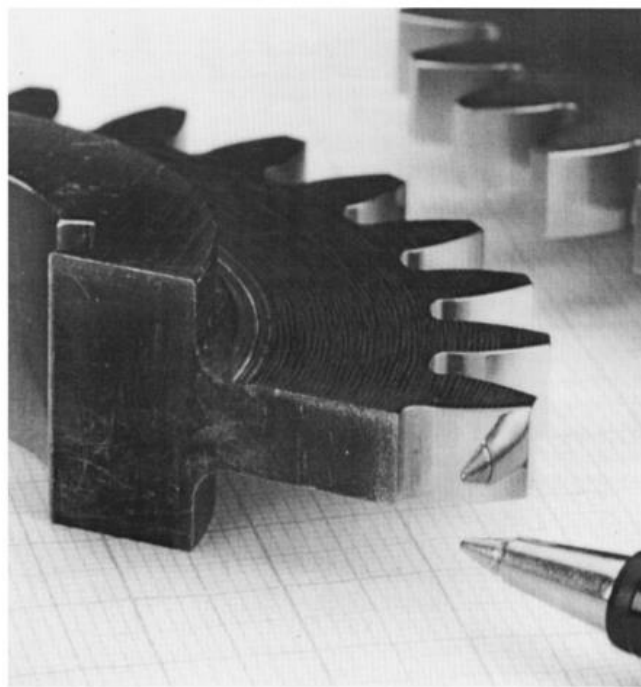


Figure 9 Near-mirror quality of superfinished tooth surface (Krantz et al. 2001)

The surface texture of gear plays an important role in many aspects of gear behaviour. It has been observed that gear lifetime increases when gears are superfinished to improve their surface texture (Krantz et al. 2001). The frictional torque exerted on a gear can drop significantly as the surface texture improves (Britton et al. 2000), which is accompanied by a drop in the bulk temperature of the gear tooth and a small increase in efficiency. Increased efficiency after polishing is widely reported. The noise generated by the gears is linked to the surface waviness (Sundar et al. 2013).

Recent fatigue testing of gears in the ground and superfinished state (Krantz et al. 2001) shows the benefit to be obtained in terms of pitting life by superfinishing. Figure 8 is a Weibull plot comparing the performance of hardened, ground steel gears (mean $R_a = 0.38 \mu\text{m}$) with superfinished gears (mean $R_a = 0.07 \mu\text{m}$) of the same material. The lives of the gears with superfinished teeth in this programme were found to be about four times greater than those of the ground gears.

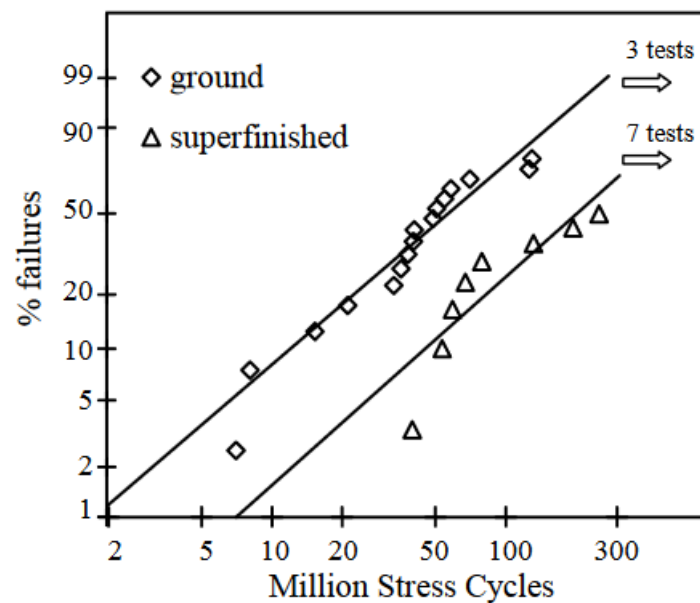


Figure 10 Results of micropitting fatigue tests on ground and superfinished gear (Snidle et al. 2003)

Early fault detection of toothed gear in exploitation conditions

Toothed gears are commonly used in various power transmission systems. During their exploitation, it is very important to obtain information about the progressing degradation processes early enough. This allows the necessary maintenance and repairs to be planned in suitable time, thus increasing the reliability of all kinematic chain elements. Techniques for diagnosing the technical condition of gears are aimed at identifying damage in the initial stage.

One of the most frequently used methods is the measurement of the vibroacoustic signal and on its basis determining the measures sensitive to various types of damage. The rate of propagation of vibroacoustic disturbances caused by the change of the gear condition makes vibroacoustic methods particularly useful in diagnosing early stages of damage.

The initial phases of the tooth crest chipping in the toothed gear do not have a significant impact on the overall vibration level. Hence, the detection of this type of damage at an early stage is very difficult.

The research conducted so far shows that the use of non-contact laser measurement of the transverse vibration speed of the rotating shafts of the gear train combined with advanced signal processing methods such as the Wigner-Ville distribution (WV) or the continuous wavelet transform (CWT) enables the detection of this damage in its initial stages. This method of measurement eliminates the influence of the complex transmittance of the bearing-gear casing system (Łazarz, Wojnar and Czech, 2007).

Figure 11 shows the processing of the recorded vibration signal. In the time and frequency analysis WV distribution, there is an increase in amplitude over the angle of rotation of the pinion corresponding to the cooperation of the damaged tooth.

Based on the graphs, it can be concluded that the processing of the signal of the speed of transverse vibrations of shafts, measured in the direction of the force between the teeth and the use of analyzes simultaneously in the fields of time and frequency or time and scale (CWT), allows for effective detection of tooth tip chipping (Łazarz, Wojnar and Czech, 2007).

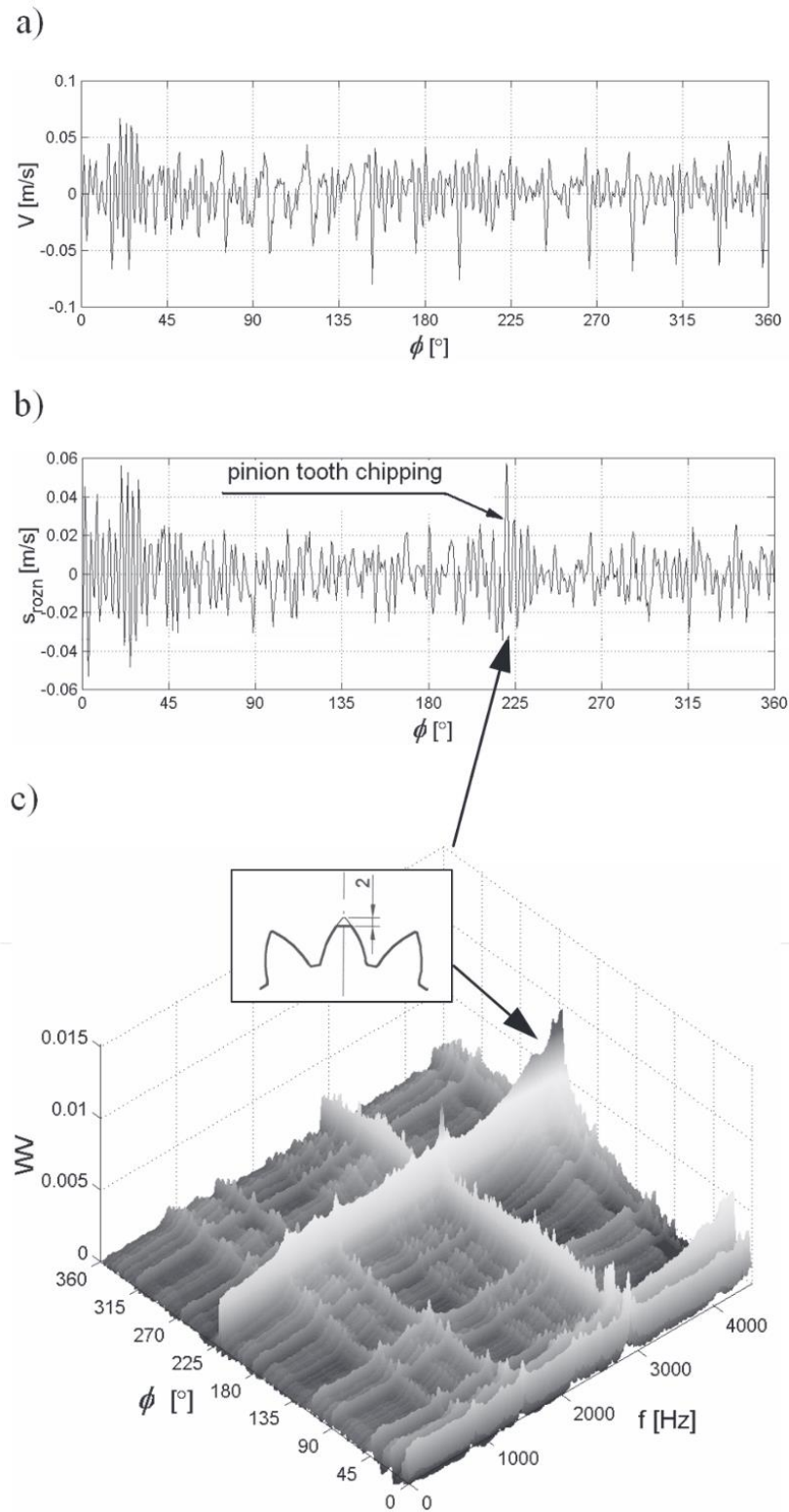


Figure 11 Chip of the pinion tooth – 2 mm (contact ratio $\varepsilon\alpha = 1,08$): measurement of vibration speed of pinion shaft in the direction of the force acting between the teeth (a), differential signal (b), WV Time/frequency distribution of differential signal (c) (Łazarz, Wojnar and Czech, 2011)

Discussion

Gear transmissions are very useful and commonly used devices in most of the world's industries. Their trouble-free operation may affect human health and safety, which is why a very important aspect is taking care of their proper and failure-free functioning. For this to be the case, it is necessary to ensure the appropriate design and selection of materials for the production of their components. Thanks to the use of appropriate mechanical and heat treatment, the transmission components, such as gears and bearings, will withstand long-term operation under high pressure and speeds. Additionally, the application of coatings to the relevant gear parts can minimize the occurrence of surface fatigue which leads to tooth chipping. Unfortunately, such uses may turn out to be short-term. The best way to keep the transmission in safe working order is to periodically inspect and observe the equipment. This behavior will allow to detect the slightest damage, and thus a quick response and possible quick repair of the gear train.

Conclusion

The report presents:

- The purpose of gear trains and their design,
- The listed potential damage that may appear on the gear wheel,
- Examples of materials used in the production of gears and the exact justification of their choice,
- Production process of gears starting from casting and finishing with surface finishing,
- The definition, description and effects of surface fatigue - pitting,
- Performed non-destructive testing showing the degree of damage to the WD200 gears teeth,
- Verification of gears damage, measurements of gears, measurements of clearance between gears, measurements of shafts and their runout (attached in appendix),
- The causes and effects of the WD200 gear train damage,
- Recommendations for minimizing material damage caused by pitting,
- One of the most common methods of premature detection of tooth chipping,

The report has been constructed to show the basics of component failure analysis. Only a small number of ways to minimize fatigue damage are presented in this paper, and there are many more. Gears are a very broad topic and there are still many aspects that should be considered. For example thermo-chemical treatment or a more careful consideration of their design in terms of teeth and their finishing.

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Appendices

Verification card for WD200 gear train

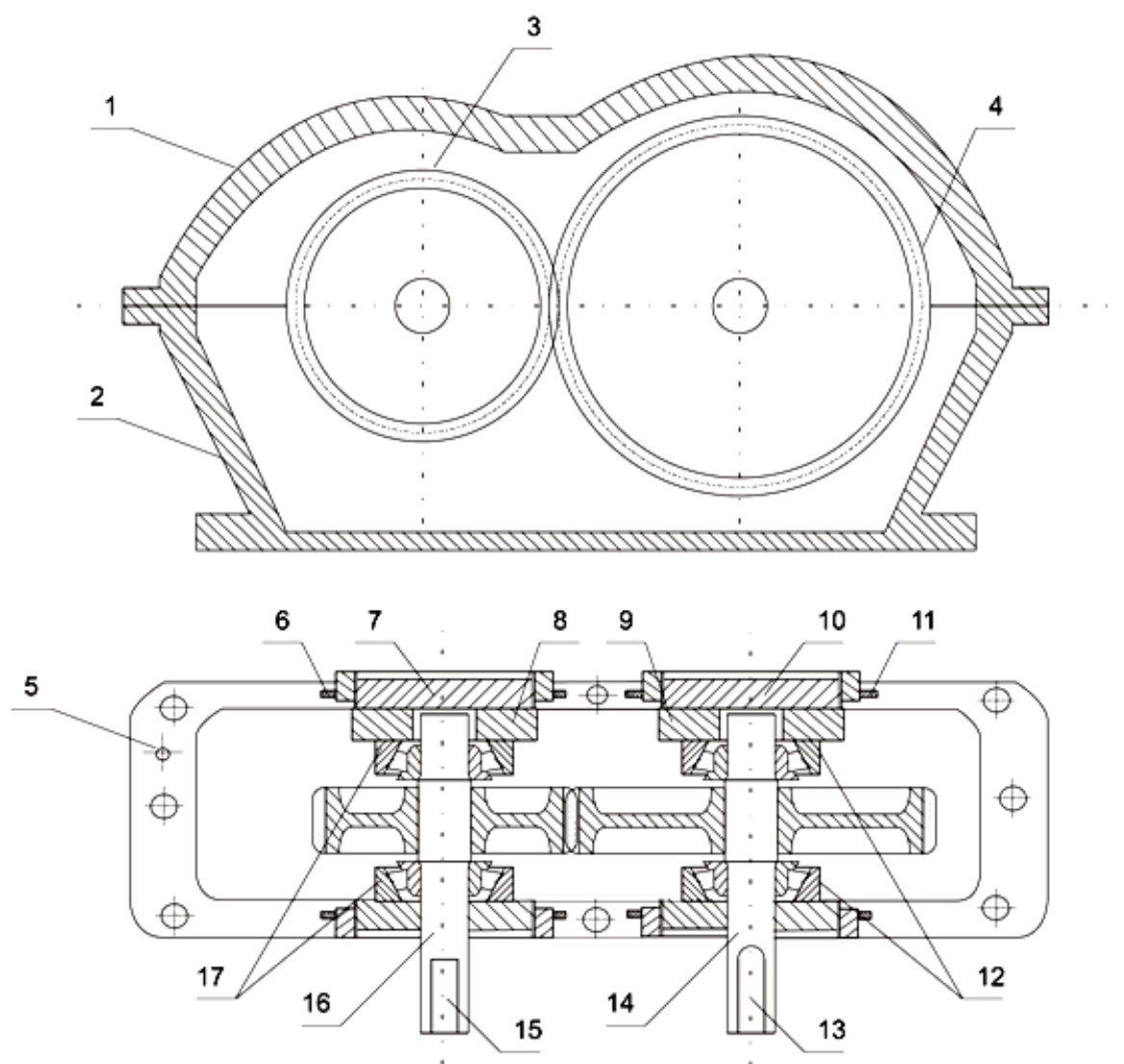


Figure 12 WD200 gear train construction (Befared S.A.)

Table 3 Verification card for WD200 gear train

no.	Part name	Material	Comments:
1	Cover	Cast iron EN-GJL-350 EN-JIL1060	Corosion
2	Body	Cast iron EN-GJL-350 EN-JIL1060	No damage
3	Driving wheel	Heat-hardened, 17CrMoV5	Tooth wear (pitting)
4	Driven wheel	Heat-hardened, 17CrMoV5	Tooth wear (pitting)
5	Locating pin	17CrMoV5	No damage
6	locating sleeve	X6Cr17	No damage
7	Pressing cover	X6Cr17	Slight corrosion
8	Pressure sleeve	X6Cr17	No damage
9	Pressure sleeve	X6Cr17	No damage
10	Pressing cover	X6Cr17	No damage
11	Retaining sleeve	Cast iron EN-GJL-350 EN-JIL1060	No damage
12	Bearings 32213	100Cr6	Backlash
13	Joggle B 14x10x100	X6Cr17	No damage
14	Driven shaft	X6Cr17E H4	No damage
15	Joggle A 14x12x63	X6Cr17	No damage
16	Driving shaft	X6Cr17E H4	No damage
17	Bearings 32210	100Cr6	Backlash

Shaft measurements

Measure wheel diameters and axle distances with a caliper.

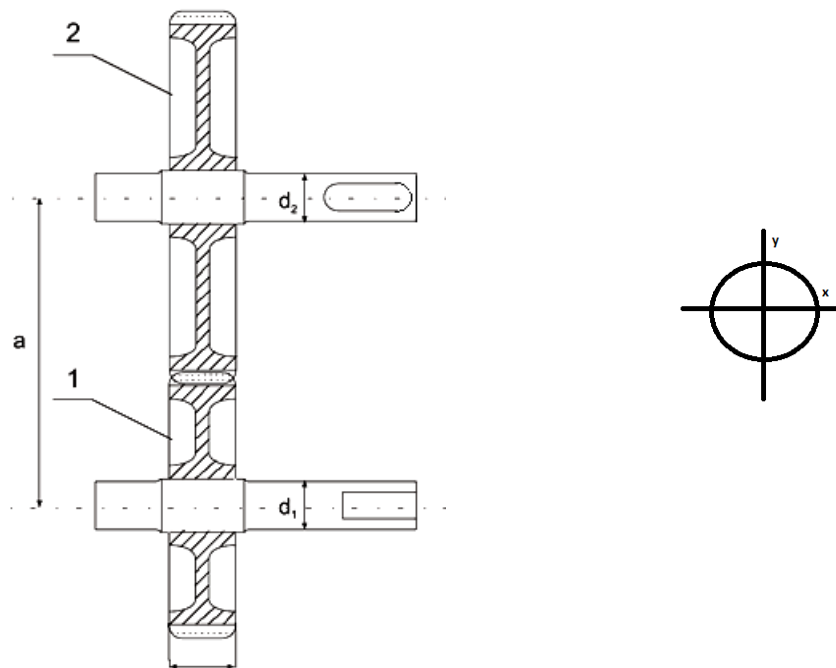


Figure 13 Shaft dimensions (Befared S.A.)

Table 4 Shaft measurement results

	Driving shaft	Driven shaft
Shaft diameter d_1 / d_2 [mm]	50,05	50,05
Distance between the axes "a" [mm]	200,00	

Gear measurements

Measure the axle wheel diameter with a calliper. Tooth and module measurements are made with a modular calliper.

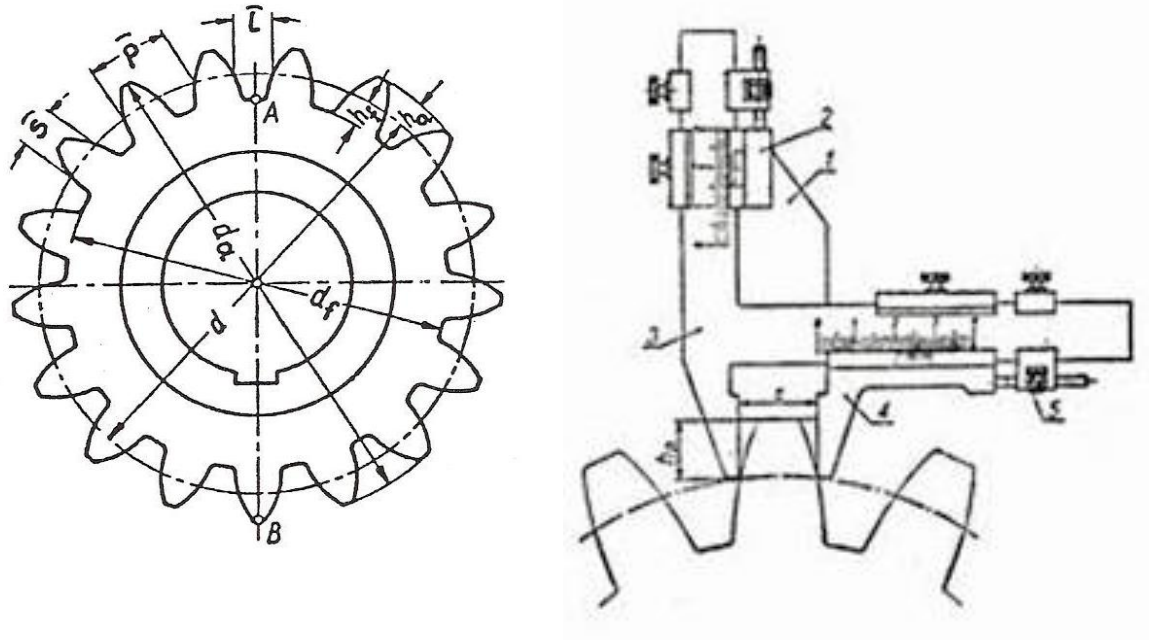


Figure 14 Gear tooth measurements (Befared S.A.)

Table 5 Gear measurements for WD200

no.	Measured quantities	Symbol	Driving wheel (small)	Driven wheel (big)
1	Top diameter [mm]	d_a	56,3	359
2	Pitch diameter [mm]	d	47,3	358,1
3	Feet diameter [mm]	d_f	38,7	357,2
4	Tooth foot height [mm]	h_f	9	9
5	Peripheral pitch [mm]	p	12,5	9
6	The distance between the teeth [mm]	e	9,7	8,5
7	Tooth width [mm]	s	6,6	6,9
8	Tooth head height [mm]	h_a	4,2	9,2
9	Number of teeth	z	11	88
10	Tooth type	-	Straight helical	Straight spherical

Shaft runout measurements

Shaft runout measurements made with the use of a workshop lathe and a dial indicator with a magnetic holder. The shaft was mounted on a lathe through a three-jaw chuck and supported by a tailstock. The measurements were read with the shaft rotating every 60 degrees in two different places. Results are within limits.



Figure 15 Shaft runout measurements

Table 6 Shaft runout measurement no.1

[mm]	I	II	III	IV	V
ΔD_1	-0,02	+0,10	+0,18	+0,04	+0,06

Table 7 Shaft runout measurement no.2

[mm]	I	II	III	IV	V
ΔD_1	+0,12	-0,04	+0,05	+0,04	-0,05

Measurements of clearance between gear's teeth

Measure the clearance between the teeth using the indirect method, through the impression of the lead wire. Measure the wire with a micrometre with an accuracy of 0.01 mm. Results are within limits.



Figure 16 Measuring clearance between the gear's teeth

Table 8 Clearance between the gear's teeth

Measurement number	Clearance [mm]
1	0,39
2	0,39
3	0,40