Gear Lubrication: Long-Term Protection for Wind Turbines

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The chemical and physical properties of gear oils may change, depending — more or less — upon their formulation and the environmental conditions under which they are used.

This is why — after three years of use in a wind turbine — a gear oil was examined to determine if indeed changes were evident and if the protection of the gears and rolling bearings still met the same requirements as would be expected of fresh oil. Our findings revealed that the existing gear oil — as well as its ability to protect the gears and rolling bearings — had degraded very little compared to fresh oil.

Introduction

An oil condition analysis (OCA) was performed to find out if the chemical and physical properties of the used oil were still within acceptable limits. For this purpose, its viscosity, oxidation, and the water and element contents of the additives and impurities respectively were measured. Ideally, oil condition analyses should be performed at certain intervals to determine a trend with regard to oil aging. The changes of chemical and physical oil properties can serve to estimate the appropriate moment for an oil change based on empirically established figures. However, the question whether gear oils maintain their ability to protect gears and rolling bearings in a gear unit over a longer period of time remains unanswered.

The gear oils of today are expected to protect gears and rolling bearings against damage such as wear or micropitting even under critical lubrication conditions and during the entire oil change interval. Gear oils are normally tested in standardized mechanic-dynamic test procedures using fresh oil. In contrast to this, a high-performance gear oil was tested after three years of use to find out if chemical or physical changes were evident and if the protection of gears and rolling bearings would still be as high as with fresh oil.

Typical Gear Failures

Figure 1 shows typical limits of the load-carrying capacity for case-hardened gears according to Niemann (Ref. 12). In the range of slow and medium circumferential speeds, the micropitting risk is increased, compared to very low circumferential speeds where the risk of slow-speed wear prevails. Tooth fracture is not influenced by the lubricant.

Micropitting failure of gears. Micropitting is a type of fatigue failure occurring on hardened tooth flanks of highly loaded gears (Ref. 12). This failure consists of very small cracks and pores on the surface of tooth flanks. Micropitting looks grayish and causes material loss and a change in the profile form of the tooth flanks, which can lead to pitting and breakdown of the gears. A typical micropitting gear failure is shown (Fig. 2). In this case, misalignment was the reason for micropitting formation.
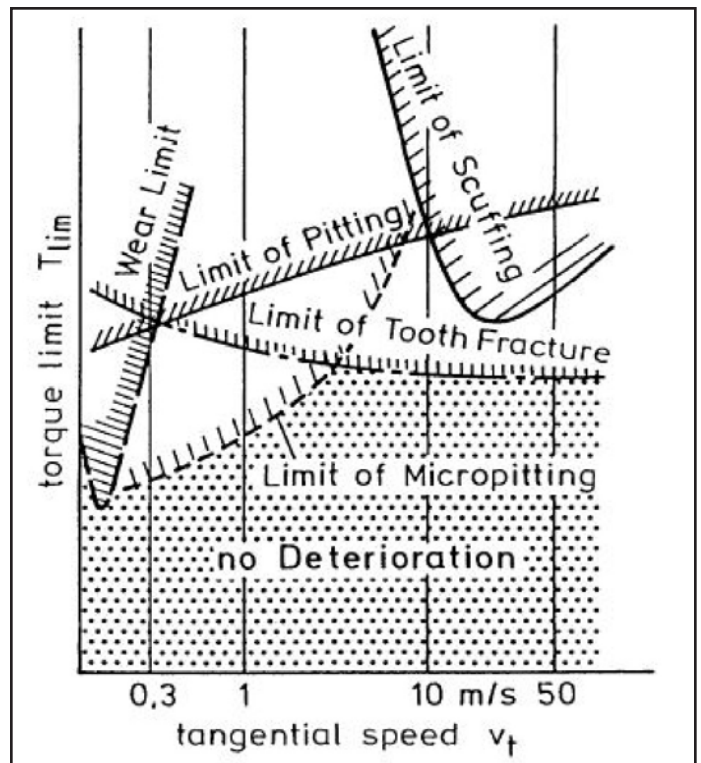

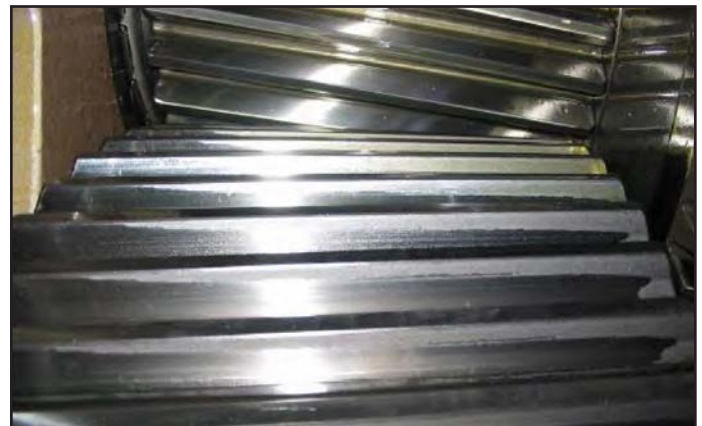Figure 1   Typical limits of load-carrying capacity for case-hardened gears.

Figure 2   Example: micropitting gear failure.

The formation of micropitting depends on different influences; besides material, surface roughness and geometry of the tooth flanks, it is the lubricant and the operating conditions that have a major influence on micropitting formation.

In modern gearboxes, the gears are often highly loaded and run under conditions of mixed lubrication. In such cases the tooth flanks of the mating gears are not fully separated by the lubricant film, and the additives of the lubricant have to protect the tooth flanks against micropitting formation.

Scuffing failure of gears. Scuffing occurs at failure of the surface protection at excessive temperatures in the tooth contact (Ref. 11). With this failure the tooth flanks of pinion and wheel weld locally and are torn apart immediately. The tooth flanks are partially destroyed, which could result in breakdown of the gears. A typical scuffing failure on the tooth flanks of a gear is shown in Figure 3.

The scuffing load-carrying capacity depends on different influences; particularly high sliding, vibrations and non-optimized flank surfaces—low manufacturing quality or missing running-in, for example—increase risk of scuffing (Ref. 3). In addition, lubricant and operating conditions have a major influence on scuffing.

Wear failure of gears. Wear is an abrasive material removal occurring on the tooth flanks of gears. This failure proceeds continuously, causing material loss and a change in the profile form of the tooth flanks, thus leading to breakdown of the gears. Typical wear on the tooth flanks of a gear is shown (Fig. 4).

What's more, the wear behavior depends on different influences. Besides the surface hardness, material, and geometry of the tooth flanks, it is again the lubricant and the operating conditions which have a major influence on wear behavior.

Failures of rolling bearings. Gear damage is also often caused by high rolling bearing wear or premature fatigue of rolling bearings (Ref. 15). Failures based on material or production mistakes are very seldom. However, type, condition, and quantity of lubricant have a major influence on bearing failure, as well as hard or liquid contaminations (Ref. 14; Fig. 5).

The additives contained in gear oils may have a decisive effect on rolling bearing damage.

Figure 3   Example: scuffing gear failure.
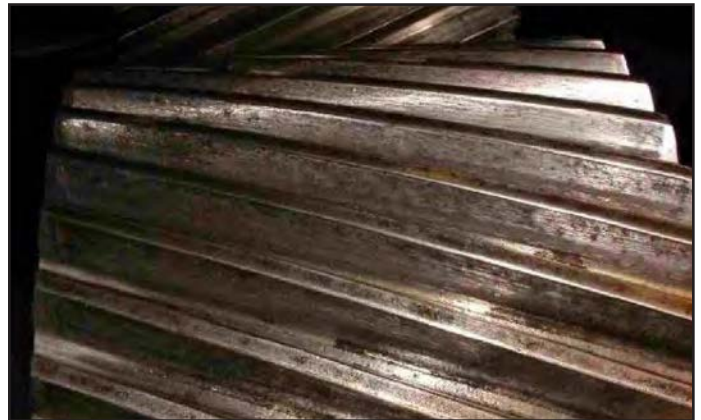

Figure 4   Example: wear gear failure.

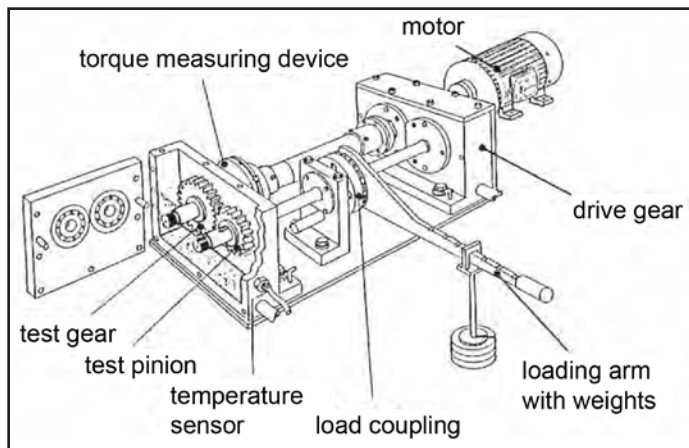Figure 5   Example: typical rolling bearing failures.
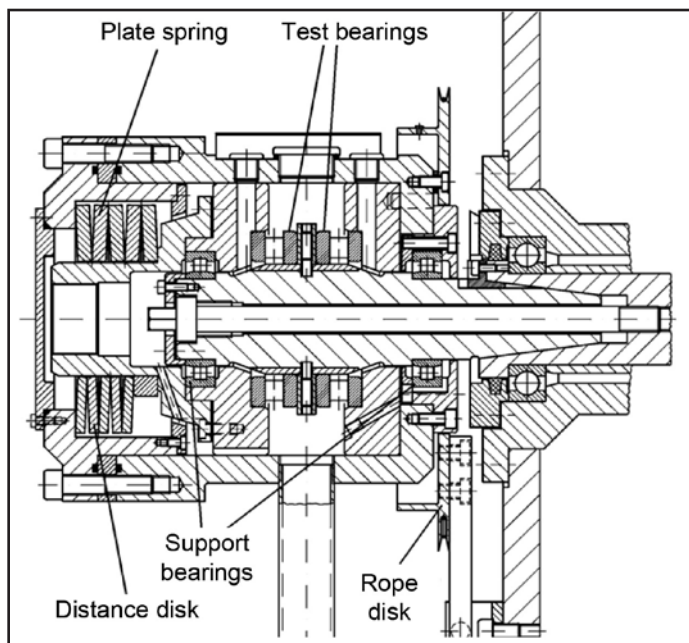
Figure 6   FZG back-to-back gear test rig.

Figure 7   FE8 bearing test rig.

Test Equipment

Investigation of micropitting load-carrying capacity and wear behavior of gears. The test runs conducted to determine the micropitting load-carrying capacity and the wear behavior of gear oils on gears were performed on a FZG back-to-back gear test rig (Ref. 7; Fig. 6).

The FZG back-to-back gear test rig utilizes a recirculating power loop principle — also known as a four-square configuration — in order to provide a fixed torque (load) to a pair of test gears. The test gearbox and drive gearbox are connected with two torsion shafts. One shaft is divided into two parts and contains a load coupling used to apply the torque (load) through the use of weights hung on the loading arm. Heating and cooling elements are used to control the oil temperature, as required by the operating test conditions.

In order to investigate the micropitting load-carrying capacity, test gears type C-GF of the standard micropitting test, according to FVA 54/7 (Ref. 10), are used. The slow-speed wear behavior is investigated by using test gears type C-PT, according to DGMK 377-01 (Ref. 2). The geometric data and manufacturing details of the test gears type C-GF and type C-PT are given in FVA 54/7 and FVA 2/IV.

Investigation of the wear behavior of rolling bearings. The test runs conducted to determine the wear behavior of gear oils on rolling bearings were performed on an FE8 bearing test rig (Ref. 5) required for lubricating oils CLP, according to DIN 51517-3 (Ref. 4; Fig. 7). The wear behavior of rolling bearings according to DIN 51819-3 (Ref. 5) is investigated with test bearings type-D (81212, according to DIN 722).

Investigation of the foam behavior of gear oils. The foam behavior of gear oils is determined on the foam test apparatus, according to ISO 12152 (Ref. 6) developed by Flender. The test apparatus (Fig. 8, Ref. 9) comprises a sealed gear unit housing to receive the gear oil sample to be tested. A pair of
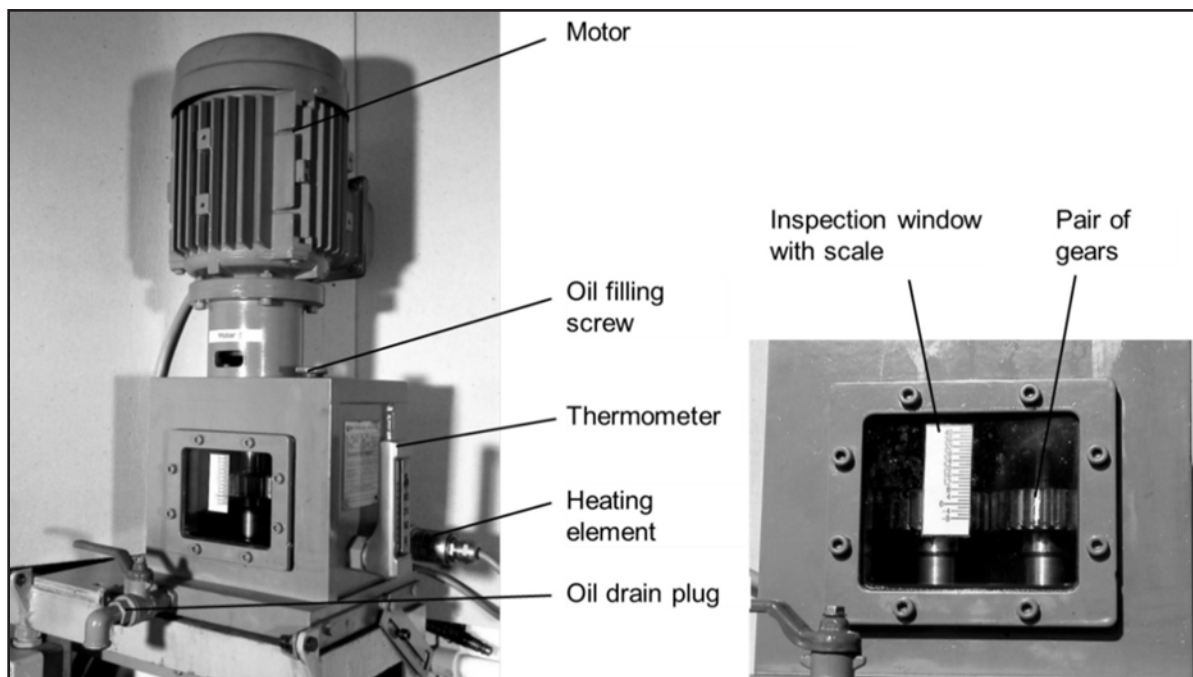

Figure 8   Foam test apparatus.

test gears is mounted on two vertically arranged shafts in order to mix 1.0 liter of the gear oil with air and generate foam.

Test Procedures

To determine the performance capacities of gear oils with regard to the prevention of micropitting and wear, they are today subjected to standardized tests under critical lubricating conditions and temperatures that are commonly encountered in practice. The micropitting resistance in gears is analyzed on the FZG micropitting test according to FVA 54/7 (Ref. 10) at an oil temperature of $\vartheta_{oil} = 90°C$. Meanwhile, it has become increasingly common to conduct micropitting tests also at a reduced oil temperature of $\vartheta_{oil} = 60°C$ in order to determine if micropitting can be reliably prevented at these lower temperatures, which are encountered, for example, in wind turbine gearboxes. The standard scuffing test according to ISO 14635-1 (Ref. 7) is conducted at a circumferential speed of $v_t = 8.3$ m/s. In order to intensify the requirements of a gear oil, the scuffing load-carrying capacity is tested at an increased circumferential speed of $v_t = 16.6$ m/s. The slow-speed wear behavior of gears is analyzed in the FZG wear test according to DGMK 377-01 (Ref. 2) at oil temperatures of $\vartheta_{oil} = 90°C$ and 120°C. The influence of temperature is thus taken into account—albeit on a rather high level. The wear behavior of rolling bearings is examined in the FE8 wear test according to DIN 51819-3 (Ref. 5) at an oil temperature of $\vartheta_{oil} = 80°C$. The foam behavior is analyzed according to the foam test of ISO 12152 (Ref. 6).

FZG micropitting test (GF-C/8.3/90 or GF-C/8.3/60). The micropitting test GF-C/8.3/90 or GF-C/8.3/60 according to FVA 54/7 consists of a load stage test and an endurance test performed on a FZG back-to-back gear test rig (Ref. 7). Test gears type C-GF run at a circumferential speed of $v_t = 8.3$ m/s and an oil temperature of $\vartheta_{oil} = 90°C$ or 60°C. The load and the test periods are varied.

In the load stage test, the load is increased stepwise from load stage LS 5 to load stage LS 10, with a running time of 16 h per load stage. After the load stage test, an endurance test with a running time of 80 h in load stage LS 8 and 5×80 h in load stage LS 10 is performed. The pinion torque and the corresponding Hertzian pressure of the different load stages are given in Table 1. In load stage LS 10, the test gears are highly loaded; the endurance limit of the material is about $\sigma_{Hlim} = 1,400$ N/mm².

At the end of the load stage test and the endurance test with the first test gears, the load stage test is repeated with new test gears to check repeatability.

After each test period, the test gears are disassembled and the profile of the tested flanks is measured using a 3-D measurement system.

In the load stage test, the failure criterion has been reached once the mean profile form deviation due to micropitting exceeds the limiting value of 7.5 µm. The load stage in which the failure criterion is reached is called "failure load stage." An overview regarding the classification of test results obtained in the micropitting test is given in Table 2.

Lubricants with a high micropitting load-carrying capacity reach the failure criterion of a profile form deviation of 7.5 µm due to micropitting in load stage $\geq$ LS 10 of the load stage test (GFT-high) (Figs. 9, 10).

Table 1	Load stages of the micropitting test	
Load stage	**Pinion torque, T1, Nm**	**Hertzian pressure, pc, N/mm2**
LS 5	70.0	795.1
LS 6	98.9	945.1
LS 7	132.5	1093.9
LS 8	171.6	1244.9
LS 9	215.6	1395.4
LS 10	265.1	1547.3

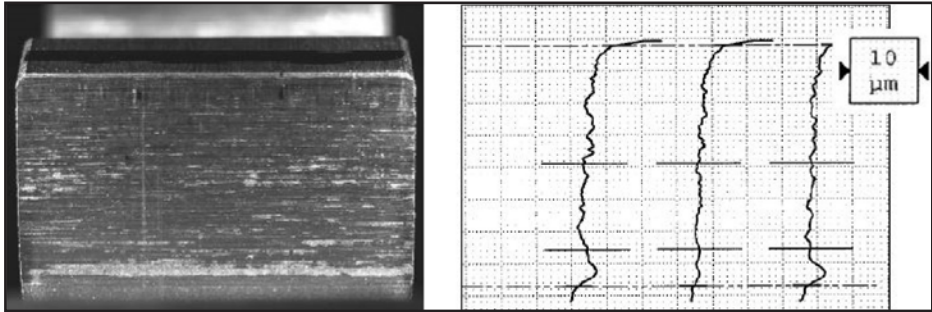| Table 2	Classification of test results of the micropitting test		
Description	**Failure load stage**	**Micropitted area**	**GF-class**
Low micropitting load-carrying capacity	$\leq$ LS 7	Sometimes more than 50%	GFT – low
Medium micropitting load-carrying capacity	LS 8 – LS 9	About 30%	GFT – medium
High micropitting load-carrying capacity	$\geq$ LS 10	Less than 20%	GFT - high

Figure 9 Pinion type C-GF; with measurement of the profile, nearly no micropitting failure.
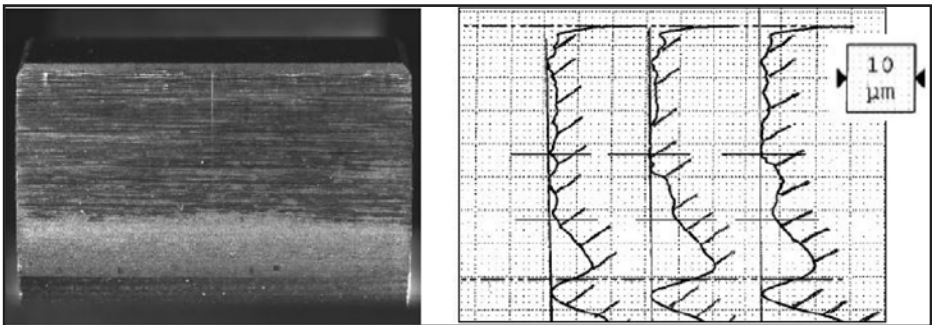

Figure 10 Pinion type C-GF; with measurement of the profile; micropitting failure in the range of the failure criterion.
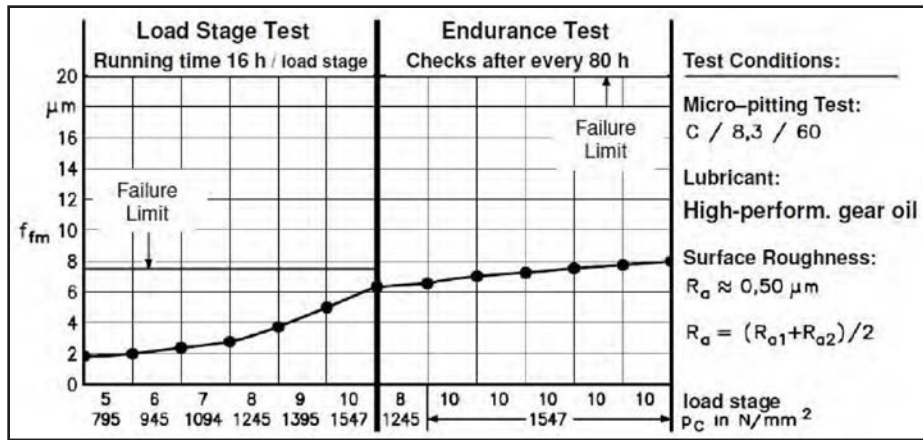
Figure 11   Micropitting test of a high-performance gear oil; measurement of the profile form deviation.

In the endurance test, a stagnation of micropitting formation compared with the micropitting area at the end of the load stage test is preferred but not required. For high-performance gear oil with a high micropitting performance, a test result is given (Fig. 11) showing the profile form deviation due to micropitting. The profile form deviation of the pinion is below the failure criterion for the whole load stage test (GFT-high). In the endurance test, the profile form deviation stagnates compared with the step test.

FZG scuffing test (A/16.6/90). The scuffing test A/16.6/90 according to ISO 14635-1 is performed on a FZG back-to-back gear test rig. The test gear type A runs at an increased circumferential speed of $v_t = 16.6\,\text{m/s}$ and an oil start temperature of $\vartheta_{oil} = 90°C$. Per stage the test lasts approximately 7.5 min due to a revolution of $n = 21,700\,\text{min}^{-1}$ (Ref. 7). The load is increased stepwise from load stage LS 1 to load stage LS 12, and additionally up to LS 14. The pinion torque and the Hertzian pressure of the different load stages are given (Table 3). In load stage LS 12, or even LS 14, the test gears are highly loaded. After each test stage the test gears are disassembled and the surface of the tested flanks is analyzed.

The test is completed when a scuffing failure occurs or the whole range runs without any failure. The failure criterion is reached if the sum of all gear failures on the pinion flanks (width of all scuffing and scoring marks) exceeds 20 mm. The load stage in which the failure criterion is reached is called failure load stage (Fig. 12).

FZG slow-speed wear test (C/0.05:0.57/90:120/12). The results of the FZG slow-speed test according to DGMK 377-01 (Ref. 2) can be used for relative ranking of gear oils to a reference oil and, in addition, specific wear rates c_{1T} can be derived for inclusion in the wear calculation method developed by Plewe (Ref. 13).

The FZG slow-speed wear test C/0.05:0.57/90:120/12 according to DGMK 377-01 determines the wear characteristics of gear oils at two different temperatures under mixed and boundary lubrication conditions (Ref. 2). With an additional test part, the influence of circumferential speed can be investigated.

Test gears type C-PT run at a very low circumferential speed of $v_t = 0.05\,\text{m/s}$. The load applied is load stage LS 12,

Table 3	Load stages of the scuffing test	
Load stage	**Pinion torque, T_1, Nm**	**Hertzian pressure, p_c, N/mm²**
LS 1	3.3	146
LS 2	13.7	295
LS 3	35.3	474
LS 4	60.8	621
LS 5	94.1	773
LS 6	135.5	929
LS 7	183.4	1080
LS 8	239.3	1223
LS 9	302.0	1386
LS 10	372.6	1539
LS 11	450.1	1691
LS 12	534.5	1841
LS 13	626.9	1996
LS 14	714.2	2130

a) Appr. 5 mm failure   b) Appr. 12 mm failure   c) Appr. 20 mm failure

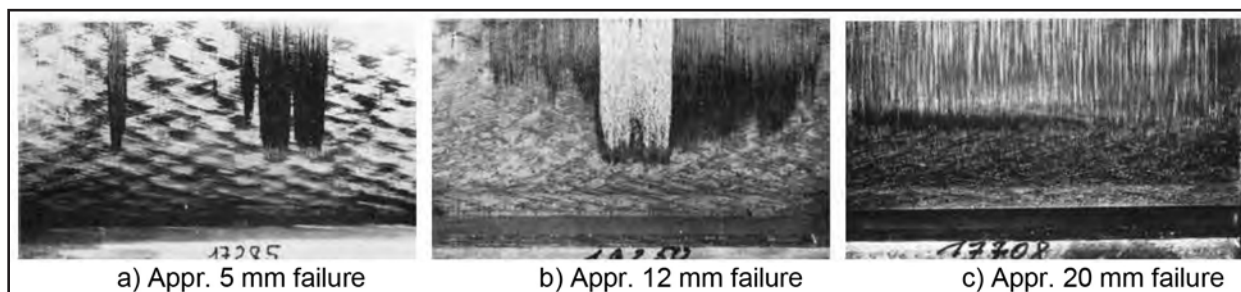**Figure 12   Scuffing failures on tooth flanks.**

which is equivalent to a pinion torque of $T_1 = 378.2$ N-m. This corresponds to a Hertzian pressure of $p_c = 1,853$ N/mm² in the gear contact. The oil temperature is $\vartheta_{oil} = 90°C$ during test part 1 of 2×20 hours and $\vartheta_{oil} = 120°C$ during test part 2 of 2×20 hours. In the optional test part 3 of 1×40 hours a higher circumferential speed of $v_t = 0.57$ m/s is run at an oil temperature of $\vartheta_{oil} = 90°C$.

The test is run on a modified FZG back-to-back gear test rig according to ISO 14635-1 (Ref. 7) using an additional reducer gearbox after the drive motor in order to run very low speeds. After each test interval the pinion and the wheel are disassembled and weighed separately. The classification of the results of the FZG slow-speed wear test is shown (Table 4).

For high-performance gear oil, a test result of the FZG slow speed wear test is given (Fig. 13) showing a very low wear behavior. The sum wear of pinion plus wheel is below the failure criterion of 40 mg (wear category low) — not only for the individual test part of 40 h but also for the whole test procedure of 120 h.

FE8 wear test (D 7.5/80-80). The influence of gear oils on the wear behavior of rolling bearings is examined in the FE8 wear test D 7.5/80-80 according to DIN 51819-3 (Ref. 5) using the FE8 bearing test rig. In this test, axial cylinder roller bearings type D are subjected to a speed of $n = 7.5$ min⁻¹ with an axial force of $F_a = 80$ kN at a steady-state temperature of 80°C over a period of 80 h. With a C/P < 2, a very high load is applied. Wear is then determined gravimetrically. Gear oils in the FE8 wear test according to DIN 51819-3 have to show a roller wear of ≤ 30 mg according to DIN 51517-3 (Ref. 4); only the cage wear must be reported (Table 5).

Foam test. The foam behavior of gear oils is examined in the foam test according to ISO 12152 (Ref. 6). At the beginning of the test the oil temperature is at $\vartheta_{oil} = 25°C$. The gears rotate with a speed of $n = 1,450$ rpm for 5 min. After this the observation of the foam behavior lasts 90 min. Figure 14 shows the inspection window with a scale. The mark 0 on the scale corresponds with a volume of 1.0 liter. This is also the required volume of the gear oil which has to be filled in. The total volume increase and the oil and air dispersion could be read from the scale.

The classification of the foam behavior of fresh gear oils is shown in Table 6 according to the Flender report GG-V 425 (Ref. 8). If the total percentage volume increases above 15%, the gear oil is not recommended for use in gear units, as this negatively affects the load capacity of the teeth. Additionally, the percentage volume increase of the oil and air dispersion must be lower than 10% (Ref. 9).

For used gear oils, OEMs of wind turbines typically require that a total volume increase of the foam does not exceed 20%.

Table 4	Classification of test results of the slow speed wear test
Wear category	**Sum wear per test part, mg**
low	< 40
medium	< 170
high	< 400
very high	> 400

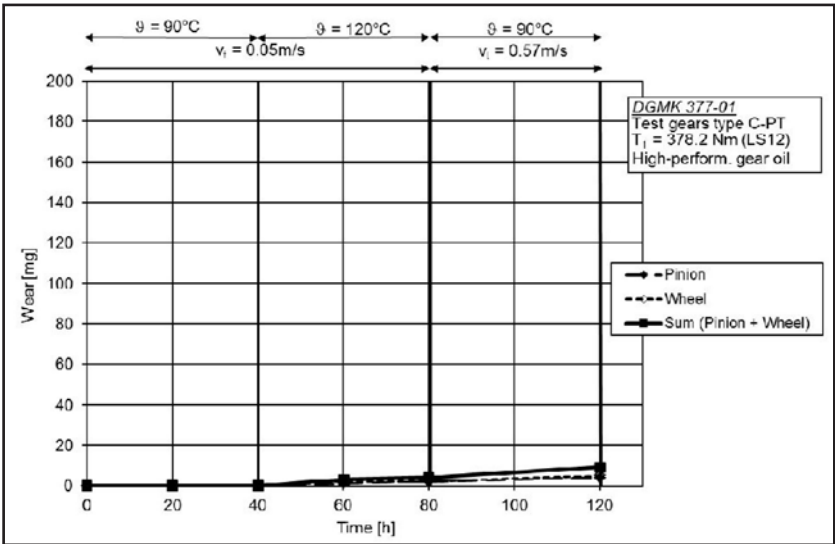| Table 5	Limits for the test results of the FE8 wear test
Description	**Failure limit, mg**
Roller wear	≤ 30

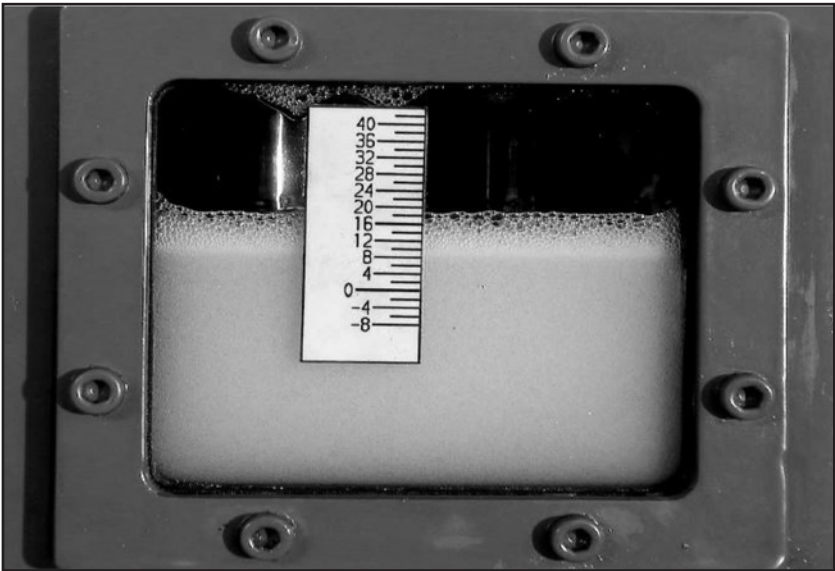Figure 13   Slow-speed wear test of a high-performance gear oil.

Figure 14   Foam measure scale of the foam test according to ISO 12152.

Table 6	Classification of foam behavior for fresh gear oils	
Evaluation foam behavior	**Total volume increase**	**Oil and air dispersion**
good	up to 5%	up to 4%
satisfactory	up to 10%	up to 7%
still permissible	up to 15%	up to 10%
excessive	over 15%	over 10%

Tested Lubricant

The tested high-performance gear oil is on the basis of polyalphaolefin showing high wear protection, high scuffing resistance as well as a high micropitting load-carrying capacity. It shows a very low wear behavior of gears determined in the FZG slow-speed wear test according to DGMK 377-01 (Ref. 2) at oil temperatures of 90°C and 120°C. The scuffing, load-carrying capacity tested in the FZG test rig according to ISO 14635-1 (Ref. 7) at a circumferential speed of $v_t = 16.6$ m/s is very high. The micropitting load-carrying capacity tested in the FZG micropitting test according to FVA 54/7 (Ref. 10) at an oil temperature of 60°C is high as well. The wear behavior of rolling bearings examined in the FE8 wear test according to DIN 51819-3 (Ref. 5) at an oil temperature of 80°C is also very low.

The tested gear oil is of ISO VG 320 and is a specified CLP gear oil according to DIN 51517-3 (Ref. 4), which includes the minimum requirements for industrial gear oils and is similar to ANSI/AGMA 9005-E02 (Ref. 1).

The oil data of the tested gear oil is shown in Table 7.

High-performance gear oils based on polyalphaolefin are typically used in wind turbines today. Klübersynth GEM 4-320 N is one such gear oil and in fact was used for three years in the field and in these investigations. The application was a 750 kW GE wind turbine in Spain. During operation the gearbox was filtered with an in-line filtration system (50 μm) and an off-line system (5 μm). The performance of the oil was constantly monitored and at the time of oil change, the chemical and physical properties of the used oil were analyzed. To show that the oil maintains its ability to protect gears and rolling bearings reliably over the entire duration of use, the mechanic-dynamic tests described above were performed.

Test Program

To find out if the high-performance gear oils of today are able to reliably protect gears and rolling bearings in gearboxes against damage also

Table 7 Oil data of the tested high-performance gear oil

Product	Klübersynth GEM 4-320 N
Symbol	GEM 4-320 N
ISO VG	320
Base oil	Polyalphaolefin
DIN 51517, ANSI/AGMA 9005-E02 designation	CLP HC, EP oil
FZG micropitting test acc. to FVA 5 54/7 θ_{oil} = 60°C	GFT-high
FZG scuffing test acc. to ISO 14635-1 θ_{oil} = 90°C	≥ LS 14
FZG slow speed wear test acc. to DGMK 377-01 θ_{oil} = 90°C and 120°C	≤ 20 mg
FE8 wear test acc. to DIN 51819-3 θ_{oil} = 80°C	≤ 10 mg
Foam test according to ISO 12152 (total volume increase)	< 10%

Table 8 Test program for the fresh and used high-performance gear oil

Test procedure	GEM 4-320 N (fresh)	GEM 4-320 N (used)
Oil condition analysis	X	X
FZG micropitting test acc. to FVA 5 54/7 θ_{oil} = 60°C	X	X
FZG scuffing test acc. to ISO 14635-1 θ_{oil} = 90°C	X	X
FZG slow speed wear test acc. to DGMK 377-01 θ_{oil} = 90°C and 120°C	X	X
FE8 wear test acc. to DIN 51819-3 θ_{oil} = 80°C	X	X
Foam test acc. to ISO 12152	X	X

Table 9 Oil condition of a high-performance gear oil

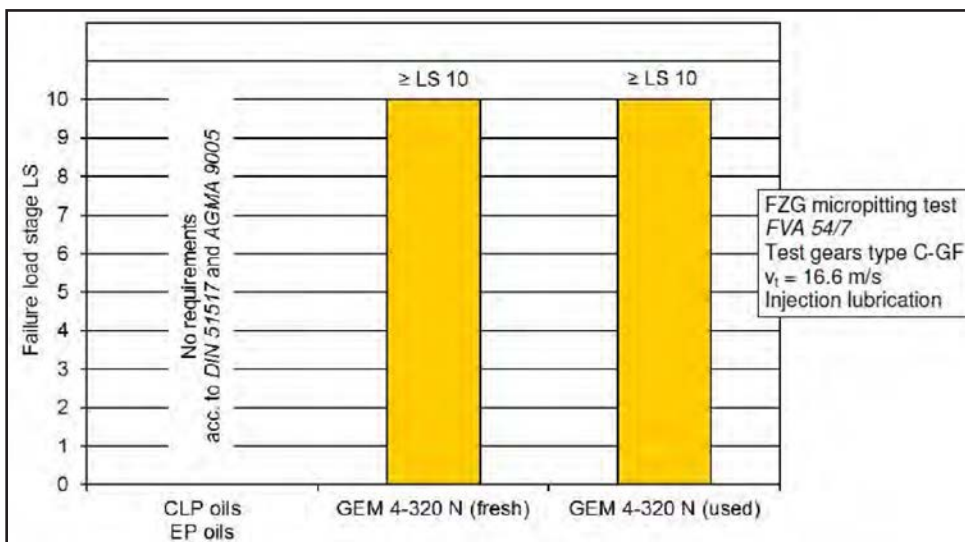| Criterion	Limits GEM 4-320 N (fresh)	Limits GEM 4-320 N (used)	Results GEM 4-320 N (used)
Water content in %	< 0.3	< 0.3	0.005
Viscosity at 40°C, mm²/s	268 ... 352	256 ... 384	322
Viscosity at 100°C, mm²/s	32 ... 40	29 ... 43	37
Cleanliness	--	--	18/16/12
Elements			
Sulfur (% deviation from fresh oil)	90 ... 110	80 ... 120	113
Phosphor (% deviation from fresh oil)	90 ... 110	80 ... 120	95
Iron, ppm	< 10	Depending on	< 10
Copper, ppm	< 10	application	< 10
Infrared spectroscopy	no deviation	no deviation	corresponds without any deviation

Figure 15   Micropitting of gears can be prevented by using a high-performance gear oil.

in long-term use, the standardized test methods mentioned in Clause 4 had to be considered for used oil tests. Table 8 shows the tests for fresh oil as well as for used oil.

Today's high-performance gear oils show chemical and physical changes which are under 20% — even after long-term use. Regarding the protection of the tooth flanks and bearings, the load carrying capacity should be nearly unchanged.

During use, the foam behavior could be affected negatively through contamination and filtration.

Regarding the used gear oils, OEMs of wind turbines typically require a test result of at most 20% in the foam test according to ISO 12152.

Test Results

The aim of this research is to determine whether a gear oil that was used for three years in a wind turbine can protect gears and bearings like a fresh gear oil. The test results show that the chemical and physical properties of the high-performance gear oil have changed very little compared to the fresh oil (Table 9).

For the high-performance gear oil based on polyalphaolefin, an FZG micropitting test at an oil temperature of $\vartheta_{oil} = 60°C$ was performed showing a high micropitting load-carrying capacity for the fresh oil. Additionally, the FZG micropitting test with used oil reached a high micropitting load-carrying capacity of GFT-high. This shows that the additives can prevent micropitting at the surface of the tooth flanks after three years of use. Fig.15.

For the high-performance gear oil based on polyalphaolefin, an FZG scuffing test at an oil temperature of $\vartheta_{oil} = 90°C$ and a circumferential speed of $v_t = 16.6$ m/s was performed showing a high scuffing load-carrying capacity of ≥ 14 for the fresh oil. The FZG scuffing tests with the used oil reached the same scuffing load-carrying capacity and shows that even the gear oil after three years in use provides the same scuffing protection compared to fresh oil. See Figure 16.
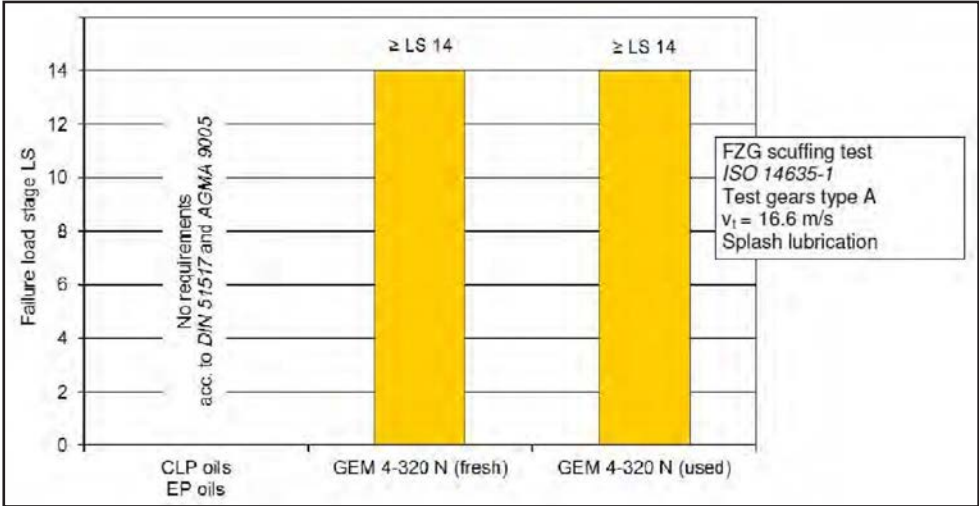

Figure 16   Scuffing load-carrying capacity for gears by using a high-performance gear oil.
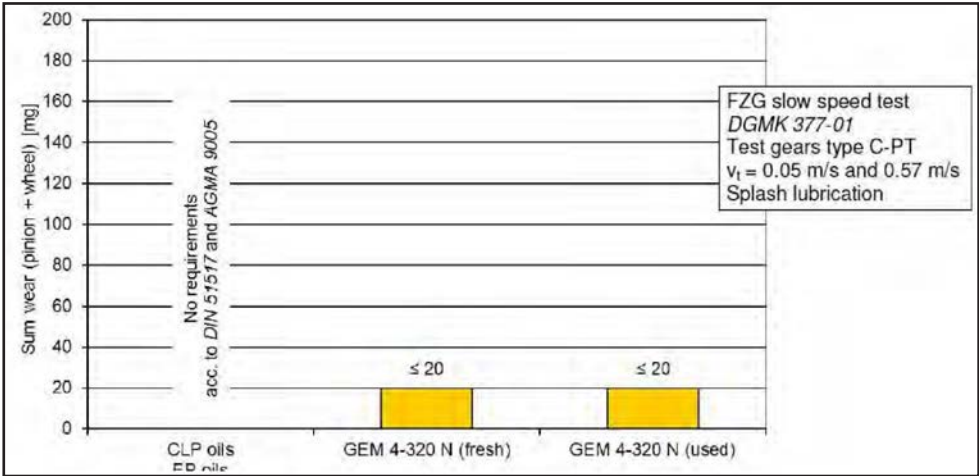

Figure 17   Gain wear protection for gears by using a high-performance gear oil.
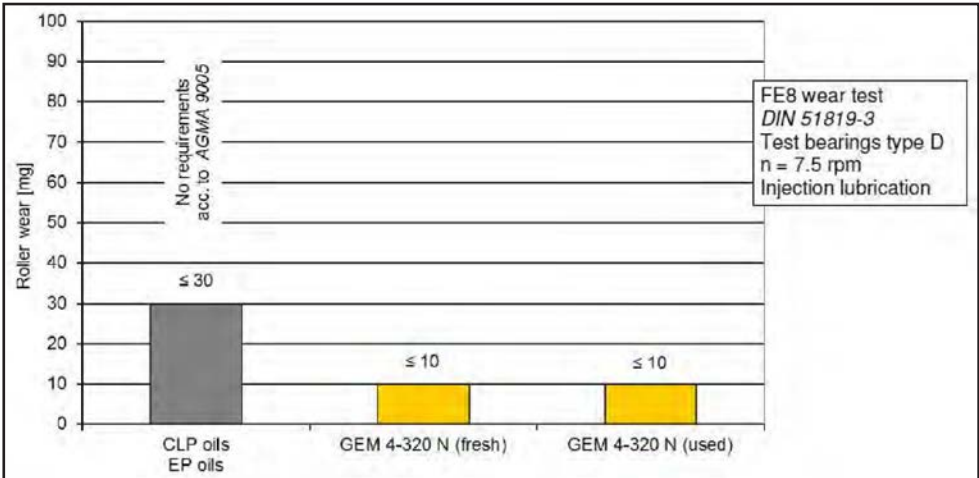

Figure 18   Gain wear protection for rolling bearings using a high-performance gear oil.

Both the fresh and the used high-performance gear oil based on polyalphaolefin show very low wear behavior with a sum wear on pinion plus wheel of less than 20 mg at the oil temperatures of $\vartheta_{oil}=90°C$ and $120°C$ of the FZG slow speed wear test. This shows that the advanced oil technologies can prevent wear after three years of use. See Figure 17.

The FE8 wear test shows that the tested high-performance gear oil based on polyalphaolefin provides an optimum wear protection at the oil temperature of $\vartheta_{oil}=80°C$. After three years in use the gear oil offers the same wear protection compared to the fresh oil. See Figure 18.

A foam test according to ISO 12152 was also performed for the high-performance gear oil. The results show that the total volume increase for fresh oil is ≤15% and for used gear oil ≤20%. This shows that the gear oil perform the required foam behavior by OEMs of wind turbines after three years of use (Fig. 19).

Figure 19   Much longer life with high-performance gear oil.

Conclusions

The gear oils of today are expected to protect gears and rolling bearings against damage such as wear or micropitting — even under critical lubrication conditions and during the entire oil change interval. Gear oils are normally tested in standardized mechanic-dynamic tests using fresh oil. However, the chemical and physical properties of gear oil in use may change more or less depending on its formulation and the operating conditions.

The test results show that the chemical and physical properties of the investigated high-performance gear oil have changed very little compared to the fresh oil after three years of use in a wind turbine.

Also by the end of the oil change interval, the oil provides full micropitting and wear resistance as well as a good anti-foam performance.

In conclusion, it could be shown that high-performance gear oil can offer its full performance spectrum and protection of gears and rolling bearings over the entire duration of use. **PTE**

References

1. Standard: ANSI/AGMA 9005-E02. *Industrial Gear Lubrication.*
2. Standard: DGMK 377-01. *Method to Assess the Wear Characteristics of Lubricants – FZG Test Method C/0.05/90:120/12.*
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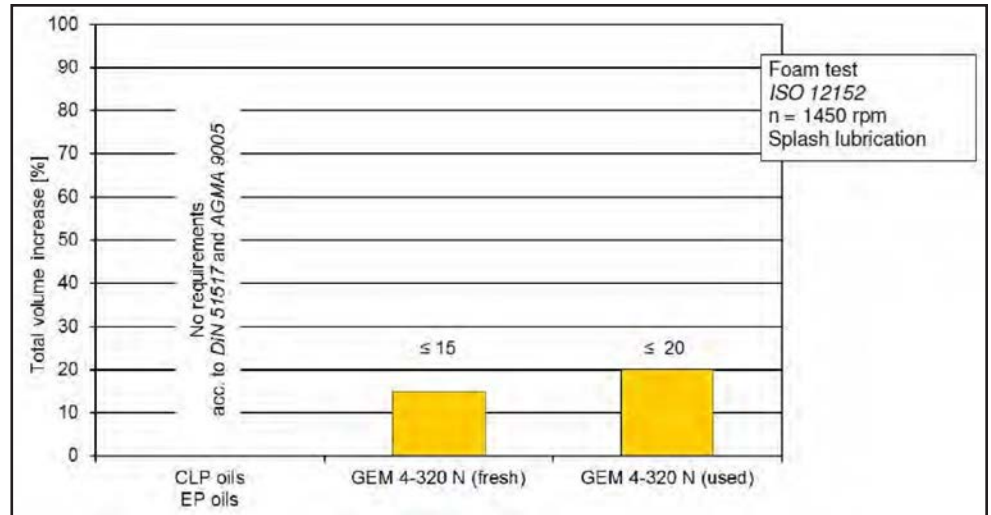6. Standard: ISO 12152:2012-08. *Lubricants, Industrial Oils and Related Products — Determination of the Foaming and Air Release Properties of Industrial Gear Oils Using a Spur Gear Test Rig/ Flender Foam Test Procedure.*
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