

Not all synthetic gear oils are created equally

How differences in synthetic oil formulations affect fatigue failure, low-temperature performance, service life and shear stability

- Learn how differences in synthetic-lubricant formulations affect performance.
- See test results on different performance properties.

Introduction

Using synthetic oils instead of mineral oils has numerous advantages for gear and gearbox lubrication (Figure 1). Synthetic oils are generally more resistant to breakdown under high loads, less vulnerable to oxidation and provide longer service life.

Nevertheless, there are substantial differences in synthetic base oil quality, and carefully formulated additive chemistries, that can cause significant variations in lubricant performance. This discussion examines how those differences affect four critical areas: micropitting (fatigue failure), low-temperature performance, service life and the effect of base oil purity on shear stability.

This discussion provides highlights of test results, which are detailed in an available Appendix.

Base oil	Advantages	Disadvantages
Mineral oil	<ul style="list-style-type: none"> • Low cost • Good lubricity • Easy to additivate • Almost neutral to sealing materials 	<ul style="list-style-type: none"> • 212°F (100°C) max. • Poor vis./temp. (V-T) relationship • Very poor biodegradability
Polyalphaolefins (PAO)/SHCs	<ul style="list-style-type: none"> • Low evaporation up to 284°F (140°C). Can be good to -58°F (-50°C) • Some types are nontoxic H1 • Miscible with mineral and ester 	<ul style="list-style-type: none"> • \$\$\$ • May shrink seals • Poor wear • Poor biodegradability
Ester	<ul style="list-style-type: none"> • Usable up to 320°F (160°C) • Little residue formation even at >392°F (200°C) • Good vis./temp. (V-T) • Miscible with SHC and PAG • Some are nontoxic H1 • Many biodegrade rapidly 	<ul style="list-style-type: none"> • \$\$\$ • Seals may swell • Paints may be affected
Polyglycol (PAG/PG)	<ul style="list-style-type: none"> • Service to 160°C • Excellent load-carrying capacity • Good wear protection, esp. under sliding friction • Some types are nontoxic H1 • Suitable for worm gears 	<ul style="list-style-type: none"> • \$\$\$ • Only miscible with ester • May affect seals and paint • Tendency to stick slip and low sliding speeds

Figure 1: Advantages of synthetic oils compared to mineral oils.

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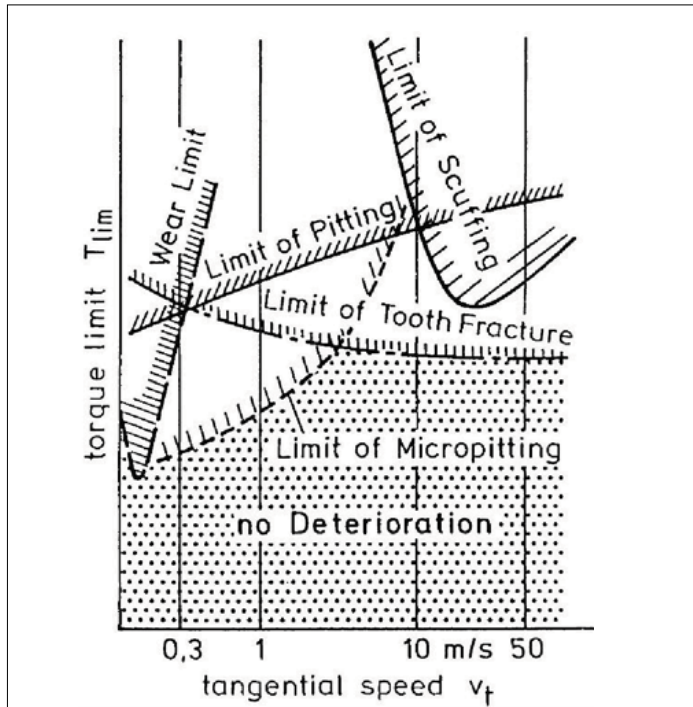


Figure 2: Typical limits of the load-carrying capacity for case-hardened gears. (Source: Hochmann, Michael and Hermann Siebert. "Gear Lubrication—Stopping Micropitting by Using the Right Lubricant," Gear Solutions, June 2012.)

I. MICROPITTING PROTECTION

Understanding the issue

Micropitting is a type of fatigue failure occurring on hardened tooth flanks of highly loaded gears. Figure 2 shows typical limits of the load-carrying capacity for case-hardened gears. This failure consists of very small cracks and pores on the surface of tooth flanks. Micropitting looks greyish 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 of an industrial gearbox is shown in Figure 3. In this case, misalignment was the reason for micropitting formation.

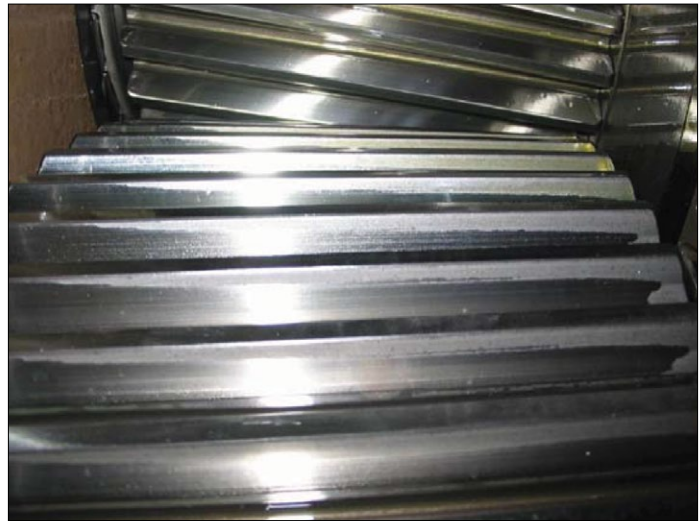


Figure 3: Micropitting gear failure of an industrial gearbox. (Source: Hochmann and Siebert. Gear Solutions, June 2012.)

Advantages of advanced lubricant formulations

Synthetic gear oil formulations that use advanced additives can actually stop micropitting formation. These advanced formulations can induce beneficial reactions on gear and tooth flank surfaces. With common gear oil formulations in highly loaded gearboxes, the tooth flanks of the gears are not fully separated by the lubricant film. In that case, the lubricant's additives serve to protect the tooth flanks against micropitting formation.

Important conditions and factors

While lubricant selection plays a role in micropitting protection, operating conditions and material, surface roughness and geometry of the tooth flanks are also factors (Figure 4).

Along with micropitting, wear is an issue when abrasive material removal occurs on the tooth flanks of gears. This failure proceeds continuously at a rapid rate and causes material loss and a change in the profile form of the tooth flanks, which can lead to breakdown of the gears. Typical wear on the tooth flanks of an industrial gear is shown in Figure 5.

Factor	Variable
Lubricant	Chemistry of the base oil Viscosity of the base oil Type and amount of additives
Tooth flank surface	Surface hardness Profile modification (tip relief) Material
Operating conditions	Normal and frictional load Circumferential speed Temperature

Figure 4: Influences on wear behavior.
(Source: Hochmann, Michael. "Gear Lubrication—Gear Protection Also at Low Oil Temperature," AGMA Technical Paper, American Gear Manufacturers Association, 2012, p. 5.)

Testing to validate solutions

To determine the level of micropitting and wear protection provided by different kinds of oils, three tests were performed:

- An FZG micropitting test at high load-carrying capacity
- An FZG slow-speed wear test
- An FAG FE8 wear test was performed to show bearing protection. (This test was done at normal standard temperatures and modified for lower oil temperatures.)

Tests were performed on mineral oil, polyalphaolefin and polyglycol oils.

Test results showed that the advanced additive technologies used in high-performance synthetic gear oils can react at the surface of the tooth flanks. Even under high loads and slow speeds, micropitting formation and wear failure were substantially reduced (Figure 6).

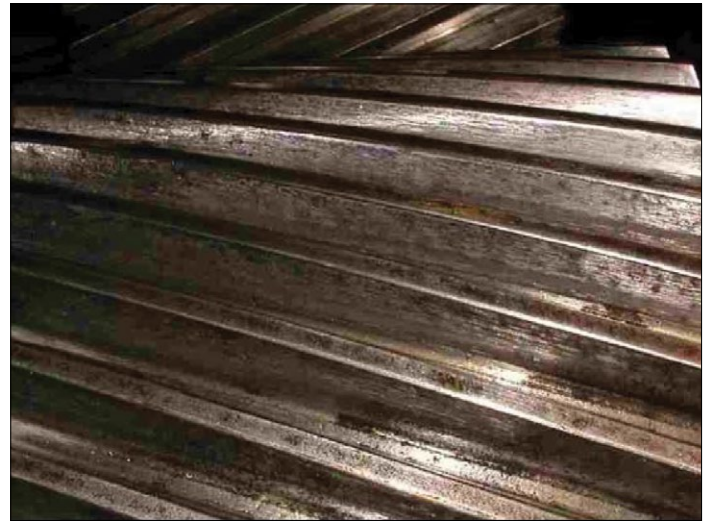


Figure 5: Typical wear on an industrial gear.
(Source: Hochmann, Michael, Steve Mazzola, and Julian Wald. "Gear Lubrication: Long-Term Protection for Wind Turbines," Power Transmission Engineering, April 2014, pp. 36-44.)

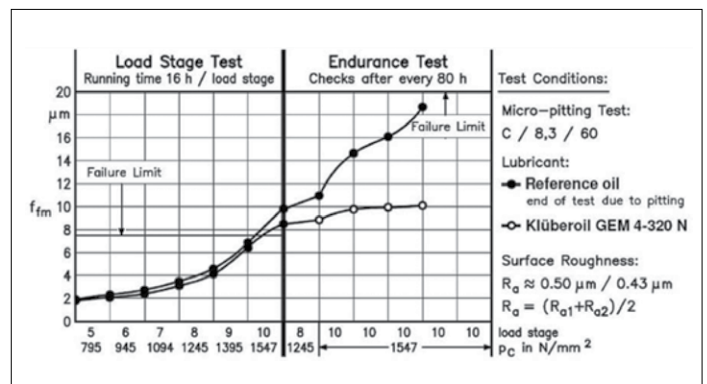


Figure 6: Stopping micropitting by using a high-performance gear oil (polyalphaolefin). This test compares a reference oil (an ISO-VG 320 mineral oil with a DIN 5157, AGMA 9005 designation of CLP, EP) to a high-performance gear oil on the basis of polyalphaolefin (Klüberoil GEM 4-320 N). After the repeated load stage test for the reference oil, an oil change to high-performance gear oil on basis of mineral oil with a high micropitting load-carrying capacity as well as a high-endurance micropitting performance was conducted. Test results show that Klüberoil GEM 4-320 N stopped the micropitting formation compared with the reference oil. The reason for the stagnation of the micropitting areas is the advanced additive technologies in this high-performance polyalphaolefin gear oil. Even after an oil change, these advanced additive technologies can react at the surface of the tooth flanks and build up a new improved reaction layer.
(Source: Hochmann and Siebert. Gear Solutions, June 2012.)

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II. LOW-TEMPERATURE PERFORMANCE

Understanding the issue

Industrial gears often operate with lower oil temperatures than would normally be generated in a fully loaded gearbox. Lower temperatures prevail, for instance, while a gearbox is being returned to use after prolonged standstill, i.e., during the time it takes for the oil to heat up from ambient temperature to service temperature. Similarly, when a gearbox is being operated below its full load capacity, with reduced speed or with frequent stop-and-go, the operating temperature of the oil will be lower than it would be under full load. Such applications require synthetic gear oils that reliably protect gears and rolling bearings against damage not only at full-load operating temperatures but also at lower temperatures.

Advantages of advanced lubricant formulations

Synthetic gear oils that use advanced additive technologies can react at the surface of the tooth flanks even at temperatures as low as 104°F (40°C). Depending on the type of additives, the temperature in the contact zone does not have to be elevated for the lubricant to react at the surface of gears. Consequently, advanced synthetic formulations provide a protective layer that can be maintained at slow gear speeds.

Important conditions and factors

Naturally, a reduction of the oil temperature leads to a substantial increase of oil viscosity during operation and hence to the formation of a thicker lubricant film in the contact zone. Lubricant film thickness calculations conducted for typical gearbox applications, however, show that even at oil temperatures as low as 104°F (40°C), the gearbox will still operate under mixed or boundary lubrication conditions depending on the other operating conditions. The formation of this gear oil reaction layer on the component surfaces is vital to protect the friction bodies against damage. At lower operating temperatures, the formation of this reaction layer can be difficult for some formulations. This is where it is crucial to ensure a proper chemistry that can work over a wide temperature range.

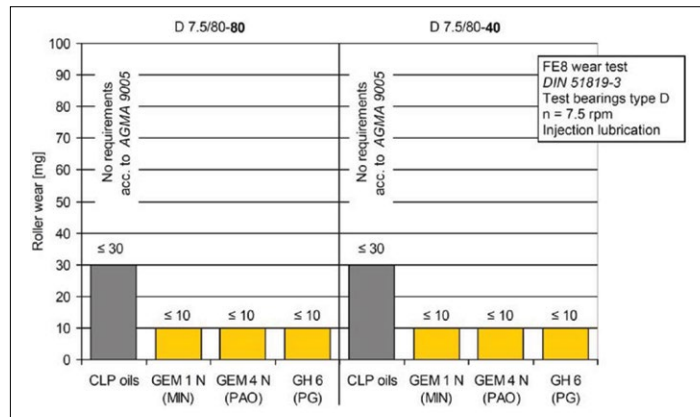


Figure 7: Wear protection for rolling bearings at low oil temperature by using high-performance gear oils. The left graph shows FE8 test results at standard 176°F (80°C) and the right graph at 104°F (40°C). Even at lower temperatures, the bearings protection is better and still within the requirements of CLP oils. (Source: Hochmann. AGMA Technical Paper, 2012.)

Testing to validate solutions

To determine how different kinds of high-performance oils protect gears in gearboxes against damage at a reduced oil temperature, the standardized FZG test methods have to be modified (see Figure 21 in Appendices). All other test conditions—including load and speed—are unchanged.

FE8 Test results showed that even at a low temperature of 104°F (40°C), advanced synthetic gear oils can react to form a protective boundary layer on the surface that reduces wear (Figure 7).

III. EXTENDED SERVICE LIFE

Understanding the issue

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. But the chemical and physical properties of gear oils may change over time, depending upon their formulation and the environmental conditions under which they are used.

For example, old lubricant can lose foam control. The bubbling action can lead to serious lubrication issues, including inadequate surface film due to cavitation and increased lubricant oxidation.

Ideally, oil condition analyses should be performed at certain intervals to determine a trend with regard to oil aging. The changes in chemical and physical oil properties can serve to estimate the appropriate moment for an oil change based on empirically established figures. However, the question of what kind of gear oil formulations maintain their ability to protect gears and rolling bearings over a long period of time requires testing.

Advantages of advanced lubricant formulations

Today's high-performance synthetic gear oils exhibit chemical and physical changes well below the limits that could impair performance even after three years of use. Also by the end of the oil change interval, advanced synthetic oil formulations provide full micropitting protection and wear resistance in addition to good antifoam performance.

Testing to validate solutions

Gear oils are normally tested in standardized mechanical-dynamic tests using fresh oil. However, the chemical and physical properties of gear oil in use may change over time depending on its formulation and the operating conditions. To find out if high-performance gear oils can protect gears in gearboxes against damage at a reduced oil temperature, both fresh and used high-performance gear oil based on polyalphaolefin were used in the same FZG tests mentioned above.

FZG test results show that the chemical and physical properties of the investigated high-performance gear oil changed very little compared to the fresh oil after three years (Figure 8).

Moreover, 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 $\leq 15\%$ and for used gear oil $\leq 20\%$.

Test procedure	GEM 4-320 N (fresh)	GEM 4-320 N (used – 3 years in continuous operation)
Oil condition analysis	PASS	PASS
FZG micropitting test acc. to FVA 54/7 $\varnothing_{oil} = 140^{\circ}\text{F}$ (60°C)	PASS	PASS
FZG scuffing test acc. to ISO 14635-1 $\varnothing_{oil} = 194^{\circ}\text{F}$ (90°C)	PASS	PASS
FZG slow-speed wear test acc. to DGMK 377-01 $\varnothing_{oil} = 194^{\circ}\text{F}$ (90°C) and 248°F (120°C)	PASS	PASS
FE8 wear test ¹ acc. to DIN 51819-3 $\varnothing_{oil} = 176^{\circ}\text{F}$ (80°C)	PASS	PASS
Foam test acc. to ISO 12152	PASS	PASS

Figure 8: Test program for fresh versus used high-performance gear oil. This table shows that the selected oil used for three years passed all tests required by any oil to properly protect gears and bearings. (Source: Klüber Lubrication. June 2017.)

The ISO foam test shows that the selected gear oil exhibited the required foam behavior after three years of use.

Also by the end of the oil change interval, advanced synthetic oil conclusively provides full micropitting and wear resistance as well as a good antifoam performance.

¹ DIN 51819-3: Testing of lubricants – Mechanical-dynamic testing in the roller bearing test apparatus FE8 – Part 3: Test method for lubricating oils, axial cylindrical roller bearing, 2005.

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IV. BASE OIL PURITY TO PROTECT AGAINST SHEARING

Understanding the issue

To protect all the components in a system, evaluation of lubricant viscosity is imperative. The kinematic viscosity of an oil is affected by a number of factors. One inherent physical property of a lubricant is its ability to maintain its viscosity after prolonged exposure to heat and use (shear). Maintaining a consistent viscosity during operation is imperative to protecting your equipment.

When formulating a lubricant, viscosity improvers (which are often polymer based) can be used in the base oil to increase the viscosity and viscosity index (VI). Viscosity modifiers are used in some environmentally acceptable lubricants (EALs), for example, to push the viscosity of a low-viscosity biodegradable oil to a higher viscosity value. Using viscosity modifiers with a low-viscosity base oil to manufacture a lubricant can be more cost effective than to use a high-viscosity base stock.

However, a lubricant containing viscosity improvers may not be as effective in high shear, high pressure and extreme temperatures. In these conditions, the oil can exhibit a temporary loss of viscosity. When shearing continues or if the forces are high enough, the polymers can break down, eventually causing a permanent loss of viscosity.

Advantages of advanced lubricant formulations

One measure of a lubricant's protective value is its ability to withstand shearing under pressure. Shear stability describes a lubricant's ability to resist a decrease in viscosity due to exposure to mechanical loads. Maintaining the appropriate and OEM-recommended viscosity is critically important to both protect the equipment and extend the time between oil change intervals.

Lubricant thinning under stress is the result of the breakdown of viscosity modifiers. Under stress, viscosity modifiers can either align at the molecular level, causing a temporary loss of viscosity—or they can break apart, causing a permanent loss in viscosity. Either scenario reduces their effectiveness in service. Increasing viscosity through the use of high-viscosity base stocks—without the use or only moderate use of viscosity modifiers—tends to provide better shear stability.

Important factors in stern tube bearings/shaft applications

Stern tube systems and thrusters stress the lubricant due to high loads, speed of rotation and heat. In a stern tube system, the weight of the propeller shaft and high thrust forces, combined with the speed of rotation and surface area, create significant shear stress on the lubricant.

Of course, the function of a lubricant is to protect the components it is lubricating, as well as improve efficiency by reducing friction and reduce heat generation. But to properly protect the components, an oil relies on two main properties: viscosity and additives.

Determining proper viscosity is necessary to ensure a proper elastohydrodynamic (EHD) lubrication film. This film is essentially a wedge of oil that builds up between two moving surfaces and provides a separation. It is this separation that helps protect the surfaces from wear, pitting and scuffing. EHD film thickness is a function of speed, pressure, surface condition, temperature and viscosity.

A reduction in viscosity, either temporarily or permanently, will reduce the lubricant's ability to create a fluid film to separate the shaft from the bearing. Thrusters operate under extreme loads as they transfer power generated by the vessel's engines through the bevel gears of the z-drive and onto the propeller. When the correct viscosity is not maintained, an increase in micropitting and gear wear may occur. The lubricant selected to

protect shafts, bearings and gears must be able to withstand high shearing forces.

Importance of monitoring oil viscosity and other factors

In practice, a good oil sampling program can be used to monitor the condition of the oil. Tracking the viscosity over time will detect loss of viscosity due to shearing. That's why monitoring trending data is part of a successful oil analysis program. The condition of oil should always be checked against a representative baseline. A baseline can be established by directly sampling the sump soon after filling with a fresh oil and after a short duration of operation. The frequency of sampling is typically established by the OEM or, depending on the application and operating conditions, an appropriate schedule of resampling can be established. An adequate interval is typically based on the number of service hours or at set intervals to check for viscosity stability. If one of the tested parameters ever falls out of the OEM-recommended range for the equipment, it should be replaced and a new baseline should be established.

Testing to validate solutions

While an oil analysis program will help accurately measure how the current oil is performing, there are numerous tests that manufacturers can perform, as detailed in the Appendix.

In general, it is important to note that many gear oils are made with polyisobutylenes (PIBs) to increase the viscosity of the base oil. This is done because it is less expensive to use a low viscosity oil and to artificially increase the viscosity with PIBs (Figure 9). When formulating a high-performance synthetic gear oil, Klüber Lubrication takes care to use only the highest quality raw materials to produce a gear oil that does not shear thin.

All of our products are made with oils that are inherently viscous. Otherwise, PIBs can be sheared during operation, which leads to permanent loss of viscosity and an insufficient lubricant film to protect your machinery. As lubricants with PIBs break down, they

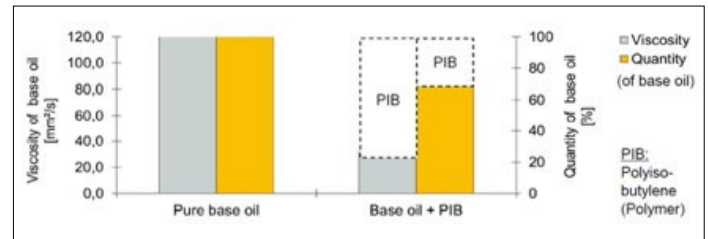


Figure 9: A comparison of viscosity based on composition of oils from Klüber Lubrication (yellow) versus competitive formulation (grey). (Source: Klüber Lubrication. June 2017.)

can release acids that can attack components. PIBs also make the oil much less resistant to aging, and after use, the oil can start to corrode and attack metals. This is confirmed by testing the oils after they have been put through simulated operation—and then testing the viscosity, oxidation stability and checking Total Acid Number (TAN) levels.

CONCLUSION

The advanced synthetic gear oils of today are expected to protect gears against damage such as wear or micropitting — even under critical lubrication conditions and during the entire oil change interval.

The test results show that the chemical and physical properties of advanced synthetic oils provide full micropitting and wear resistance as well as a good antifoam performance.

Concerns about low-temperature performance at slow operating speeds can be addressed by selecting advanced synthetic gear oil formulations.

In conclusion, high-performance synthetic gear oil can offer a wider spectrum of performance and protective benefits over the entire duration of use in a wide range of operating environments.

Consult with an expert to benefit from all the advantages now available with advanced synthetic oil formulations to optimize specific applications.

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APPENDICES:

A. INTRODUCTION

Methods

To determine the performance capacities of gear oils with regard to the prevention of micropitting and wear, the oils were subjected to standardized tests under common operating conditions and temperatures. Tested factors include:

1. The micropitting resistance in gears test:² Analyzed on the FZG micropitting test according to FVA 54/7 at an oil temperature of $\vartheta_{oil} = 194^{\circ}\text{F}$ (90°C). (It has become increasingly common to conduct micropitting tests at a reduced oil temperature of $\vartheta_{oil} = 140^{\circ}\text{F}$ (60°C) to determine if micropitting can be reliably prevented at these lower temperatures, which are encountered, for example, in wind turbine gearboxes.)
2. The slowspeed wear behavior of gears test:³ Analyzed in the FZG wear test according to DGMK 377-01 at oil temperatures of $\vartheta_{oil} = 194^{\circ}\text{F}$ (90°C) and 248°F (120°C). The influence of temperature is thus taken into account—albeit on a rather high level.
3. Foam behavior was analyzed according to the ISO 12152 foam test.
4. Low-temperature performance at 104°F (40°C) was tested using FZG back-to-back gear test rig by modifying the standardized test methods.

Tested lubricants

For micropitting tests, the selected high-performance gear oils employ a polyalphaolefin formulation showing high wear protection, high scuffing resistance as well as a high micropitting load-carrying capacity. This oil shows very low gear wear determined by the FZG slow-speed wear test according to DGMK 377-01 at oil temperatures of 194°F (90°C) and 248°F (120°C).

The scuffing, load-carrying capacity tested in the FZG test rig according to ISO 14635-1 at a circumferential speed of $v_t = 8.3 \text{ m/s}$ is very high⁴. The micropitting load carrying capacity tested in the FZG micropitting test according to FVA 54/7 at an oil temperature of 60°C is high as well. Another tested gear oil is of ISO VG 320 and is a specified CLP gear oil according to DIN 51517-3 requirements.⁵ This includes the minimum requirements for industrial gear oils and is similar to ANSI/AGMA 9005-F16 Industrial Gear Lubrication standard.⁶

High-performance gear oils based on polyalphaolefin are typically used in wind turbines. Klübersynth GEM 4-320 N is one such gear oil and, in fact, was used for three years in the field, and it was employed 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 ($50 \mu\text{m}$) and an off-line system ($5 \mu\text{m}$). 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.

Fresh and used oil was employed to test length of service life as a variable VV. This variable determined 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 (Figure 10).

Low-temperature tests were also conducted using mineral oil, polyalphaolefin or polyglycol oils.

All tested gear oils are of ISO VG 220 and are specified according to DIN 51517-3, which includes the minimum requirements for industrial gear oils and is similar to AGMA 9005. The oil data of the tested gear oils are shown in Figures 10 and 11.

²FVA 54/7: Test procedure for the investigation of the micro-pitting capacity of gear lubricants, FVA information sheet, Forschungsvereinigung Antriebstechnik e.V., 1993.

³DGMK 377-01: Method to assess the wear characteristics of lubricants – FZG test method C/0.05/90:120/12, 1997.

⁴ISO 14635-1:2000 Gears – FZG test procedures – Part 1: FZG test method A/8.3/90 for relative scuffing load-carrying capacity of oils, 2000.

⁵DIN 51517-3: Lubricants – Lubricating oils – Part 3: Lubricating oils CLP; Minimum requirements, 2011.

⁶AGMA 9005-E02: Industrial Gear Lubrication Standard.

Criterion	Limits		Results
	GEM 4-320 N (fresh)	GEM 4-320 N (used)	GEM 4-320 N (used)
Water content in %	<0.3	<0.3	0.005
Viscosity at 104°F (40°C), mm ² /s	268 ... 352	256 ... 384	322
Viscosity at 212°F (100°C), mm ² /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
Copper, ppm	<10	Depending on application	<10
Iron, ppm	<10	Depending on application	<10
Infrared spectroscopy	No deviation	No deviation	Corresponds without any deviation

Figure 10: Oil condition of fresh and used high-performance gear oils. (Source: Hochmann, Mazzola, and Ward. Power Transmission Engineering, 2014.)

Product	Klüberoil GEM 1-220 N	Klübersynth GEM 4-220 N	Klübersynth GH 6-220
Symbol	GEM 1 N	GEM 4 N	GH 6
ISO VG	220	220	220
Base oil	Mineral oil	Polyalphaolefin	Polyglycol
DIN 5157, AGMA 9005 designation	CLP, EP oil	CLP HC, EP oil	CLP PG, EP oil
FZG slow-speed wear test according to DGMK 377-01, $\dot{\omega}_{oil} = 194^{\circ}\text{F}$ (90°C) and 248°F (120°C)	≤ 20 mg	≤ 20 mg	≤ 20 mg
FZG micropitting test according to FVA 54/7 $\dot{\omega}_{oil} = 140^{\circ}\text{F}$ (60°C)	GFT-high	GFT-high	GFT-high
FZG wear test according to DIN 51819-3 $\dot{\omega}_{oil} = 176^{\circ}\text{F}$ (80°C)	≤ 10 mg	≤ 10 mg	≤ 10 mg

Figure 11: Oil data of the tested high-performance gear oils. (Source: Hochmann, Mazzola, and Ward. Power Transmission Engineering, 2014.)

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Load stage	Pinion torque, T_1 , Nm	Hertzian pressure, p_c , N/mm ²
LS5	70.0	795.1
LS6	98.9	945.1
LS7	132.5	1093.9
LS8	171.6	1244.9
LS9	215.6	1395.4
LS10	265.1	1547.3

Figure 12: Load stages of micropitting test. (Source: Hochman. AGMA Technical Paper, 2012.)

B. 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 an FZG back-to-back gear test rig.⁷ Test gears type C-GF run at a circumferential speed of $v_t = 8.3$ m/s and an oil temperature of $\vartheta_{oil} = 194^\circ\text{F}$ (90°C) or 140°F (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 Figure 12. 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 $7.5 \mu\text{m}$. 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 Figure 13.

Lubricants with a high micropitting load-carrying capacity reach the failure criterion of a profile form deviation of $7.5 \mu\text{m}$ due to micropitting in load stage \geq LS 10 of the load stage test (GFT-high) (Figures 14 and 15).

Classification of test results for micropitting test.			
Low micropitting load-carrying capacity	\leq LS7	Sometimes more than 50%	GFT – low
Medium micropitting load-carrying capacity	LS8 – LS9	About 30%	GFT – medium
High micropitting load-carrying capacity	\geq LS 10	Less than 20%	GFT – high

Figure 13: Classification of test results for micropitting test. (Source: Hochman. AGMA Technical Paper, 2012.)

C. 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 can be used for relative ranking of gear oils to a reference oil. Furthermore, specific wear rates cIT can be derived for inclusion in the wear calculation method developed by Plewe.⁸

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. 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 $v_t = 0.05$ m/s. The load applied is load stage LS 12, 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 $\vartheta_{oil} = 194^\circ\text{F}$ (90°C) during test part 1 of 2×20 hours and $\vartheta_{oil} = 248^\circ\text{F}$ (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 $\vartheta_{oil} = 194^\circ\text{F}$ (90°C).

The test is run on a modified FZG back-to-back gear test rig according to ISO 14635-1 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 (Figure 16), as well as the failure limits (Figure 17).

For high-performance gear oil, a test result of the FZG slow-speed wear test is given showing a very low wear behavior (Figure 18). 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.

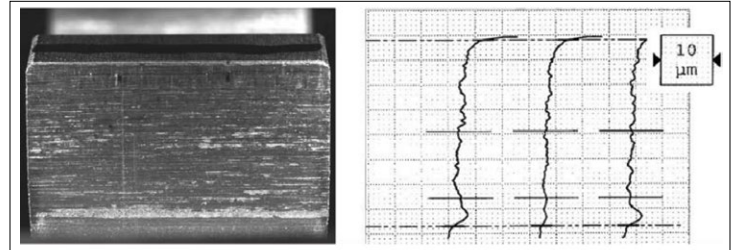


Figure 14: Pinion type C-GF; with measurement of the profile: Nearly no micropitting failure.
(Source: Hochmann. AGMA Technical Paper, 2012.)

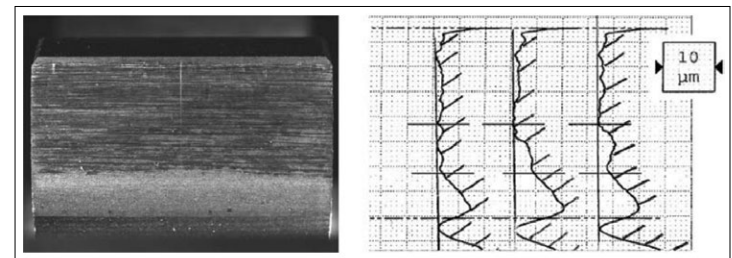


Figure 15: Pinion type C-GF; with measurement of the profile: Micropitting failure in the range of the failure criterion.
(Source: Hochmann. AGMA Technical Paper, 2012.)

Wear category	Sum wear per test part, mg
Low	<40
Medium	<170
High	<400
Very high	>400

Figure 16: Classification of test results of the slow-speed wear test.
(Source: Hochmann. AGMA Technical Paper, 2012.)

Description	Failure limit, mg
Roller wear	≤ 30

Figure 17: Limits for the test results of the FE8 wear test.
(Source: Hochmann. AGMA Technical Paper, 2012.)

⁸ Plewe H.-J.: Untersuchungen über den Abriebverschleiß von geschmierten, langsam laufenden Zahnrädern, Dissertation, TU München, 1980.

Not all synthetic gear oils are created equally

How differences in synthetic oil formulations affect fatigue failure, low-temperature performance, service life and shear stability

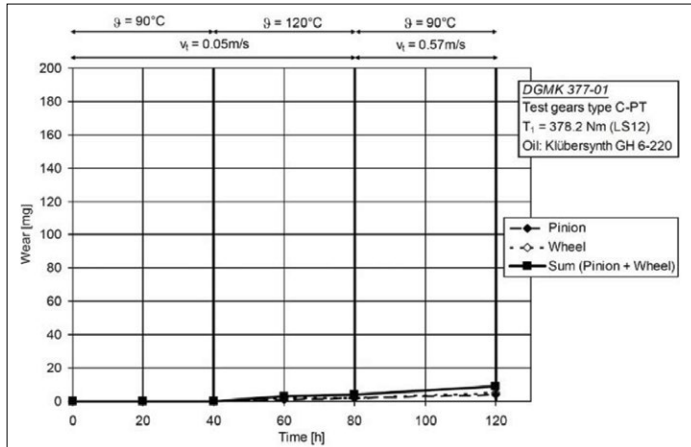


Figure 18: Slow-speed wear test of a high-performance gear oil. (Source: Hochmann. AGMA Technical Paper, 2012.)

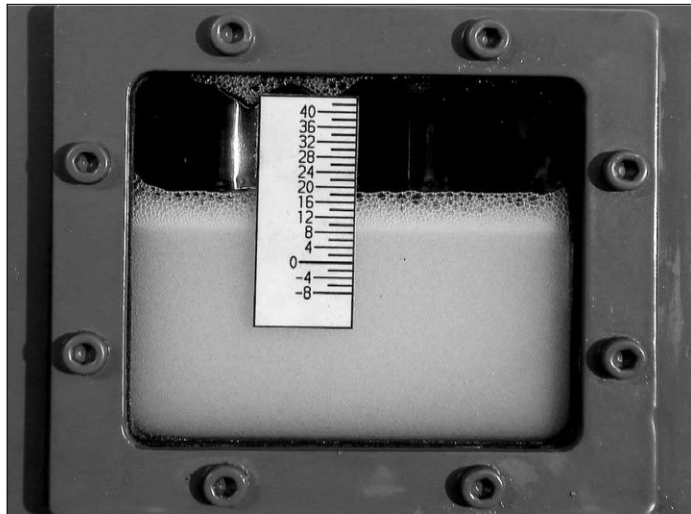


Figure 19: Foam measure scale of the foam test according to ISO 12152.

D. ISO 12152 FOAM TEST⁹

At the beginning of this test, the oil temperature is at $\vartheta_{oil} = 25^{\circ}\text{C}$. The gears rotate with a speed of $n = 1,450$ rpm for 5 min. After this, the observation of the foam behavior lasts 90 minutes. Figure 19 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 that has to be filled in. The total volume increase and the oil and air dispersion can be read from the scale.

The classification of the foam behavior of fresh gear oils is shown in Figure 20 according to the GG-V 425 Flender report.¹⁰ 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% (Figure 20).

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

E. LOW-TEMPERATURE TESTS: MODIFIED FZG MICROPITTING AND SLOW-SPEED METHODS

To find out if the high-performance gear oils of today can reliably protect gears and rolling bearings in gearboxes against damage at lower oil temperatures, the standardized test methods have to be modified. For the FZG micropitting test according to FVA 54/7, the FZG slow-speed wear test according to DGMK 377-01 is used with the oil temperature reduced to 104°F (40°C).

All other test conditions—including load and speed—are unchanged. The modification of the micropitting test GF-C/8.3/40 consists of a load stage test and an endurance test performed on an FZG back-to-back gear test rig. Test gears type C-GF run at a circumferential speed of $v_t = 8.3$ m/s and a lubricant temperature of $\vartheta_{oil} = 104^{\circ}\text{F}$ (40°C). The load and the test periods are varied.

The wear behavior is determined in the modified FZG slow-speed wear test C/0.05:0.57/40:40/12 (see Figure 21). Test gears type

⁹ 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.

¹⁰ Flender Foaming Test GG-V 425. "Description of Test Apparatus," test conducted 2001.

Evaluation of 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%

Figure 20: Classification of foam behavior for fresh gear oils.
(Source: Klüber Lubrication, Foam test procedure according to FLENDER report GG-V 425.)

C-PT run at a circumferential speed of $v_t = 0.05\text{m/s}$ and are loaded with load stage LS 12. The oil temperature is $\vartheta_{oil} = 104^\circ\text{F}$ (40°C) during test part 1 of 2×20 hours and $\vartheta_{oil} = 104^\circ\text{F}$ (40°C) during test part 2 of 2×20 hours. In the optional test part 3 of 1×40 hours, a higher circumferential speed of $v_t = 0.57\text{m/s}$ is run at an oil temperature of $\vartheta_{oil} = 104^\circ\text{F}$ (40°C).

Test results show that the advanced additive technologies used in today's high-performance gear oils are capable of inducing the required reactions on the surfaces of gears and bearings at 104°F (40°C), thus providing reliable damage protection even under these operating conditions.

High-performance gear oils (GEM 1 N, GEM 4 N and GH 6) based on mineral oil polyalphaolefin and polyglycol were used. An FZG micropitting test at an oil temperature of $\vartheta_{oil} = 140^\circ\text{F}$ (60°C) was performed showing a high micropitting load-carrying capacity of GFT-high for all tested gear oils. Additionally, the FZG micropitting tests at the reduced oil temperature of $\vartheta_{oil} = 104^\circ\text{F}$ (40°C) reached a high micropitting load-carrying capacity of GFT-high for these gear oils. This shows that the advanced additive technologies can react at the surface of the tooth flanks after also at low oil temperatures and build up a reaction layer. Micropitting formation can be prevented even under these operating conditions.

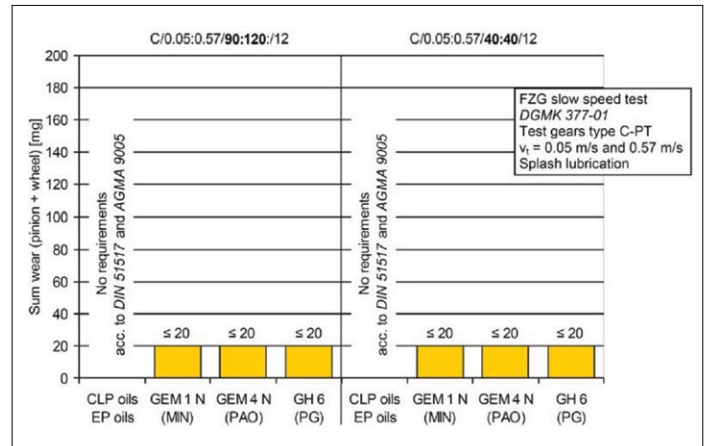


Figure 21: Wear protection for rolling bearing at mid oil temperature by using high-performance gear oils. The left graph shows the test at the standard 194°F (90°C) and 248°F (120°C) and the right graph at 104°F (40°C) for the duration. While most additive packages need higher temperatures to activate protection, with Klüber Lubrication oils, the wear on gears remained low even at low temperatures.
(Source: Hochmann. AGMA Technical Paper, 2012.)

Not only were oil temperatures of $\vartheta_{oil} = 194^\circ\text{F}$ (90°C) and 248°F (120°C) used for the FZG slow-speed wear test but also the modified FZG slow-speed wear test used a reduced oil temperature of $\vartheta_{oil} = 104^\circ\text{F}$ (40°C). In all conditions, the tested high-performance gear oils (GEM 1 N, GEM 4 N and GH 6) based on mineral oil, polyalphaolefin and polyglycol demonstrated their very low wear behavior with a sum wear on pinion + wheel of less than 20mgm.

The reason for this is, once again, the advanced additive technologies in these high-performance gear oils. Even at reduced oil temperatures, these advanced additive technologies can react at the surface of the tooth flanks and build up a reaction layer, preventing wear failure.

This white paper has been prepared by Klüber Lubrication to serve as a general guide. If a more detailed explanation is required, please contact your nearest Klüber Lubrication representative or the manufacturer of the lubricant you are using.

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How differences in synthetic oil formulations affect fatigue failure,
low-temperature performance, service life and shear stability

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