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TEST METHODS FOR GEAR LUBRICANTS

Abstract

Base oil type, oil viscosity, additive type and content have a strong influence on typical gear failures. In general it is not possible to quantify the lubricant influence on load carrying capacity simply from the knowledge of physical or chemical oil data. Therefore many test methods were developed for the evaluation of mechanical-technological lubricant properties. Simple low-cost bench test methods often show poor correlation with practice. From experience and systematic investigations it can be shown that testing of gear lubricants can adequately be performed only in gear test rigs using specified test gear geometry [1].

In continuous work over many years the standard FZG back-to-back gear test rig was developed and improved for different types of gear failure simulation. The standard FZG oil test A/8,3/90 is widely used for the evaluation of the scuffing properties of industrial gear oils. Automotive gear oils of GL4 level can be tested in the step test A10/16.6R/90, axle oils of GL5 level in the shock test S-A10/16.6R/90. For the slow speed regime the wear test C/0.05/90:120/12 can be applied. The influence of lubricants on the micropitting performance of gears can be evaluated in a screening short test GFKT-C/8,3/90 or in the full micropitting test GF-C/8,3/90. Different pitting tests are available as single stage test PT-C/9:10/90 or application test PTX-C/SNC/90.

The aim of the paper is to describe the influence of the lubricant on the different failure modes in gears, how to quantify this influence in adequate test methods and how to introduce the results of such tests as "strength values" for the lubricant into load carrying capacity rating methods.

1. Introduction

For better efficiency in transmissions, lower viscosity grades of gear oils and less oil volumes are used. With increasing power density and extended oil drain intervals the demands on the lubricant as a design element increase accordingly. The introduction of lubricant properties in load carrying capacity rating requires not only knowledge of their physical properties as e.g. viscosity, viscosity-temperature- or viscosity-pressure-behaviour but also the quantitative influence of an EP oil on scuffing, wear, micropitting and pitting of gears. Numerous test methods were developed to describe lubricant properties. Simple and low-cost bench tests on the one end as well as full scale field testing on the other end can be taken into consideration [1]. The aim would be a test method as simple, cheap and quick as possible to produce comparable results to practical applications.

Figure 1 shows some of the test arrangements developed for the prediction of scuffing and wear properties of gear oils. Closest to practice are methods using test gears. Methods on disk type rigs often simulate one point on the path of contact of a gear mesh with its local rolling and sliding velocity. Most of the rigs use simple specimen under pure sliding conditions.

Figure 2 shows scuffing results on some of these rigs for different "lubricants" including milk and beer [2]. In the often specified four ball and Timken tests milk and beer are rated with higher scuffing load capacity as a non-EP mineral oil ISO VG 220 or a hydraulic oil with ZDTP additives ISO VG 46. Only the FZG test using test gears gives a correct relative rating of these lubricants. Even results from twin disk machines with a close simulation of the kinematics of one point on the path of contact can be quite misleading. Two standard hypoid gear oils and one with an additional MoS_2 content were evaluated in a hypoid gear, a spur gear and a twin disk test (Figure 3). While the two gear tests showed rather poor performance for the MoS_2 containing lubricant of less than 50 % of the standard oils the twin disk result was at 300 %.

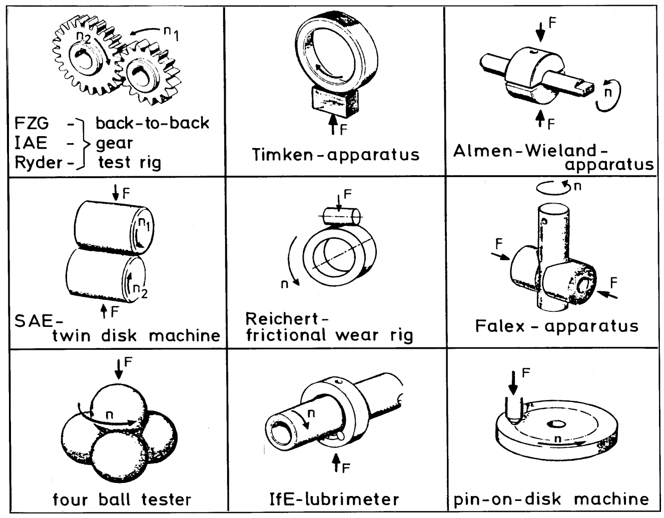


Figure 1: Lubricant test arrangements (schematic)

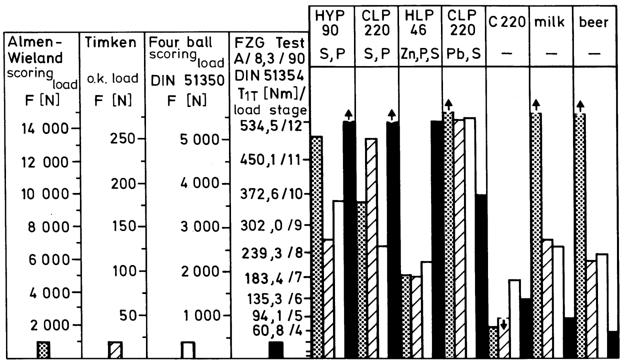
2. Test rig and test gears

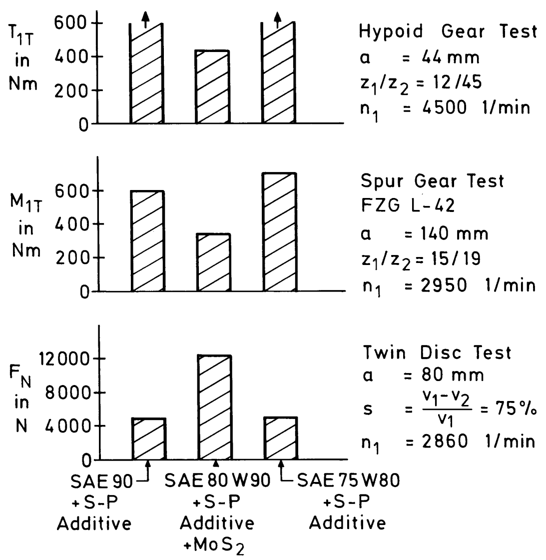
With this experience a number of test methods for gear lubricants was developed using the FZG back-to-back gear test rig where over 500 machines are available world-wide [3].

2.1 Test Rig

The FZG gear test rig is a back-to-back rig with centre distance a=91.5 mm [4]. The test gears and the slave gears are connected by two shafts. One shaft is divided in two parts with the load clutch in between. One half of the load clutch can be fixed to the foundation with the locking pin while the other half is twisted e.g. by means of a lever and weights. After bolting the clutch together the load can be removed and the shaft be unlocked. Thus a static torque is applied to the system which can be checked

Figure 2: Scuffing results for different lubricants [2]





Arrows indicate results outside test range

Figure 3: Scuffing results in disk and gear tests

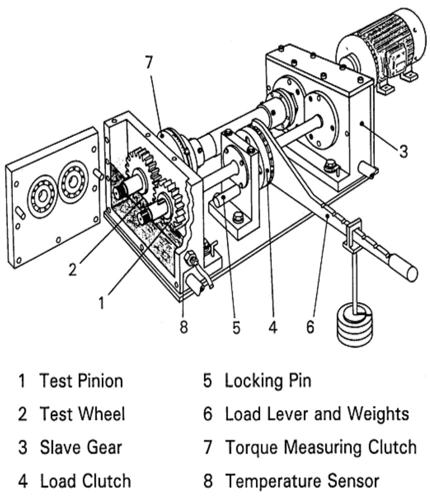


Figure 4: FZG back-to-back gear test rig

in the torque measuring clutch as the twist of a calibrated torsion shaft. The rig can be operated either with a two speed AC motor at 1500/3000 rpm or a variable speed DC motor between n = 100 - 3000 rpm. The gears are normally dip lubricated with a heater and a cooling coil in the test head for temperature control. With an additional oil supply device also spray lubrication can be applied.

2.2 Test Gears

For the different standard tests there are two standard test gear geometries in use [3]. For scuffing tests gear type A with high sliding at the pinion tip is used while gear type C with balanced sliding is used for wear, micropitting and pitting tests. The main data of the test gears are summarized in Table 1. Test gears are case carburised with a surface hardness of HRC = 60 + 2 and a case depth of Eht = 0.6 - 0.9 mm. The surface roughness is controlled to the required values of the respective test procedure. Test gears are manufactured in batches of 100 pairs by one manufacturer and closely controlled to metallurgical properties, gear accuracy and surface finish.

3. Test Methods

For the different gear failure modes which can be influenced by the lubricant type, viscosity and additive system adequate test methods were developed in close co-operation with industry. In some cases different modifications of the test methods are available adjusted to the specific application. In the following often used methods are described.

Table 1: Main data of test gears

		symbol	unit	A-type	C-type
centre distance		a	mm	91,5	
number of teeth	pinion	z_1	-	16	
	gear	z_2	-	24	
module		m	mm	4,5	
pressure angle		α	°	20	
helix angle		ß	°	0	
face width		b	mm	20	14
profile shift factor	pinion	x_1	-	0,8532	0,1817
	gear	x_2	-	-0,5	0,1715
pitch diameter	pinion	d_{w1}	mm	73,2	
	gear	d_{w2}	mm	109,8	
tip diameter	pinion	d_{a1}	mm	88,8	82,5
	gear	d_{a2}	mm	112,5	118,4
material		MAT	-	20MnCr5	16MnCr5
heat treatment		-	-	case carburized	

3.1 Scuffing Load Capacity Tests

A widely used test method for the evaluation of the scuffing properties of industrial gear lubricants is the FZG gear oil test A/8.3/90 according to DIN ISO 14635-1 [4], which is equivalent to other standards as IP 334 [5], ASTM D-5182 [6], CEC L-07-A-95 [7] and identical to ISO DIS 14635-1 [8].

A-type gears are loaded stepwise in 12 load stages between a Hertzian stress of pC = 150 to 1800 N/mm². They are operated for 15 min at a pitch line velocity of 8.3 m/s and a starting oil temperature of 90 ^{0}C in each load stage, under conditions of dip lubrication without cooling. In the visual test the gear flanks are inspected after each load stage for scuffing marks. Failure load stage is indicated when the faces of all pinion teeth show a summed total width of damaged areas which is equal or exceeds one tooth width. In the gravimetric test the gears are dismounted and weighed to determine their weight loss. From the curve of the weight loss the specific wear parameter can be evaluated as well as the scuffing load stage which is indicated by a steep increase of the wear curve.

lubricant type	typical ISO VG	typical scuffing load stage		
		non EP	mild EP	EP oil
ATF	32-46	2-4	ATF	32-46
turbine oil	32-68	3-5	turbine oil	32-68
industrial gear oil	100-320	5-7	industrial gear oil	100-320
transmission oil	100-220	-	transmission oil	100-220
axle oil	150-220	-	axle oil	150-220

Table 2: Typical results of the standard scuffing test

Table 2 shows typical results of gear lubricants in this test. It is obvious that for industrial applications with high scuffing demands of minimum API GL3 as e.g. in street cars or wind turbines as well as in automotive applications as e.g. in manual transmissions of commercial vehicles with API GL4 and in hypoid rear axles with API GL5 requirements the standard test has not sufficient discriminating power.

For automotive gear oils of API GL4 level no accepted test method is available, for API GL 5 oils the CRC or the FZG L-42 test [9] can be used. In systematic investigations on the standard FZG gear test rig the scuffing risk of the standard procedure was increased by varying speed and specific load, load application and sense of rotation. A step test A10/16.6R/90 for lubricants up to the level of GL 4 and a shock test S-A10/16.6R/90 for discrimination between GL4 and GL5 were developed. A-type test gears with reduced pinion face width to b = 10 mm (A10) are used at increased speed of 16.6 m/s (16.6) and reversed sense of rotation (R), at oil temperature of 90 °C (90). In the step test load is stepwise increased until scuffing occurs. In the shock test (S) the gears are directly loaded in the expected load stage and PASS or FAIL is stated. A detailed description of the test procedures can be taken from the FVA Information Sheet [10].

A comparison of results from different scuffing test methods is shown in Figure 5. With these tests it is possible to cover the whole range of scuffing load capacity between API GL1 to GL5. Besides a relative ranking of lubricants with respect to their scuffing performance the results of these tests can also be recalculated to critical scuffing temperatures and be introduced into the DIN [11] and ISO [12] standards of scuffing load capacity rating. On the basis of the critical scuffing temperature, different test methods can be compared as shown in Figure 6.

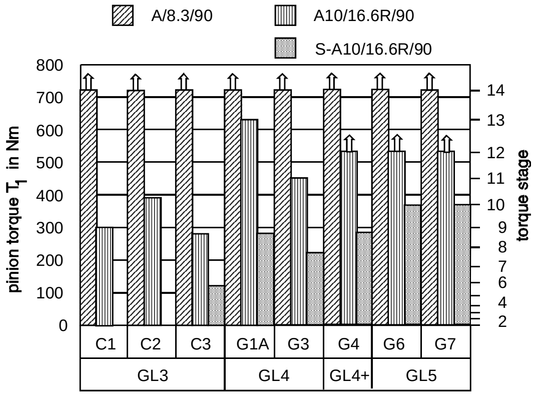


Figure 5: Scuffing results for different lubricants

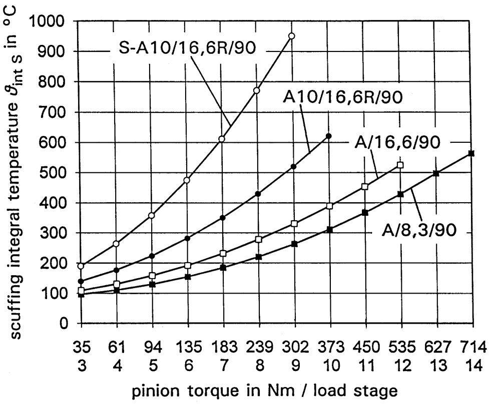


Figure 6: Comparison of scuffing test methods

3.2 Slow Speed Wear Test

The Chevron Test [13] for tractor hydraulic fluids of low viscosity grade can normally not discriminate different industrial or automotive gear oils of higher viscosity. Therefore a new universal wear test C/0.05/90:120/12 was developed (see Table 3). Pitting test gears type C-PT (C) are used at a pinion speed of 0.05 m/s (0.05) - equivalent to 13 rpm at the pinion - at oil temperatures of 90 and 120 C (90:120) at highest load stage 12 (12) - equivalent to a pinion torque of T1 = 378,2 Nm. As a minimum the method consists of two test parts. A detailed description of the test procedure can be taken from the DGMK Information Sheet [14]. For running the test

test conditions	C/0,05/90/12	C/0,05/120/12	C/0,57/90/12
pitch line velocity	0,05 m/s	0,05 m/s	0,57 m/s
pinion speed wheel speed	13 rpm 8,7 rpm	13 rpm 8,7 rpm	150 rpm 100 rpm
oil temperature	90°C	120°C	90°C
pinion torque	378,2 Nm	378,2 Nm	378,2 Nm
running time	2 x 20 h	2 x 20 h	1 x 40 h
revolutions of shaft 2	2 x 10400	2 x 10400	1x240000
test result	weight loss of pinion and gear		

Table 3: Test conditions of the wear test C/0,05/90:120/12

the standard FZG rig must be modified with a speed reducer between driving motor and slave gear box.

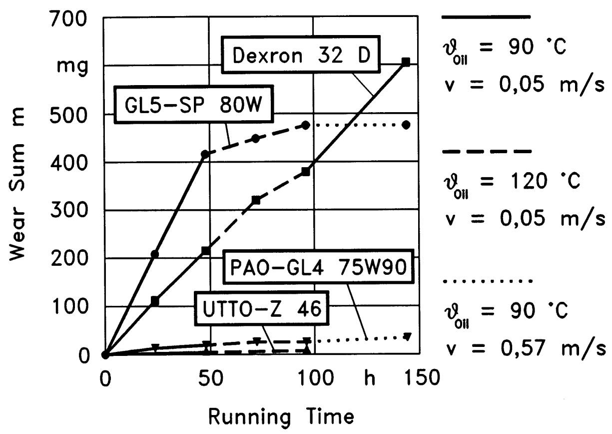
Part 1: C/0.05/90/12 Part 1 runs two times 20 h with intermediate weighing of pinion and gear. The pitch line velocity is v = 0.05 m/s, and the oil sump temperature is maintained at ϑoil = 90℃. This condition gave the highest wear rat es for all tested lubricants.

Part 2: C/0.05/120/12 Part 2 runs also two times 20 h with intermediate weighing of pinion and gear. The oil sump temperature is increased to ϑoil = 120℃ with the other parameters kept constant, to check the additive reaction at elevated temperature.

The two parts have always to be carried out for testing a lubricant. Part 3 can be added for more detailed information in one operating condition.

Part 3: C/0.05/90/12 or C/0.05/120/12 or C/0.57/90/12 Part 3 runs 40 h without intermediate weighing. C/0.05/90/12: Repeating the test conditions of part 1 can show how mechanical and chemical changes on the flank surface are relevant under changing operating conditions. C/0.05/120/12: Repeating the test conditions of part 2 can be appropriate when the operating conditions in practice are predominantly at a higher temperature level and the results of part 2 are not yet sufficient or have not yet arrived at a steady state level. C/0.57/90/12: Changing the pitch line velocity to v = 0.57 m/s, corresponding to a pinion speed of n1 = 100rpm, can show the influence of higher speed and thus higher film thickness and better lubricating conditions on the wear behaviour. The oil temperature of ϑoil = 90℃ was chosen, because in most cases at the lower temperature higher wear rates were found.

Figure 7: Results from the FZG wear test



Different gear lubricants - hydraulic oils, ATFs, turbine oils, industrial gear oils and automotive gear oils of GL4 and GL5 performance - were tested under these conditions. Typical test results are shown in Figure 7. It can be seen from this Figure that different categories of wear behaviour can occur:

- high or medium wear rate in both parts 1 and 2 (e.g. Dexron 32 D)
- high or medium wear rate in part 1 and low wear rate in part 2 (e.g. GL5-SP 80W)
- low wear rates in both parts 1 and 2 (e.g. UTTO-Z 46).

Predictions of wear results from viscosity parameters or additive content are not possible. The experimental results of the wear test can be introduced as specific wear rate values clt into the wear calculation method according to Plewe [15].

3.3 Micropitting Test

For low churning losses and high efficiency in torque converters low viscosity grade lubricants are often used. To compensate for the wear and scuffing performance loss due to a lack of viscosity, various anti wear and EP additives are used in higher concentrations. The type of the base oil and the additive type show a large influence on micropitting failure of gears [16].

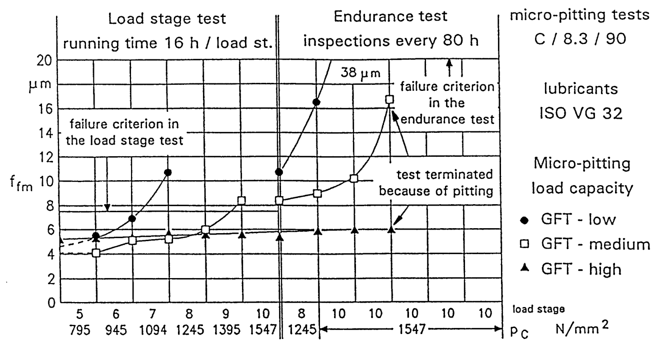


Figure 8: Typical micropitting test results

The standard test method GF-C/8,3/90 for the evaluation of the micropitting performance of lubricants was established. The test requires an oil spray device for constant oil temperature of ϑoil = 90 C (90) at an oil flow rate of V = 2 l/min. Gear type C with a specified high surface roughness of Ra = 0.5 ± 0.1 µm (GF-C) are run at a pitch line velocity of v = 8.3 m/s (8,3). A one hour run-in in load stage 3 (pC = 500 N/mm2) is followed by the short term test in load stages 5 through 10 (pC = 800 - 1500 N/mm2). Running time is 16 h per load stage. After every load stage the gears are dismounted and the profile deviation is measured. If the profile has changed to a profile deviation of 7.5 µm (corresponding to a change of DIN accuracy from 5 to 6) the test is terminated, the failure load stage is reached.

In case of failure in load stages 8, 9, 10 or over 10 an endurance test with the same gear pair is performed. 80 h in load stage 8 are followed by maximum 5 times 80 h in load stage 10. The gears are inspected after every test sequence and the profile deviation is again measured. When the profile error exceeds 20 µm (corresponding to a change of the DIN accuracy to 9) or large pitting occurs, the endurance test is terminated. A detailed description of the test method can be found in [17]. Figure 8 shows examples of lubricants with different micropitting capacity.

Because of the very long running time of the standard micropitting test an additional micropitting short test GFKT-C/8,3/90 for screening purposes was developed [18]. The test is run at dip lubrication conditions and in a shortened step test procedure.

The one hour run-in in load stage 3 is followed by 16 h each in load stages 7 and 9. The test result is the evaluation of the micropitting class. When the failure criterion of 7,5 µm profile deviation is exceeded after load stage 7 the lubricant is rated with micropitting capacity low, if 7,5µm is exceeded after load stage 9 the rating is micropitting capacity medium and if the profile deviation after load stage 9 is below 7,5 µm the rating is micropitting capacity high. A comparison between results of the standard test and the short test showed good correlation (Figure 9).

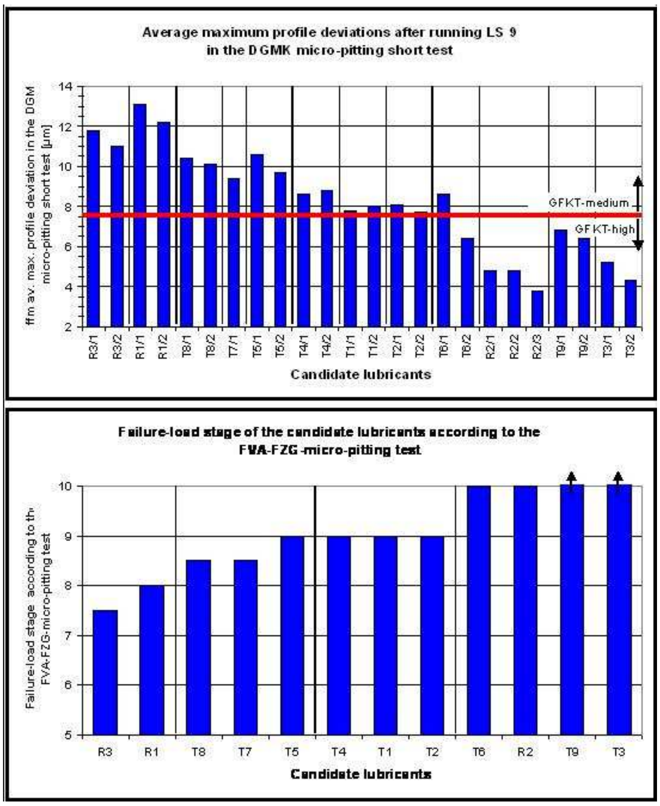


Figure 9: Results of short and standard micropitting test

Predictions of micropitting results from viscosity parameters or additive content are not possible. The experimental results of the tests can be introduced into a micropitting capacity rating method according to Schrade [19].

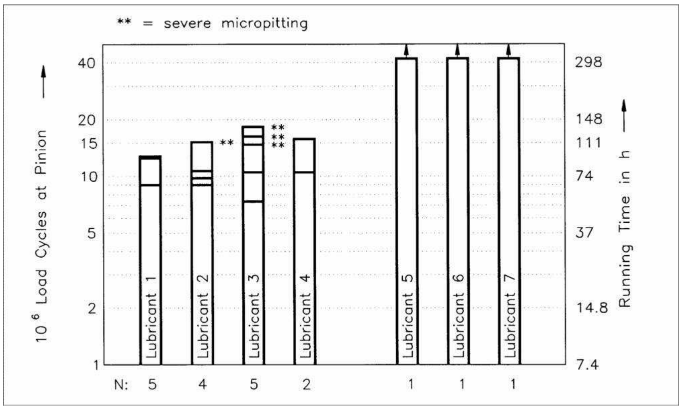
3.4 Pitting Tests

Lubricant type, viscosity and additive system influence the pitting life of gears. Especially for automotive gear oils a single stage test method PT-C/9:10/90 for the evaluation of the relative pitting life was developed. Running an oil in the pitting test requires a minimum scuffing load stage of at least load stage 9 (pC = 1350 N/mm²). Otherwise the gears will experience scuffing under the conditions of the pitting test.

Gear type C with a specified low surface roughness of Ra = 0.3 ± 0.1 µm (PT-C) are run at a pitch line velocity of v = 8.3 m/s in torque stage 9 for low viscosity gear oils below VG 100 and in torque stage 10 for medium and high viscosity gear oils of VG 100 or higher (9:10). The gears are dip lubricated with a constant oil temperature of ϑoil = 90 C (90). A cooling coil with water supply has to be mounted on the top cover of the test gear box.

A run-in of 2 h in torque stage 6 (pC = 1100 N/mm²) is followed by the test run in the respective torque stage until the failure criterion is reached. Failure criterion is normally 4 % pitted area on one tooth flank of the pinion. The number of load cycles until failure is reported and compared to the life of a reference oil. Because of the rather large scatter of pitting life, at least 3 test runs with one lubricant are required for a statistically meaningful result. For the pitting failure life a Weibull distribution is assumed and the load cycles for 50% (L50) failure probability are reported [20]. This value is compared with the L50 values of reference lubricants. Figure 10 shows results of different gear lubricants in the standard single stage test PT-C/9/90.

The result of the standard pitting test is often strongly influenced by the occurrence of micropitting. Therefore a practice relevant pitting test PTX-C/10/90 was developed using modified test gears PTX-C with tip and root relief as well as lengthwise crowning at the wheel together with superfinished surfaces of pinion and wheel to suppress micropitting. The application test PTX-C/SNC/90 [21] extends the test method to two different load levels dependent of the result of the single stage test in load stage 10. If the mean pitting life of three runs in load stage 10 is equal or less than 15 million pinion cycles at least two more test runs are added in load stage 9. If the result in load stage 10 is over 15 million cycles the test is followed by additional test runs in load stage 11.



N: number of test runs for each lubricant

Figure 10: Pitting results in load stage 9 for different lubricants

Figure 11 shows the result of a lubricant in the application test.

Test results from the pitting test can be introduced into the ISO calculation procedure [22] by defining a new time strength branch of the SN-curve compared to the standard SN-curve for the non-EP oil of same viscosity. The approach is very conservative because the endurance level is kept constant. Improvements are therefore only calculated for gear pairs with limited life.

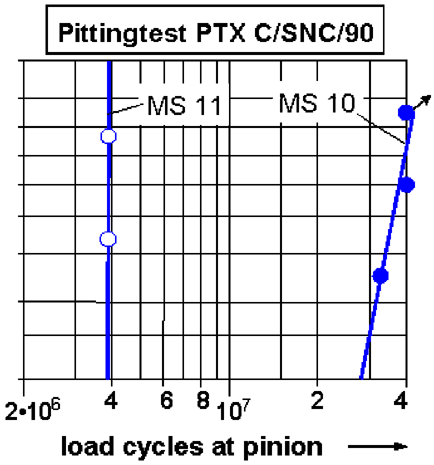


Figure 11: Result of the application test

4. Summary

The standard FZG back-to-back gear test rig and required modifications for certain tests are described. Standard and standardized test methods for the evaluation of lubricant influence on scuffing, wear, micropitting and pitting failures of gears are described. Test results of different gear oils from the market place and their introduction in calculation methods are shown.

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621.892.094	maziva za zupčaste prijenosnike	gear lubricants
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