

New Test Methods for the Evaluation of Wear, Scuffing and Pitting Capacity of Gear Lubricants

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American Gear Manufacturers Association



TECHNICAL PAPER

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[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

For maximum energy savings low viscosity lubricants are frequently used. Increasing transmitted power leads to higher temperatures and thus thinner lubricating films. These tendencies increase the failure probability in gear contacts with respect to wear, scuffing, micropitting and pitting performance.

New test methods on modified FZG gear test rigs were developed to evaluate the load carrying capability of gear lubricants.

For the low speed regime a wear test using C-type gears at low pitch line velocity of 0.05 m/s, and two different temperatures of 90 and 120 °C to consider different additive response at high loading of load stage 12 (C/0.05/90:120/12) was developed and applied to many different lubricants.

New scuffing procedures for gear lubricants of scuffing performance between API GL 3 and GL 5 were developed. The step test A10/16.6R/90 uses A-type gears of 10 mm pinion face width at 16.6 m/s pitch line velocity with a driven pinion. A discrimination of all gear oils up to the level of API GL 4 is possible. A shock test S-A10/16.6R/90 with direct loading in the expected load stage discriminates between GL 4 and GL 5 lubricants.

Different standard pitting tests are available for different lubricant viscosity grades using C-type gears at 8.3 m/s pitch line velocity and 90 °C in load stages 9 (PT C/9/90) or 10 (PT C/10/90). For automotive applications load spectrum testing is possible at low (PT C/LLS/90) and high (PT C/HLS/90) loads. For applications with long oil drain intervals a combined pitting and oil ageing test was developed (PITS C i85 TS) using C-type gears at variable load, speed and temperature conditions. At high temperature conditions between 120 and 150 °C the oil ageing properties together with their influence on pitting characteristics is evaluated in correlation to a reference oil.

The test methods are described. Test results with different market products are discussed.

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NEW TEST METHODS FOR THE EVALUATION OF WEAR, SCUFFING, AND PITTING CAPACITY OF GEAR LUBRICANTS

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1 Introduction

The lubricant as a design element can play an important role in the slow speed wear, scuffing, micropitting and pitting behavior of gears in power trains. With the demand of extended oil drain intervals, predominantly in automotive applications, not only the performance of the new oil but also that of used oils with thermal and oxidative degradation has to be observed. Base oil type, viscosity and additive system influence the different failure modes. Comprehensive knowledge of the lubricant performance under comparable test conditions is the key factor for lubricant optimization for transmissions in practice.

A number of test methods was developed using the FZG back-to-back gear test rig where over 500 machines are available world-wide. These methods are the Chevron wear test A/0.57/120/10 for tractor hydraulic fluids [1], the scuffing test A/8.3/90 [2, 3], the micropitting test GF C/8.3/90 [4] for industrial gear oils, and the pitting test PT C/9:10/90 [5] for automotive gear oils (see **Table 1**). Continuous oil development, cost reduction and new market demands made it necessary to develop new test methods for gear oils. These new methods on the FZG gear test rig are presented and discussed.

2 General Considerations on Test Strategies

The best test configuration for full comparability is the actual gearbox under typical operating conditions. For industrial gear applications this is always too

expensive and for automotive gear applications this is mostly too time consuming.

The second best are test procedures using defined test gears with high reproducibility in geometry, heat treatment and surface finish being exposed to exaggerated operating conditions in order to reduce test time. Parameters which are modified versus operating conditions have to be chosen very carefully for best simulation.

Test Gears

High reproducibility of test gears can only be achieved when one manufacturer produces such gears on the basis of a commercial interest. Exotic test gears where only 200 pairs are ordered every three years, can hardly be produced to the required high quality standard. Therefore, it is highly recommended to write a new test procedure around already existing test gears, as e.g. FZG standard test gear types A and C (see **Table 2**). The production figures of FZG standard test gears type A are in the range of some 2000 per year and type C in the range of some 500 per year. The manufacturer of these gears has dedicated three grinding machines only for the finishing of A type gears. Together with the control in the CEC project group ST 007, dealing with the scuffing test, a continuously high accuracy and reproducibility of the test gears can be guaranteed.

Test gear geometry can be chosen for best simulation of the desired failure mode. A large module is in any case necessary to avoid tooth breakage. For wear investigations according to Plewe [6] the sliding

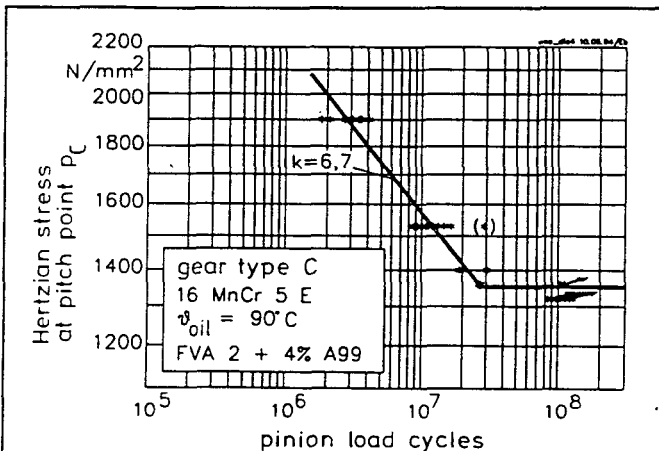
Table 1: Standard Test Methods on the FZG Gear Test Rig

Parameter	Scuffing test	Wear test	Micropitting test	Pitting test
Gear type	A	A	GF-C	PT-C
Pitch line velocity	8.3 m/s	0.57 m/s	8.3 m/s	8.3 m/s
Lubrication	Dip	Dip	Spray	Dip
Oil Temperature	90 °C uncontrolled	121 °C controlled	90 °C controlled	90 °C controlled
Driving gear	Pinion	Pinion	Pinion	Pinion
Failure criterion	Load stage to total scuffed face width > 20 mm	Wear rate in mg/kWh	Load stage to micropitting depth > 7.5 μm	Running time to pitted area on one tooth > 4%
Test procedure	15 min per LS	20 h in LS 10	16 h per LS	< 300 h in LS 9
Standards	DIN 51 354 IP 334 ASTM D-5182 CEC L-07-A-96	ASTM 4998	FVA	FVA

Table 2: Main Test Gear Data

Dimension		Symbol	Unit	A10	PT-C	GF-C
Centre distance		a	mm	91.5		
Number of teeth	pinion gear	z_1 z_2	- -	16 24		
Module		m	mm	4.5		
Pressure angle		α	°	20		
Operating pressure angle		α_w	°	22.5		
Helix angle		β	°	0		
Face width	pinion gear	b_1 b_2	mm mm	10 20	20 20	
Profile shift factor	pinion gear	x_1 x_2	- -	0.8532 -0.5000	0.1817 0.1715	
Operating pitch diameter	pinion gear	d_{w1} d_{w2}	mm mm	73.2 109.8		
Tip diameter	pinion gear	d_{a1} d_{a2}	mm mm	88.8 112.5	82.5 118.4	
Material		-	-	20MnCr5	16MnCr5	
Heat treatment		-	-	case carburized		
Surface roughness	pinion gear	R_{a1} R_{a2}	μm μm	0.35 0.30	0.30 0.30	0.50 0.50
Roughness tolerance		ΔR_a	μm	± 0.1		

properties are of minor influence. For scuffing investigations gears with high sliding are designed [7]. For endurance investigations (micropitting and pitting) gears with high local Hertzian stress resulting from unfavorable load and curvature conditions can be used [8, 9]. Profile modifications like tip relief and crowning should be avoided because more parameters - length and amount - can vary between the given tolerances. Tip relief also decreases severity and thus increases test time due to optimized load distribution along path of contact. Fig. 1 shows the influence of a crowning tolerance on the Hertzian stress level and the expected pitting life, assuming a standard slope of the pitting SN-curve.



Example

Center distance $a = 91.5 \text{ mm}$
 Number of teeth $z_1 = z_2 = 38$
 Module $m = 2.4 \text{ mm}$
 Working pressure angle $\alpha = 22.5^\circ$
 Helix angle $\beta = 0^\circ$
 Profile shift factor $x_1 = x_2 = 0.063$
 Crowning height $c = 30 \pm 5 \mu\text{m}$

Crowning height	25 μm	30 μm	35 μm
Crowning radius	720 mm	600 mm	514 mm
Hertzian stress	2146 N/mm ²	2228 N/mm ²	2304 N/mm ²
Relative pitting life	200 %	100 %	65 %

Fig. 1: Influence of Crowning Tolerance on Pitting Life

Load

High loads in the range of time strength reduce test time and increase test severity for all failure modes. However, for the investigation of the influence of lubricants on pitting, load increase is not the solution. Fig. 2 shows typical pitting SN-curves for two lubricants. Under high load conditions the pitting capacity is dominated by the material properties. Therefore, the influence of the lubricant can be neglected.

Pitting investigations of different lubricants must be planned around the endurance limit, resulting in relatively high life time (up to 50 million cycles), naturally high scatter around the endurance, but good discrimination between lubricants.

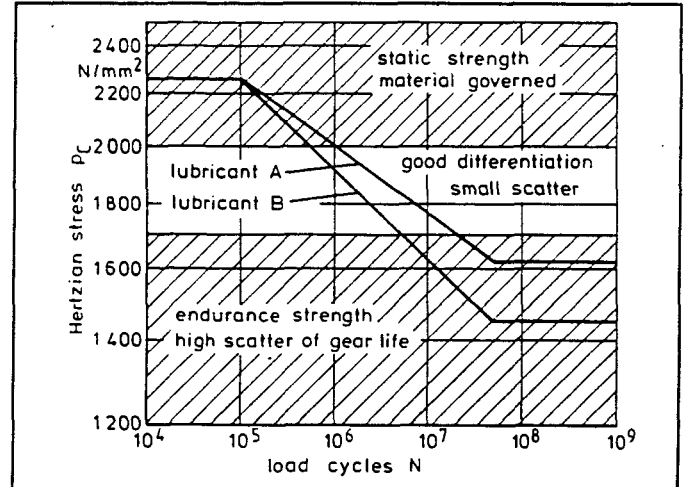


Fig. 2: Pitting SN-Curves for Two Different Lubricants

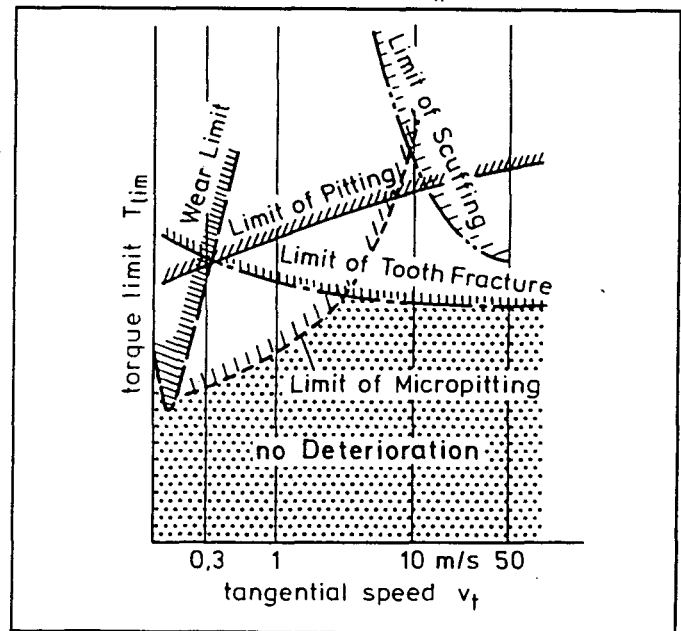


Fig. 3: Load Capacity Limits of Case Carburized Gears

Speed

The dependency of the failure modes on speed is shown in Fig. 3. For wear investigations low speed is required for unfavorable film conditions. For scuffing the critical speed between pitch line velocity of $v = 20$ and 50 m/s as the minimum of the bath tube curves can be used for high scuffing risk. For micropitting and pitting a typical operating speed can be the best compromise between increasing load carrying

capacity and increasing number of cycles per time with increasing speed.

Running Time

For stationary wear conditions beyond running-in effects a certain test time is required. Scuffing as an instantaneous failure requires only a short test time. Micropitting and pitting as fatigue failure modes require medium to long test times.

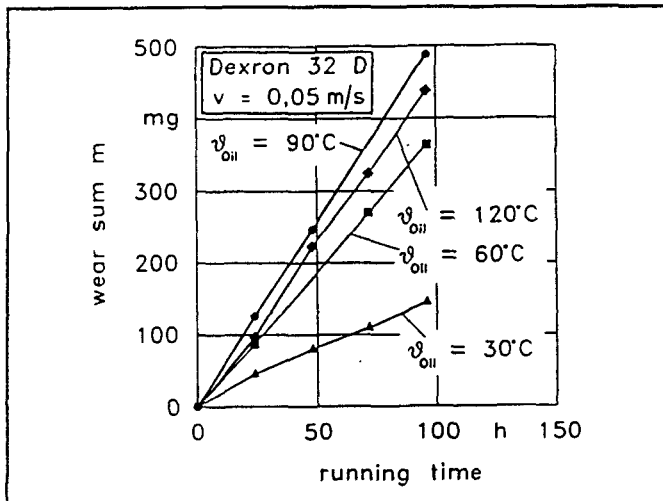


Fig. 4: Temperature Influence on Slow Speed Wear

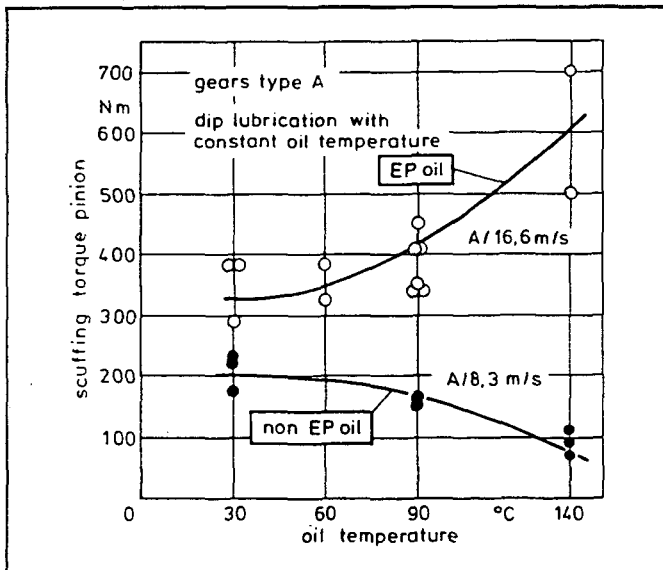


Fig. 5: Temperature Influence on Scuffing

Temperature

A general tendency can be observed that oil temperature is increased in order to increase test severity. The idea is that with increasing temperature viscosity and film thickness decrease and thus unfavorable lubricating conditions lead to early failures. This is certainly the case for non-EP oils, for EP con-

taining oils the chemical activity of the additives system has also to be considered. In many cases modern additive packages tend to provide better wear (see Fig 4) and scuffing (see Fig. 5) protection at higher oil temperatures. Therefore temperature should always be chosen in the range of actually occurring operating temperatures.

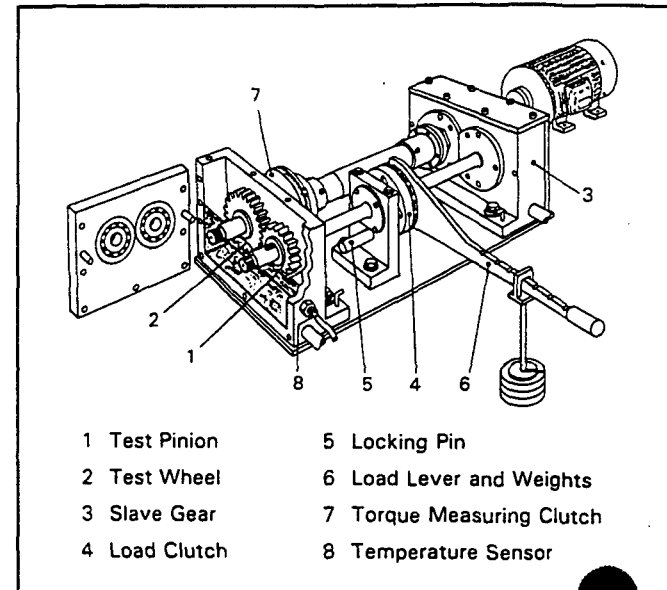


Fig. 6: FZG Back-to-Back Gear Test Rig

3 New Test Methods

Following the described strategies some new test methods for gear lubricants using the FZG back-to-back gear test rig (Fig. 6) were developed. A thorough description of the rig and the already existing standardized or at least standard test methods (see Table 1) can be found elsewhere [10].

Slow Speed Wear Test

The Chevron Test [1] (see Table 1) for tractor hydraulic fluids of low viscosity grade can normally not discriminate different industrial or automotive gear oils of higher viscosity. Therefore, in systematic investigations on the influence of load, operating speed, oil temperature, and necessary running time a proposal for 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 $T_1 = 378,2 \text{ Nm}$. 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 [11].

Part 1: C/0.05/90/12 - Part 1 lasts two times 24 h with intermediate weighing of pinion and gear.

Table 3: Test Conditions for the New Slow Speed Wear 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	13 rpm	13 rpm	150 rpm
Wheel speed	8,7 rpm	8,7 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 24 h	2 x 24 h	1 x 48 h
Revolutions of shaft 2	2 x 12 500	2 x 12 500	1 x 288 000
Test result	weight loss of pinion and gear		

The pitch line velocity is $v = 0.05$ m/s, and the oil sump temperature is maintained at $\vartheta_{oil} = 90$ °C. This condition gave the highest wear rates for all tested lubricants.

Part 2: C/0.05/120/12 - Part 2 lasts also two times 24 h with intermediate weighing of pinion and gear. The oil sump temperature is increased to $\vartheta_{oil} = 120$ °C 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 a 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 lasts 48 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 $n_1 = 100$ rpm, can show the influence of higher speed and thus higher film thickness and better lubricating conditions on the wear behaviour. The oil temperature of $\vartheta_{oil} = 90$ °C was chosen, because in most cases at the lower temperature higher wear rates were found.

The conditions of the different test parts are summarized in Table 3.

Different gear lubricants - hydraulic oils, ATFs, turbine oils, industrial gear oils and automotive gear oils of GL 4 and GL 5 performance - were tested under these conditions. Typical test results are shown in Fig. 7. It can be seen from this Figure that different categories of wear behaviour can occur:

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

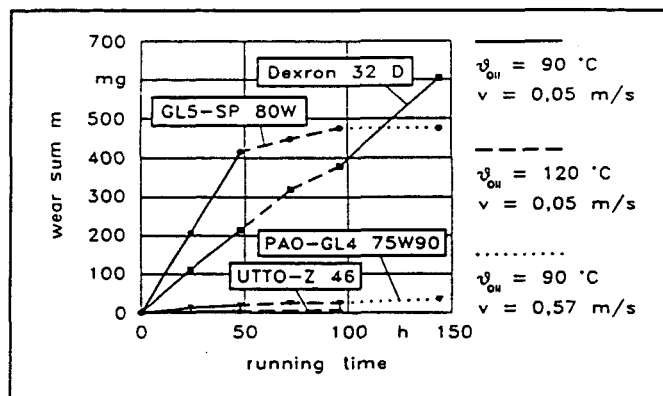


Fig. 7: Results of the Slow Speed Wear Test

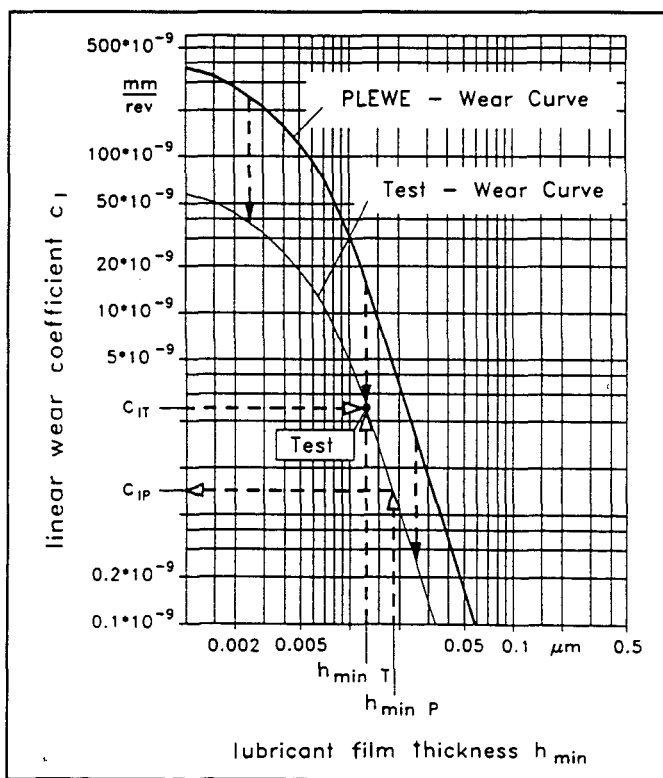


Fig. 8: Evaluation of Specific Wear Rate c_{it}

Results of the wear test can be introduced into the wear calculation method according to Plewe [6]. The total linear wear W_l of a gear in practical application can be estimated from:

$$W_l = c_{IT} \cdot \left(\frac{\sigma_{H0}}{\sigma_{H0T}} \right)^{1.4} \cdot \left(\frac{\rho_C}{\rho_{CT}} \right) \cdot \left(\frac{\zeta_W}{\zeta_{WT}} \right) \cdot N \quad (1)$$

c_{IT}	mm/rev	linear wear coefficient from test (T)
σ_{H0}	N/mm ²	nominal Hertzian stress
ρ_C	mm	relative radius of curvature at pitch point
ζ_W	-	wear relevant specific sliding
N	-	number of cycles

The decisive parameter in this equation is the linear wear coefficient c_{IT} . For straight mineral oils this parameter can be taken from a diagram as a function of the film thickness h_{min} calculated according to Dowson/Higginson [12] at operating conditions. Fig. 8 shows c_{IT} for case carburized gears. For a candidate lubricant with AW or EP additives the linear wear coefficient for the test conditions at oil temperature $\sigma_{oil} = 90^\circ\text{C}$ or 120°C can be calculated from the test result. This value together with the appropriate film thickness h_{minT} for test conditions is introduced into Fig. 8. With the assumption that lubricants with AW/EP additives behave similar as straight mineral oils, the original Plewe wear curve for non-EP lubricants is shifted parallel through the test point. The relevant linear wear coefficient for an AW/EP oil can now be taken from the diagram at the value of film thickness h_{minP} of the gearset in practice.

Scuffing Test for Automotive Gear Oils API GL 4 and GL 5

Standard test procedures like the FZG gear oil test A/8.3/90 acc. to ASTM D-5182 [2] or the Ryder gear test [13] cannot discriminate oils of high EP-level with API GL 4 or GL 5 performance. Expressing the scuffing load capacity of a lubricant as the critical scuffing integral temperature acc. DIN 3990 [14] the discriminating power of such tests is far exceeded (Fig. 9). For automotive gear oils of API GL 4 level no accepted test method is available, for API GL 5 oils the CRC or the FZG L-42 test [15] 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 GL 4 and GL 5 were developed. A-type test gears with reduced pinion face width to $b = 10\text{ mm}$ (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 in-

creased 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 comparison of these methods with the standard scuffing test is given in Table 4. A detailed description of the test procedures can be taken from the FVA Information Sheet [16].

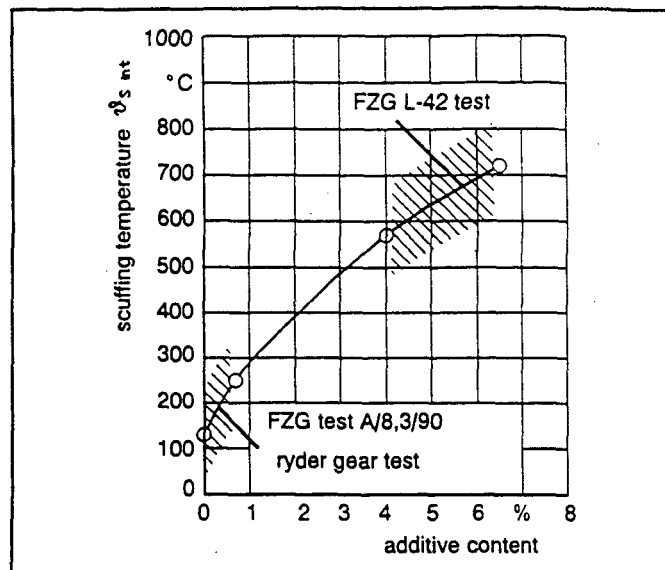


Fig. 9: Limiting Scuffing Temperature for EP Oils

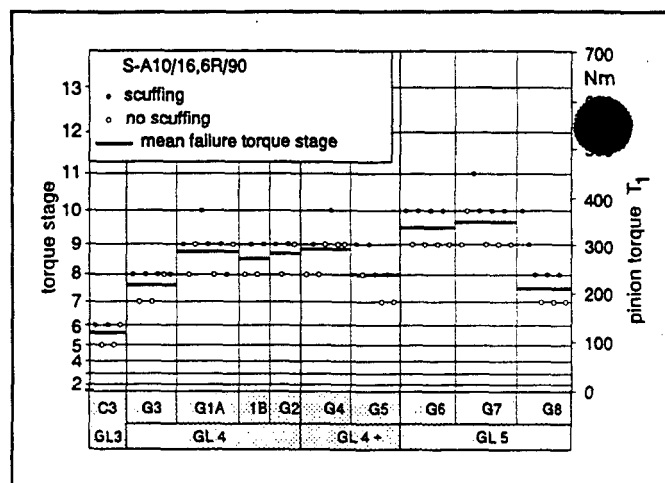
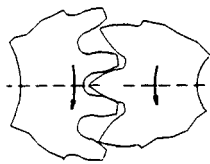
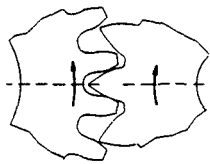
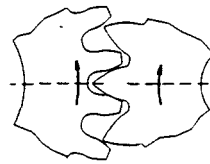


Fig. 10: Results of the Shock Test S-A10/16.6R/90

A variety of different gear lubricants were investigated. Results of the shock test are shown in Fig. 10. The repeatability of the test was acceptable within one load stage. In many cases good correlation with the additive treat level was found. Lubricant G8 which was tested as GL 5 PASS in the FZG L-42 test at 110°C oil temperature gave a clear fail in the S-A10/16.6R/90 test at 90°C oil temperature. Repeated tests S-A10/16.6R/110 at 110°C showed again the high expected scuffing level. Fig. 11 shows results of

	A/8,3/90 DIN 51 354	A10/16,6R/90 Stage test	S-A10/16,6R/90 Shock test
Gear geometry	Type A	Type A	Type A
Pinion face width	20 mm	10 mm	10 mm
Wheel face width	20 mm	20 mm	20 mm
Pitch line velocity	8,3 m/s	16,6 m/s	16,6 m/s
Driving gear	Pinion	Wheel	Wheel
Rotation			
Torque	Standard	Standard	Standard
Hertzian stress	Standard	$\sqrt{2} \cdot \text{Standard}$	$\sqrt{2} \cdot \text{Standard}$
Load application	Stages	Stages	Shock
Oil temperature	90 °C	90 °C	90 °C
Failure criterion pinion face width	≥ 20 mm	≥ 10 mm	≥ 10 mm
Test result	Failure load stage	Failure load stage	PASS - FAIL

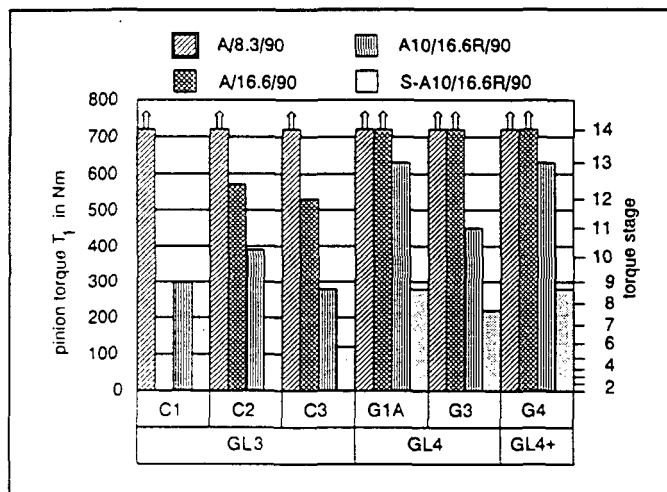


Fig. 11: Results of the Scuffing Step and Shock Test

different test methods for a wide variety of gear lubricants.

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 [14] and ISO [17] standards of scuffing load capacity rating. On

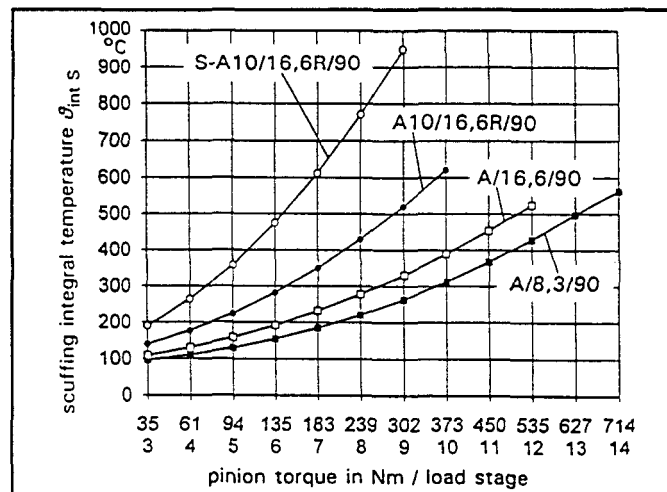


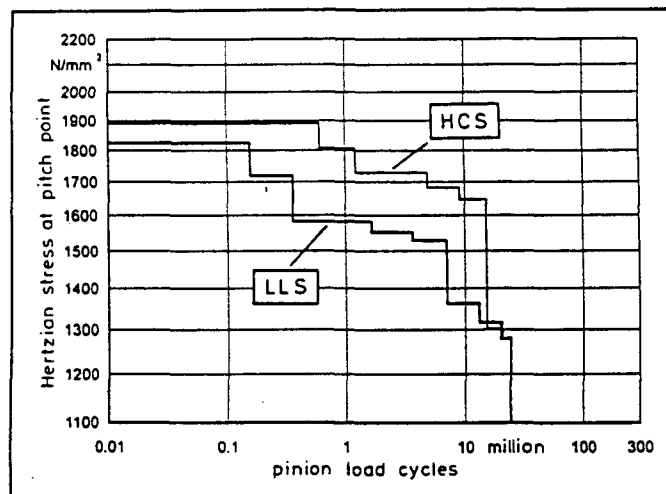
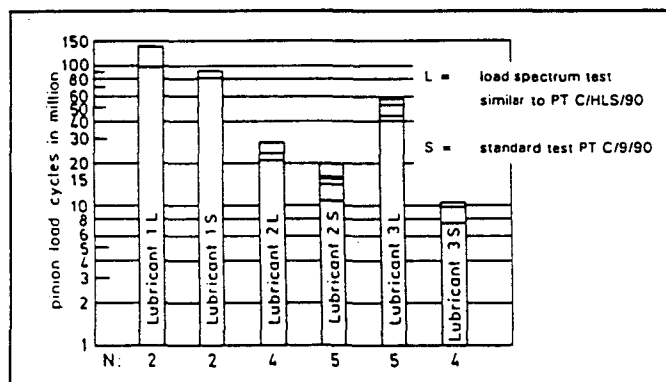
Fig. 12: Scuffing Temperature for Different Tests

the basis of the critical scuffing temperature, different test methods can be compared as shown in Fig. 12.

In an ongoing research project the official ASTM GL 5 reference oils PASS and FAIL are investigated in the S-A10/16.6R/90 test and the influence of the oil temperature is considered more closely.

Table 5: Test Conditions for Different Pitting Test Methods

Test Conditions	PT C/9/90	PT C/10/90	PT C/LLS/90	PT C/HLS/90
Pinion torque	302 Nm	372 Nm	177-360 Nm	183-387 Nm
Pitch line velocity	8.3 m/s		8.9-15.5m/s	
Oil sump temperature	90 °C			
Failure criterion	4 % pitting on one pinion tooth			
Test result	hours or cycles until failure			

**Fig. 13: LLS and HLS Load Spectra****Fig. 14: Results of Standard and Load Spectrum Pitting Test (N = number of test runs)**

Pitting Test

Besides the standard single stage pitting test methods PT C/9/90 in torque stage 9 for low viscosity gear oils below VG 100 and PT C/10/90 in torque stage 10 for medium and high viscosity gear oils of VG 100 or higher two additional procedures PT C/LLS/90 and PT C/HLS/90 using variable load and speed conditions were developed. For a closer simulation of operating conditions in automotive practice either a low

load spectrum (LLS) or a high load spectrum (HLS) is applied (see Fig. 13). The respective speed in each load stage is adjusted to simulate acceleration at high torque and low speed conditions and cruising at medium torque and high speed conditions. The test uses test gears of type C-PT (C) at a variable speed between 8.9 m/s and 15.5 m/s and an oil sump temperature of standard 90 °C. The temperature can also be adjusted to actual temperatures in practice. A comparison of the different methods is given in Table 5. A detailed description of the test procedures can be taken from the FVA Information Sheet [18].

Fig. 14 shows results of different automotive gear lubricants in the standard single stage test PT C/9/90 and a load spectrum test similar to PT C/HLS/90. The relative ranking of the lubricants is in two cases the same, one case is different. This could have to do with a totally different temperature spectrum on the flanks in a single stage test compared to a load spectrum test. In the variable load pitting tests there is a tendency of less micropitting as well as generally a higher number of load cycles until failure.

Result of a pitting test is the mean value of pitting load cycles for 50 % failure probability, evaluated from 3 to 5 individual test runs. The test results can be introduced into the ISO calculation procedure 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 (Fig. 15). The approach is very conservative because the endurance level is kept constant. Improvements are therefore only calculated for gear pairs with limited life.

Combined Pitting and Oil Ageing Test

Lubricant performance in all these test methods is always assessed for the new oil. Due to the relatively short test times, oil ageing hardly occurs. In a transmission in practice, however, components are most of their lives exposed to used oils. Therefore, in systematic investigations the influence of oil ageing on pitting life was investigated [18]. A typical temperature-time-curve (T-T-curve) for a reference oil could be established (Fig. 16) where a decrease in pitting life of more than 20 % is expected. From these investiga-

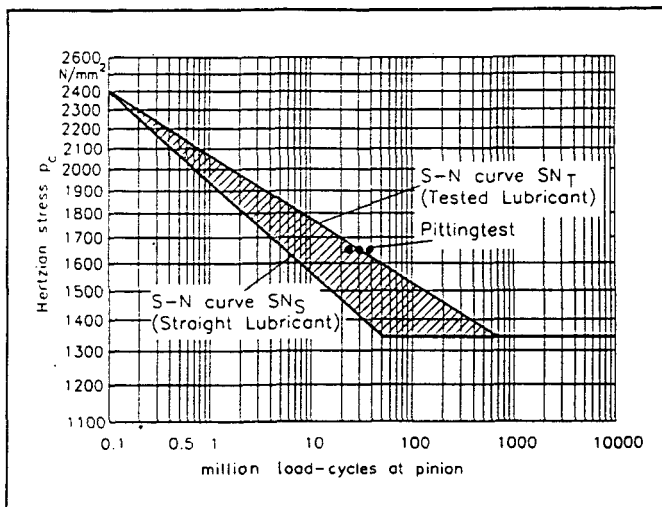


Fig. 15: Modified SN-Curve acc. to Pitting Test Result

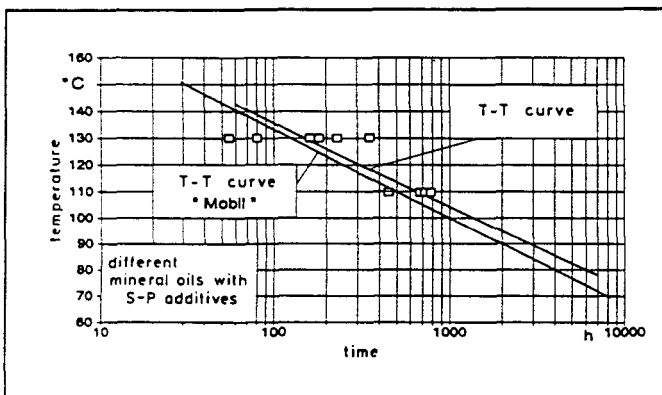


Fig. 16: Temperature-Time (T-T-) Curve for Mineral Oils with S-P-Additives

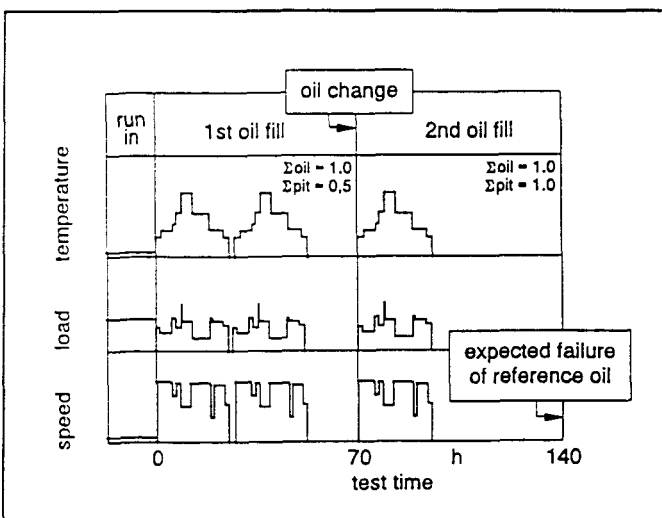


Fig. 17: Speed, Load and Temperature Spectra of the FZG PITS Test

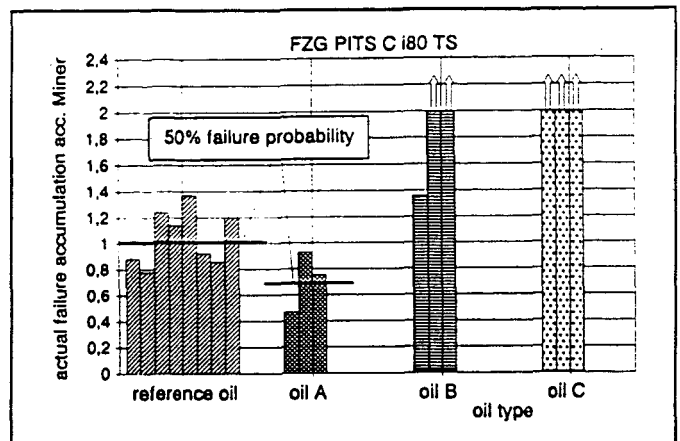


Fig. 18: Results of the PITS Test

tions a universal test method PITS C i80 TS was derived using conditions of variable load and speed at increased oil temperatures between 120 and 150 °C. The method was established for a standard mineral reference oil API GL 4 (see Fig. 17). After a one hour run-in at low speed and high torque a first sequence of the test procedure is run. During these first 70 hours the Miner sum of the oil has reached unity $\Sigma_{oil} = 1.0$ and the oil is changed. The Miner sum of the oil Σ_{oil} is calculated from the failure accumulation of the applied temperature-time-spectrum versus the T-T-curve in Fig. 16. The load spectrum is chosen such that the pitting Miner sum of the gears is $\Sigma_{pit} = 0.5$. The Miner sum of the gears Σ_{pit} is calculated from the failure accumulation of the applied load spectrum versus S-N-curves for the gear pair at different operating temperatures. With a second oil fill in the second test sequence after again 70 hours the conditions for the oil are $\Sigma_{oil} = 1.0$ and for the gears $\Sigma_{pit} = 1.0$. The gears lubricated with the reference oil fail with pitting. Candidate oils are tested against the same procedure. If no pitting occurs after the second 70 hours a third and a fourth sequence with each 70 h without oil change is added. Fig. 18 shows results of different oils from the market compared to the reference oil. For further test discrimination the load spectrum can be increased from the 80% level of load spectrum type i (i80) to e.g. 95 % (i95). This leads to a failure of the reference oil after the first test sequence of 70 h.

The method allows the relative pitting ranking of different lubricants versus a reference oil under new and aged lubricant conditions. With the determination of viscosity, acid number and IR-changes during the test, the oil ageing properties of the lubricant can also be evaluated.

4 Summary

New test methods on the standard or modified FZG back-to-back gear test rig were developed. These cover the evaluation of

- o wear performance of gear oils under thin film conditions
- o scuffing performance of automotive gears oils up to GL 4 and GL 5 level
- o pitting performance of automotive gear oils under variable load conditions
- o pitting performance of automotive gear oils with simulation of oil ageing.

The methods allow a relative ranking of different lubricants against a reference oil as well as the introduction of the results into gear load carrying capacity methods.

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