Influence of Lubrication on Pitting and Micropitting Resistance of Gears

Prof. Dr.-Ing. H. Winter & Dr.-Ing. P. Oster
Technical University of Munich, Munich, West Germany

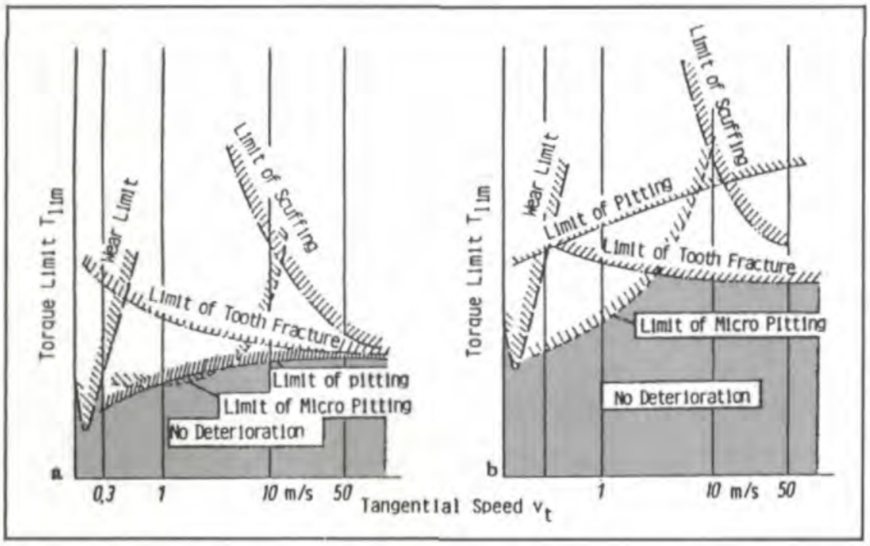


Fig. 1a – Main limits of the load capacity of through-hardened steel gears.

Fig. 1b – Main limits of the load capacity of case-carburized steel gears.

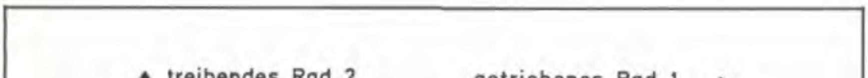


Fig. 2 – Pitting damaged tooth flanks. Application conditions: a = 200 mm; m = 9 mm; z_1/z_2 = 21/22; injection lubrication using mineral oil; v_t = 11.5 m/s.

Abstract:

Pitting and micropitting resistance of case-carburized gears depends on lubricants and lubrication conditions. Pitting is a form of fatigue damage. On this account a short time test was developed. The test procedure is described. The "pitting test" was developed as a short time test to examine the influence of lubricants on micropitting. Test results showing the influence of case-carburized gears on pitting and micropitting are presented.

Introduction

Pitting and micropitting are essential failure limits of the surface strength of gears, which are not only affected by material, but also by lubricants and lubricating conditions.

Fig. 1 shows the increasing torque limit of pitting and micropitting as a function of increasing tangential speed. The tooth fracture limit may be raised by increasing the module, so that the ruling factor is the pitting limit, even for case-carburized gears. (See Fig. 1b.) Therefore, the surface strength has to be determined by a life time test with a gear test rig. Because life time tests are very expensive, other test procedures for pitting and micropitting load capacity are worked out.[4-8]

Problems of Surface Strength

Fig. 2 shows typical pitting damage of two gear pairs. The damage appears below the pitch circle at pinion and wheel.

Pitting causes the failure of the gear pair within the testing procedure. In general, micropitting occurs during surface strength tests of hardened gears. Operative conditions (especially pressure, tangential speed, and temperature), tooth geometry (especially curvature and sliding conditions), quality of the surface, material, and lubricant features determine stress and deterioration of the gear pair. For the most part, case-carburized gears show serious pitting damage only at a few flanks, which limit the life of the gear pair. The pitting damage varies over the gear periphery.

Because failure shows fatigue characteristics, repeated tests under similar conditions show gear lives scattered in a wide range.

The method of calculation in ISO 6336/2(3) covers the influence of the lubricant only by the lubricant factor Z_L, which takes the nominal viscosity of the lubricant and the strength of material into account. (See Fig. 3.)

The range of uncertainty is very large because varying additives of the lubricant cannot be taken into account.

Fundamental rolling tests using through-hardened steel disks have systematically examined the influence of friction coefficient and lubricant film (referred to the surface roughness) on pitting resistance. (See Fig. 4.(10)) The transfer of absolute strength values from these tests to the gear pair is uncertain, because conditions differ.

The Determination of Flank Load Capacity Using FZG Back-To-Back Test Rigs

Systematic, statistically proven tests simulating real-life conditions should only be performed on a cost-effective basis, depending on the reliability of the gears required.

Back-to-back test rigs are normally used, and Wöhler curves are determined by running tests. Fig. 5 shows the test rig and testing conditions. By varying gears and conditions, many applications can be closely simulated.

Failure limit of pitting depends on application conditions and characteristic features of the gear. Fig. 6 shows the deterioration development during a fatigue test as a function of flank pressure and load cycles.

Failure criteria of case-carburized gears are defined as 4% pitted area

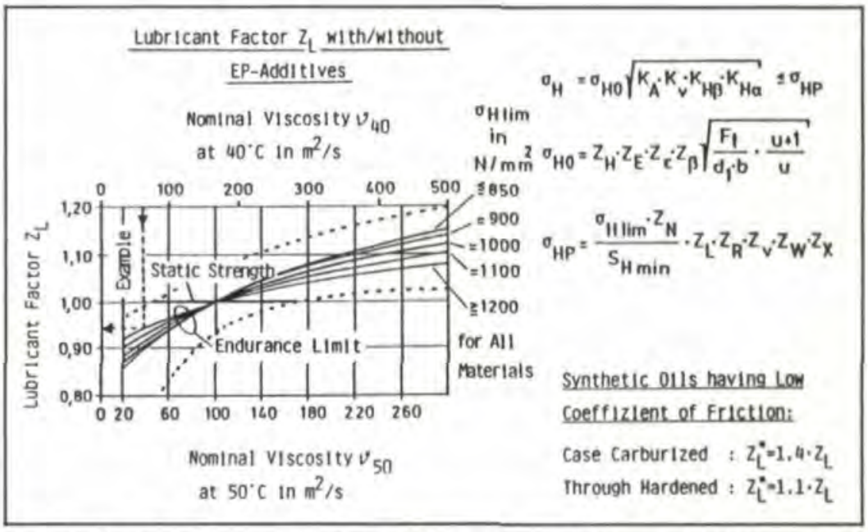


Fig. 3 – Influence of lubricants on pitting load capacity – calculation method reference ISO 6336/2.(1,3)

Surface Strength of Through-Hardened Disks (Material: 42CrMo4)

Following Factors Influencing the Life Time are Tested Separately:

– p_H Hertzian Pressure; – μ Coefficient of Friction; – ϑ_{Bl} Flash Temperature;
– v_2 Tangential Speed; – La Lubricant-Film-Thickness / Roughness.

The following equation is the result of these investigations:

$$\frac{LW_1}{LW_2} = \left(\frac{p_{H1}}{p_{H2}}\right)^{-7} \cdot \left(\frac{\mu 1}{\mu 2}\right)^{-3} \cdot \left(\frac{\vartheta_{Bl1}}{\vartheta_{Bl2}}\right)^{-2} \cdot \left(\frac{v_{21}}{v_{22}}\right)^{1.2} \cdot \left(\frac{La_1}{La_2}\right)^{2.2}$$

If $La_{1,2} > 1.0 \rightarrow La_{1,2} = 1.0$.

Surface Strength of Through Hardened Gears (Material: 42CrMo4)

The dominant influence of the coefficient of friction, apart from the influence of the pressure, is also proven at Gears.

Coefficient of Friction at EHL*-Conditions

Mineral Oil : $\mu \sim p_H^{0.6}$ $\mu \sim v^{-0.25}$ $\mu \sim Ra^{0.2}$;

Synthetic Oil: The coefficient has to be evaluated by tests.

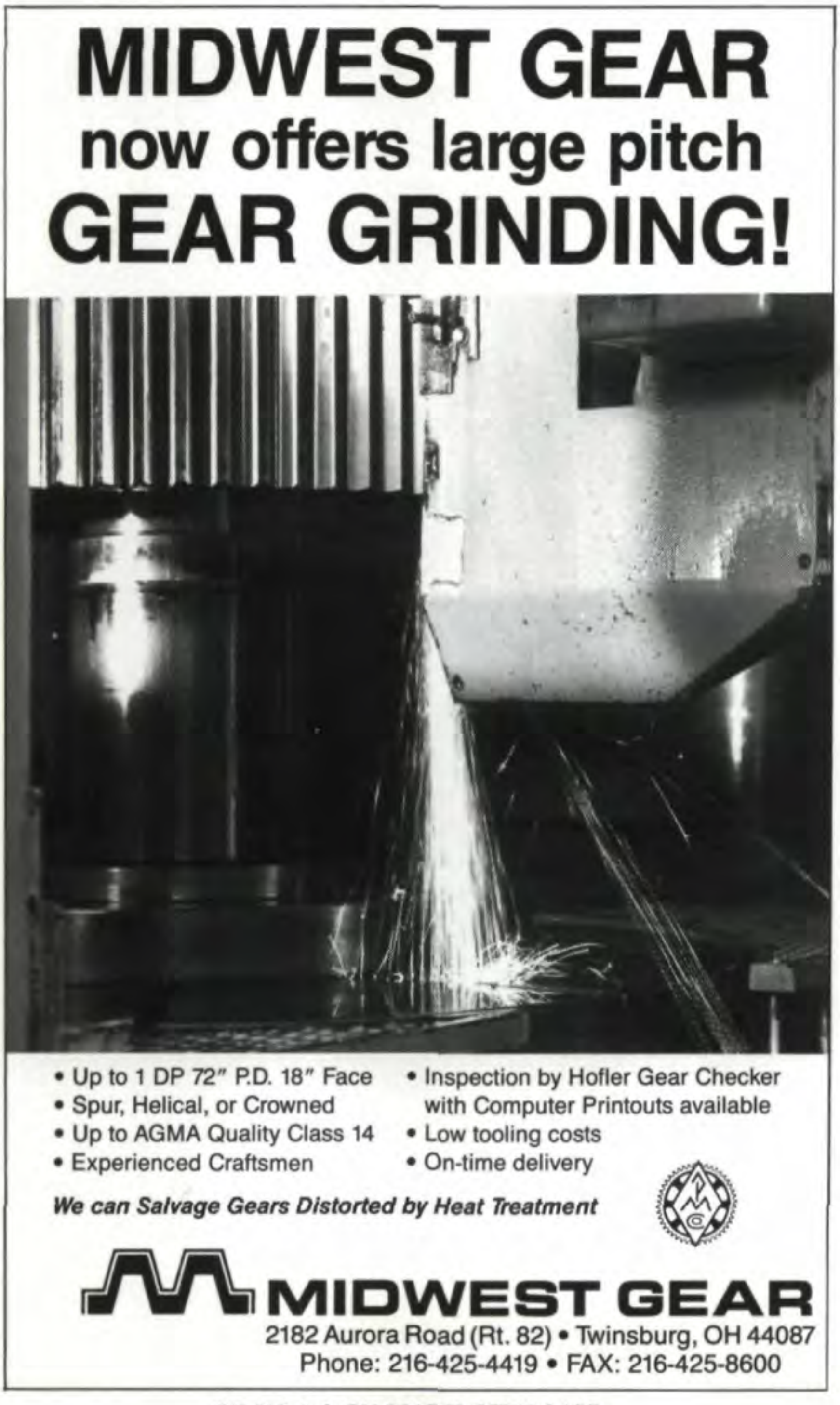
*EHL : Elasto-Hydrodynamic Lubrication

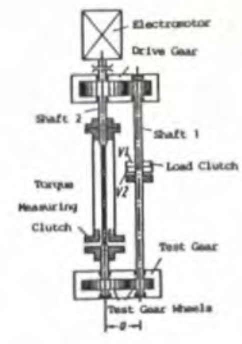
Fig. 4 – Effects of EHL-parameters on pitting load capacity – summary.

AUTHORS:

PROFESSOR DR.–ING. HANS WINTER *is the head of the Laboratory of Gear Research and Gear Design at the Technical University of Munich. He has held positions in the German gear industry since 1956 working for Zahradfabrik Friedrichshafen and DEMAG Duisburg in manufacturing, development, design, and research. He received his doctorate from the Technical University of Munich and studied as associate of Prof. Dr.-Ing h.c. Gustav Niemann.*

DR.–ING. PETER OSTER *is the chief engineer at the Laboratory for Gear Research and Design (FZG) in Munich, where he has been on the staff since 1965. He studied machine engineering at the Technical University of Munich and earned his doctoral degree there.*



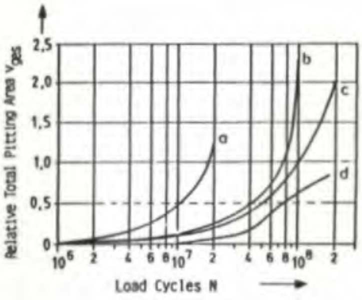


FZG Back-To-Back Test Rig:

Standard Test Gear Wheel and Testing Conditions:

a = 91.5; 112.5; 140; 200mm;
v_t = 8...16 m/s;
Mineral Oil: ν_{50} = 50...100 mm^2/s;
Spur Gears : b = 10...30 mm;
m = 2.25...8 mm; Z_1/Z_2 = 37/45...12/18;
Balanced Sliding (Gear Type: C);
DIN-Quality 4...6, Grinded Flanks;
Wöhler Curves Basing upon 7...25 Test Points.

Fig. 5 – Determination of pitting load capacity using FZG test rigs.[6]



ref. to FZG/Rettig

Evaluation of a Wöhler Curve

Material : 15CrNi6 ;
Module : 5.5 mm ;

a. $p_C = 1.20 \cdot p_{CD}$;
b. $p_C = 1.02 \cdot p_{CD}$;
c. $p_C = p_{CD}$;
d. $p_C = 0.92 \cdot p_{CD}$;

p_C : Flank Pressure at the Pitch Point;
p_{CD} : p_C Endurance Limit Occurs.

Fig. 6 – Deterioration development as a function of flank pressure and number of load cycles.

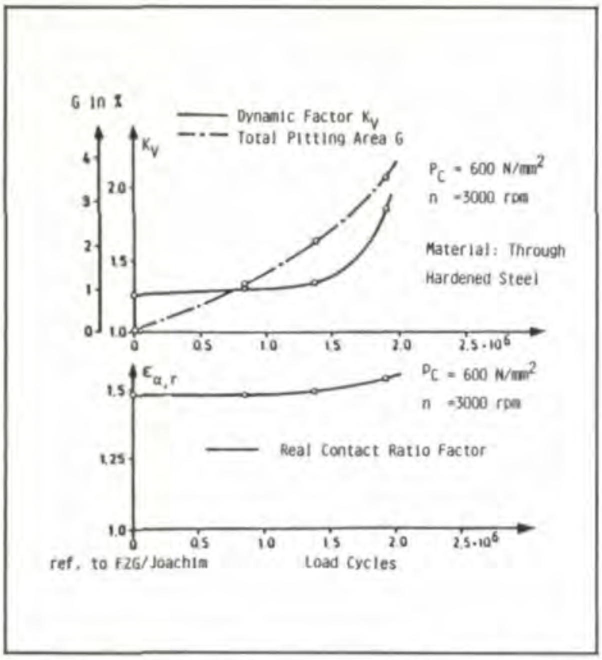


Fig. 7 – Dynamic factor, total pitting area, and real contact ratio factor as functions of load cycles.

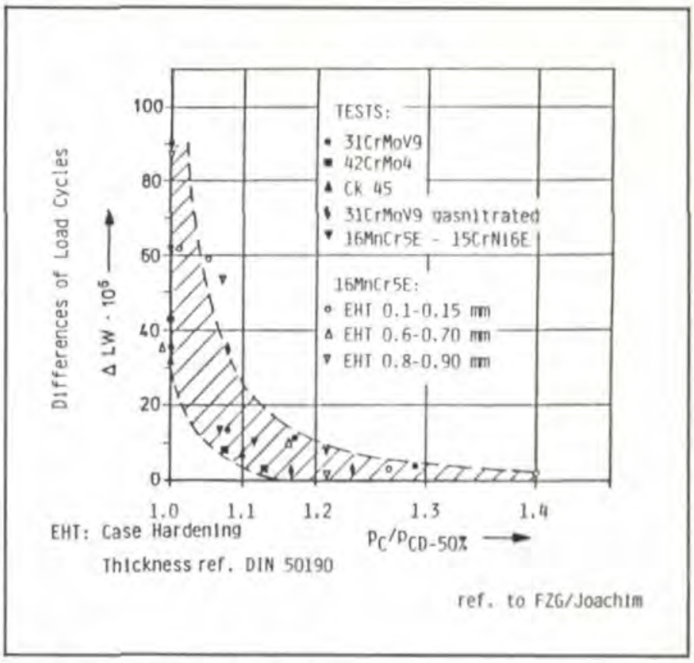


Fig. 9 – Differences of load cycles between maximum and minimum running numbers.

on one flank, or as the surface of all pitted areas exceeds 1% of the active flank area. When reversals reach $5 \cdot 10^7$ or 10^8 cycles, endurance range will be assessed.

Experimental investigations show that dynamic tooth forces progressively increase, exceeding the limited area. (See Fig. 7.)

Because gear life times until pitting occurs vary greatly, a large number of tests are required to determine fatigue strength and endurance limit. (See Fig. 8.) Then a strength value with a certain probability (e.g., Weibull-or Probit-probability curve) can be in-

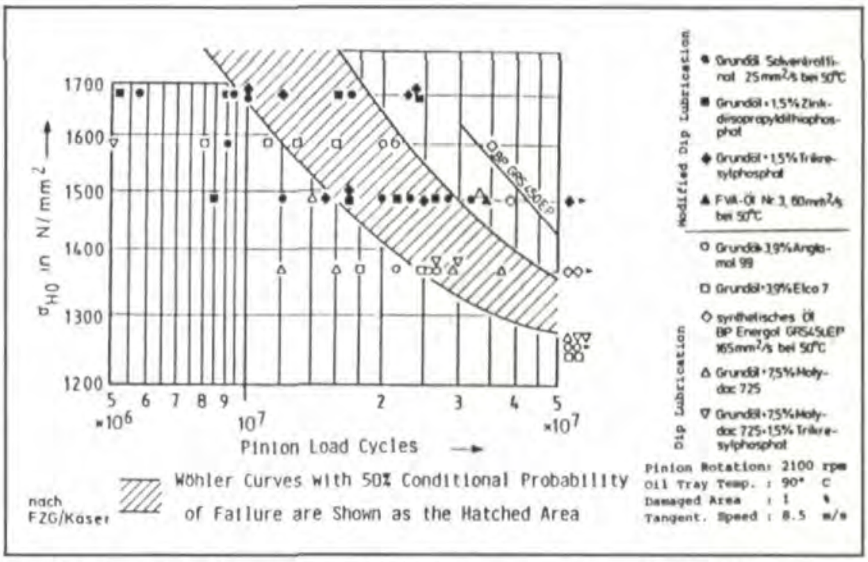


Fig. 10 – Influence of additives on pitting load capacity of case-carburized gears (16MnCr5E).

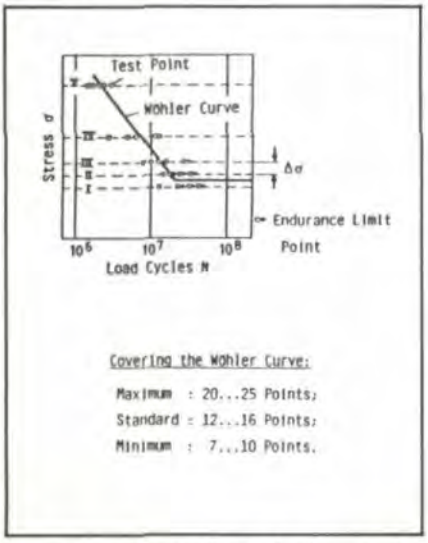


Fig. 8 – Determination of pitting load capacity by using a Wöhler curve.

FZG Back-To-Back Test Rig ref. DIN 51354:

Case Carburized and Ground Test Wheels, Gear Type: C, Dip Lubrication with Constant Oil Temperature: 90 C, Tangential Speed: v_t = 8.3m/s, Driving Pinion; Defined Running In, Repeated One Load Stage Test (p_c = 1654 N/mm²) until Reaching Failure Limit;

Failure Criterion: 4% Pitting on One Flank of the Pinion or 1% Pitting on Total Active Area of the Pinion.

Fig. 11 – Test conditions of the FZG pitting test.

dicated. One gear pair is necessary to achieve two test points, and one test point requires about 500 test rig hours to reach the endurance limit. The execution of a S-N curve is very time-consuming. To prove the fatigue stress statistically at the range of limited life fatigue, shorter running times are possible.

Fig. 9 shows the difference of load cycles between the area of limited life fatigue strength and endurance limit at pitting tests. It is evident that even at the low range of limited life fatigue $(p_C/p_{CD} \approx 1.1)$, a distinct contraction of the running time differences is to be expected.

Fig. 10 shows S-N curves which examine the influence of additives on pitting resistance of case-carburized gears. Only a limited statistical proof is possible.

The "Pitting Test" as a Short Time Test for Pitting Resistance

Based on results of the influence of additives on pitting resistance, the Forschungsvereinigung Antriebstechnik e.V., Frankfurt, (FVA) has carried out a round robin test.

The short time "pitting test" was defined and executed by five laboratories. The test conditions are shown in Fig. 11.

FZG gear test rigs having similar geometry (center distance: a = 91.5mm) to the standardized FZG scuffing test rig (DIN 51354) were used.$^{(2)}$

Gears (case-carburized 16MnCr5, Maag 0° grinding) and lubricant from one charge were placed at disposal. The results of all test rigs concerning two tested lubricants are shown in Fig. 12.

The FZG has taken part in this round robin test. Fig. 13 shows the share of the FZG. Although the load cycles widely scatter, a distinct differentiation between the two lubricants having different additives is possible.

The relative scatter (incline of the Weibull curve) of both test series is almost corresponding. If the FZG test is evaluated sequentially for the use of the test gear pairs, one can see that, despite the increasing number of running tests, the statistical mean total endurance LW_{50} hardly differs.

It would need about five or six test runs to achieve a correct value if the tests are executed carefully. (See Fig. 14.)

In the course of time the FZG has carried out further pitting tests using different gears (equal geometry, different material).

Quality of manufacture and heat treatment of these gears were identical to those used at the round robin test. Reduced load cycles have been the results of these tests. This is proven by a few comparison tests shown in Fig. 15. Especially in pitting tests, the constancy of test gear features is very important. Besides the difference of endurance, the two lubricants show a cardinal difference in the appearance of the flank surface. The flanks have a general blank look using FVA oil doped with A99, while using FVA oil doped with ZDP effects strong micropitting and heavier flank wear. (See Figs. 16-17.)

Pitting and micropitting affect each other. Depending on intensity, micropitting results in continuously increasing crater wear at the root of the flanks and in reduced pitting resistance.

Micropitting and Micropitting Resistance

Description of damage: To the naked eye, areas where micropitting has occured appear gray. (See Fig. 18.) Micropitting usually starts at the root of the pinion and spreads over the whole flank. It rarely begins at the teeth tip of the wheel.(7,9)

There is continuous loss of tooth surface material, which results in craters similar to wear craters and deteriorates the profile. Scanning electron microscope investigations prove that the failure shows fatigue symptoms. There are a lot of broken out, partly conchate particles (micropitting!) which give the gray look to the flanks.

Operative conditions: Fig. 19 shows the main conditions of the micropitting resistance comprehensively. All factors affecting the lubricating film between the flanks affect the tendency to micropitting.(6)

By use of a "thick" EHL film and "smooth" surfaces, micropitting can be eluded. Lubricants doped with different additives react to test conditions individually. Unlike ZDP additives, sulfurphosphorus (S-P) additives are advantegeous to micropitting resistance.

The Micropitting Test: A short time test to determine micropitting resistance. The micropitting test was developed by the FZG implementing a FVA

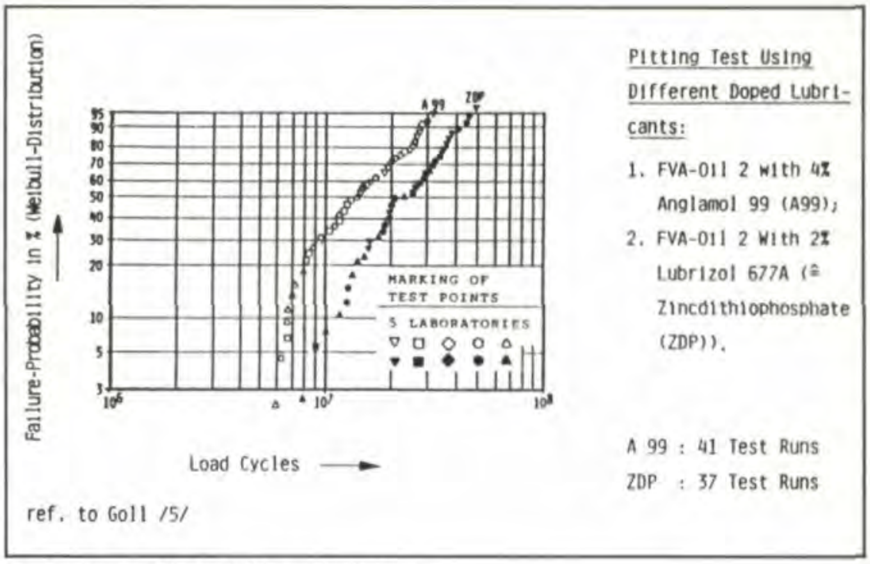
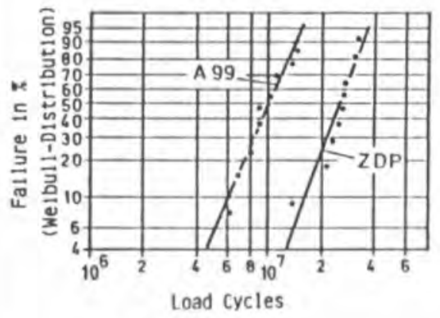


Fig. 12 – Results of the first FVA round robin test.



Lubricant	LW_{50}
FVA2+A99	$10.4 \cdot 10^6$
FVA2+ZDP	$26.0 \cdot 10^6$

Numbers of Load Cycles until Reaching the Failure Limit in Millions:

A 99	ZDP
6,3	14,0
6,9	21,6
8,1	23,1
8,3	25,1
9,0	26,4
9,1	26,9
10,3	27,5
11,1	30,0
11,2	31,2
13,9	32,4
14,7	
14,8	

Fig. 13 – Results of the FZG pitting test.

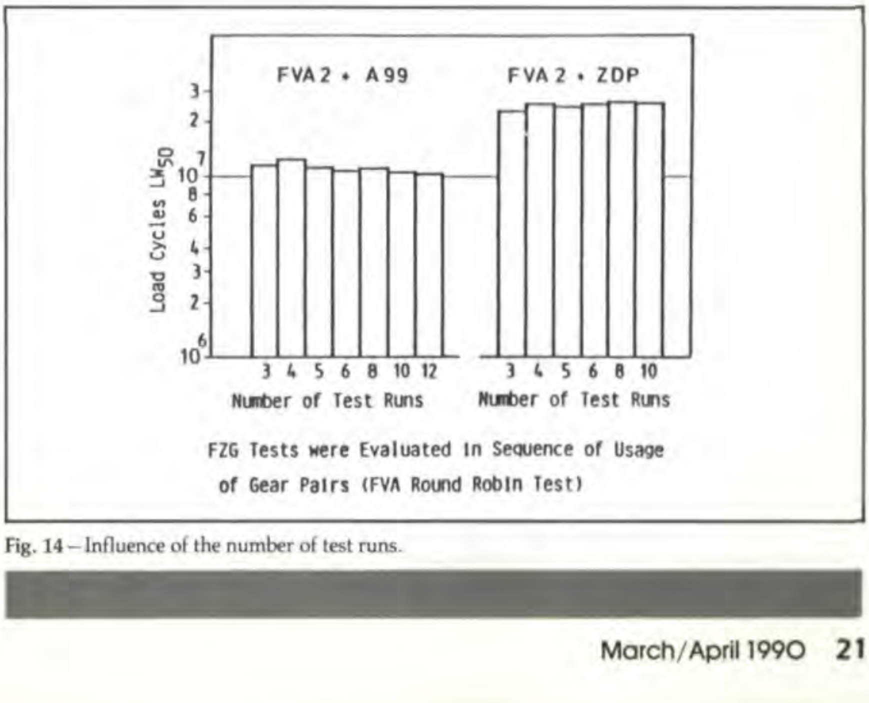


Fig. 14 – Influence of the number of test runs.

project. To test the influence of lubricants, a modified FZG test (DIN 51354) and a gear with balanced sliding at the tip of the pinion and of the wheel are used.[7,8,9] The load is raised by load stages until the amount of the profile error exceeds twice the amount of error at the beginning. To get reliable judgment and information about deterioration development (partly degressive) at longer running times, a permanent test run (10 . . . 50·10^6 load cycles) is executed afterwards.

Results of micropitting test runs: Fig. 20 shows results of a micropitting test using three lubricants doped with different additives.

Obviously there is a relation between loss of weight and the failure causing increased amount of profile error. It is remarkable that the lubricants' GFT-low and GFT-high base on the same oil. The lubricant GFT-low is doped with ZDP additive, and GFT-high with a S-P additive. Thus, the strong influence of additives on micropitting is obvious. In certain cases the torque limit of micropitting is in contradiction to the pitting limit.

Summary and Outlook

Pitting and micropitting resistance of case-carburized gears depends on lubricants and lubricating conditions. Pitting is a form of fatigue damage. Therefore, pitting endurance has to be determined by running tests, and the results shown as S-N curves. Because these tests need statistical evaluations, they are expensive, therefore, a short time test was developed. The test procedure is described. The pitting test determines the influence of lubricants doped with different additives on pitting resistance.

Test runs have shown that micropitting often occurs during pitting tests of case-carburized gears. The damage micropitting is described. The micropitting test was developed as a short time test to prove the influence of lubricants doped with different additives on micropitting resistance of case-carburized gears.

Lubricants doped with S-P additives show a higher micropitting resistance than lubricants doped with ZDP additives.

Because qualitative results of both test procedures are possible only to the

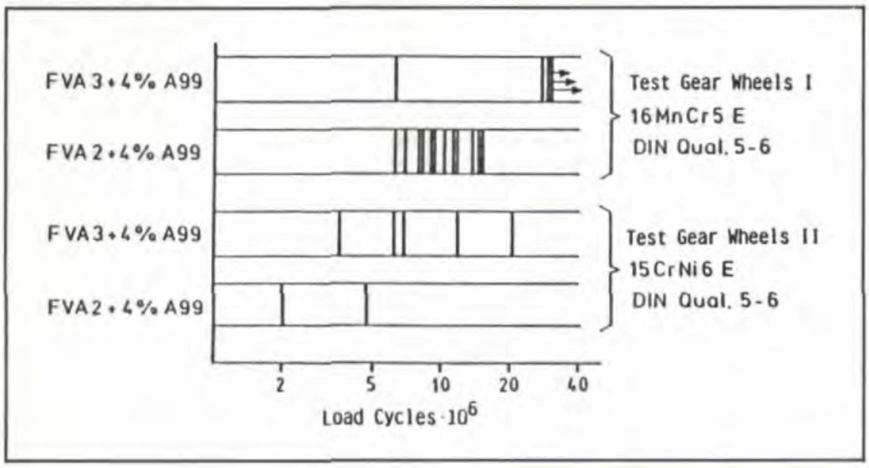
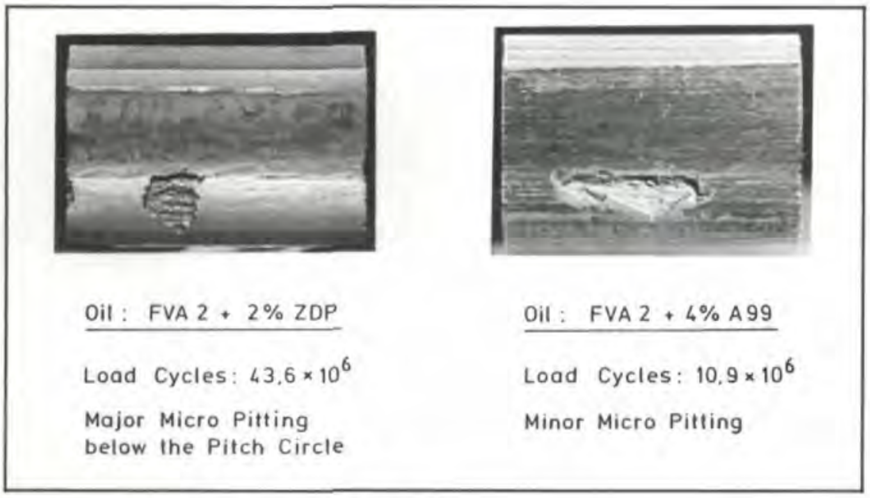


Fig. 15 – Influence of test gear wheels on pitting tests.


Oil: FVA 2 + 2% ZDP

Load Cycles: 43.6 × 10^6

Major Micro Pitting below the Pitch Circle

Oil: FVA 2 + 4% A99

Load Cycles: 10.9 × 10^6

Minor Micro Pitting

Fig. 16 – Examples of gear teeth used on pitting tests.

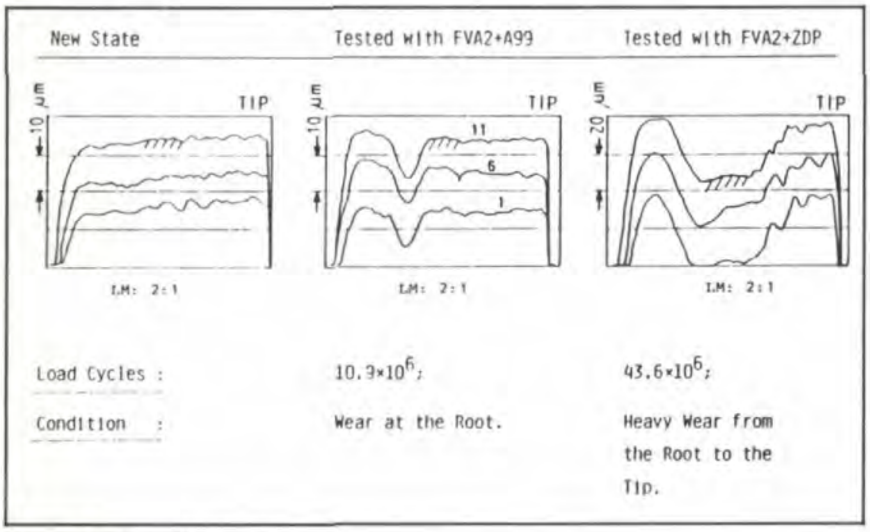


Fig. 17 – Tooth profiles of test gears.

respective damage of this test, the FZG aims at a combination of both procedures considering economic aspects.

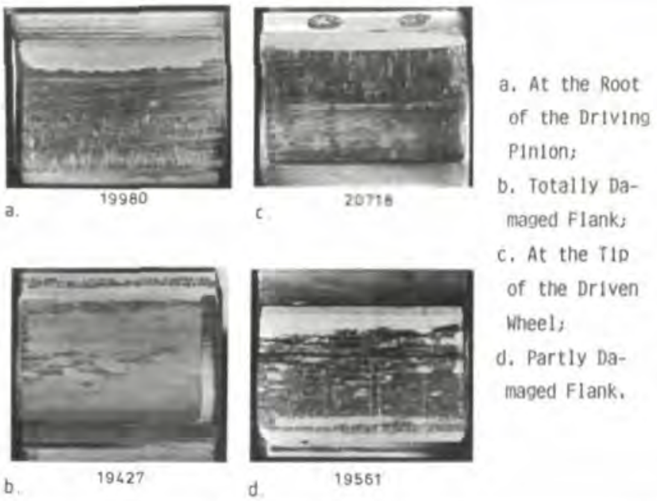


Fig. 18 – Examples of gear teeth showing micropitting.

Influencing Variable	Range
Flank Roughness: Reduction from 6μm to 3μm	1:3
Material, Heat Treatment (Advantageous Percentage of Austenite)	1:2.8
Additives (Equal Viscosity of Base Oil)	1:2
Doubled Working Viscosity	1:2
Halved Coefficient of Friction	1:1.7
Tangential Speed (Advantageous: High Speed)	1:1.3
Lowering Oil Temperature ($\Delta\vartheta = 20K$)	1:1.3

Fig. 19 – Estimated range of the influence of conditions on micropitting load capacity.

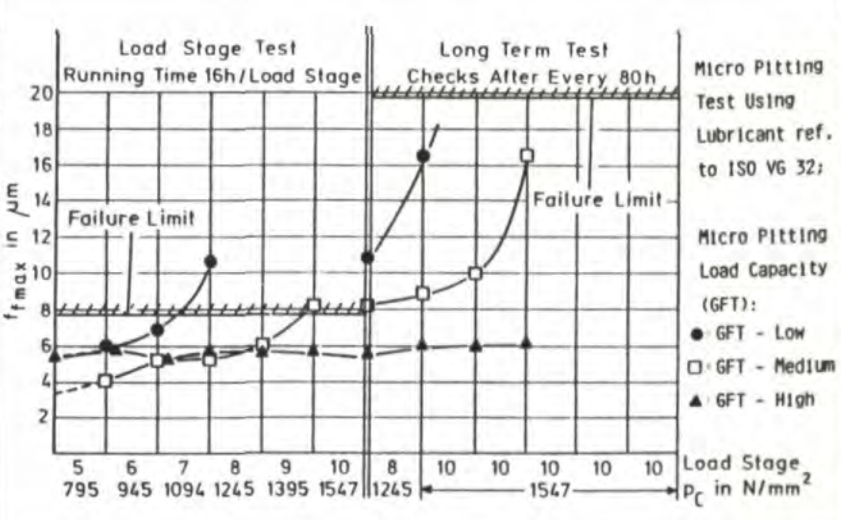


Fig. 20 – Increase of profile error at micropitting tests with different oils.

References

1. DIN 3990. "Basic Elements for Calculation of Load Capacity of Spur and Helical Gears," Draft Jan. 1986 (in German).
2. DIN 51 354. "Testing Lubricants Mechanically with the FZG-Back-to-Back Gear Test Rig," Aug. 1977 (in German).
3. ISO 6336/2. "Calculation of Load Capacity of Spur and Helical Gears, Part 2: Calculation of Surface Durability (Pitting)," ISO TC 60, Feb. 1983.
4. GOLL, S. "Influence of Lubricant on Pitting Resistance of Gears," Reports of VDI No. 626 (1987) (in German).
5. GOLL, S. "Lubricant Influence on Pitting at Gears, Results of the FVA-Round-Robin Test," *Mineralöltechnik No. 4,* April 1983 (in German).
6. NIEMANN, G., WINTER, H. *Machine Elements II,* Springer Verlag, Berlin (1985) (in German).
7. RETTIG, H. SCHÖNNENBECK, G. "Micro Pitting, A Damage Limit at Gears." *Antriebstechnik 19* (1980) No. 7 - 8 (in German).
8. SCHÖNNENBECK, G. "Testing Procedure to Determinate the Influence of Lubricants on Micro Pitting," *Antriebstechnik 24* (1985) No. 1 (in German).
9. SCHÖNNENBECK, G. "Influence of Lubricant on Tooth Profile Fatigue at a Velocity Range 1 . . . 9," m/s, Thesis, Technical University Munich (1984) (in German).
10. SIMON, M. "Measurements of Elasto-Hydrodynamic Parameters and Their Influence on Pitting Resistance of Through-Hardened Gears. Thesis, Technical University Munich (1984) (in German).

Acknowledgement: *Presented at the AGMA Fall Technical Meeting, 1987. Reprinted with permission of the American Gear Manufacturers' Association. The opinions, statements, and conclusions presented in this article are those of the authors and in no way represent the position or opinion of the American Gear Manufacturers' Association.*