PM-GEAR DESIGN BASED ON LOCAL BENDING AND ROLLING CONTACT FATIGUE DATA

C. M. Sonsino, K. Lipp

Dedicated to Dr. Andrej Šalak at the occasion of his 80th birthday.

Abstract
The use of P/M materials is rapidly expanding to include the manufacture of structural parts such as gears, which are highly loaded under rolling contact conditions and tooth root bending. The paper gives an overview as to the local stress design concept for gears on both bending fatigue for the gear teeth and rolling contact fatigue on the gear flanks. Actual test results on P/M materials are presented for fatigue and rolling contact fatigue on specimens as well as for sintered gears by example of the quenched and tempered sintered steel (Fe-1.5Mo) + 0.5C, ρ = 7.1 g.cm^{-3}. A way to transfer notch fatigue and rolling contact fatigue data from specimens, test rollers and fatigue test bars to gears, is presented on the basis of local properties.
Keywords: fatigue, bending, contact rolling, gears, sintered steels, local stress concept

INTRODUCTION

Generally, gears reveal two critical fatigue areas, Fig.1:

- The tooth root with a high local stress concentration, loaded by bending, and
- the gear flank, again with a high local stress concentration, loaded by rolling contact pressure and sliding.

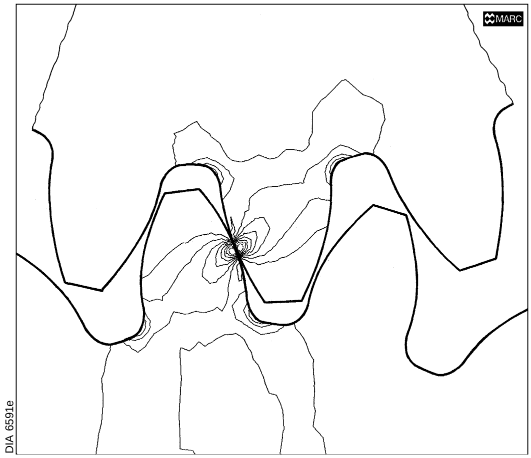


Fig.1. Equivalent stress distribution in tooth roots and on gear flanks.

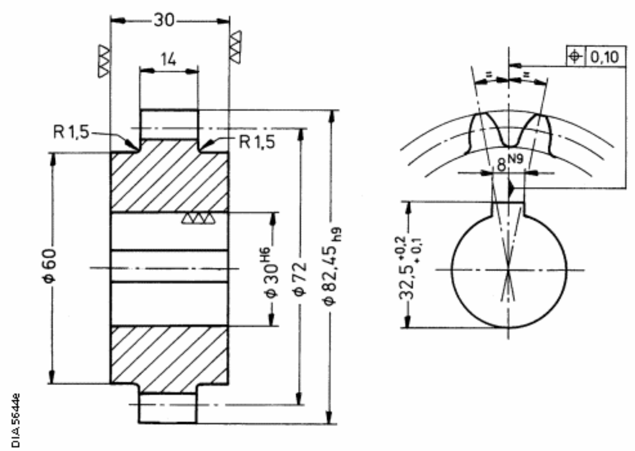
Cetin Morris Sonsino, Klaus Lipp, Fraunhofer-Institute for Structural Durability and System Reliability LBF, Darmstadt, Germany

As long as prototypes do not exist, the local stresses are assessed by particular material data obtained with specimens. The transfer of these data for assessing the part's behaviour requires the following prerequisites [1,2]:

- Comparable surface and material state of the critical areas of the specimens and parts.
- Knowledge of the occurring local equivalent stresses and their gradients caused by service loading.
- Knowledge of the local supportable stresses, which depend on the local material state and on the stress gradients.
- Equivalence between the highly stressed material volume (size effect) of the critical fatigue areas of specimens and parts.

Fatigue life is then determined by the ratio between the occurring and supportable local equivalent stresses.

The paper gives an overview as to the present state of the local stress design concept for gears with regard to the bending fatigue of the tooth roots and rolling contact fatigue (RCF) of the gear flanks, reevaluating the results of a research project carried out for the PM industry [3]. The transferability of local notch and rolling contact fatigue data from specimens, i.e. test rollers and notched fatigue test bars, to gears will be discussed by example of a standard gear, Fig.2, manufactured from the pre-alloyed sintered steel Fe-1.5Mo and admixed with 0.5C with the density $\rho = 7.1$ g/cm^3.



No. of teeth	$z = 16$
normal plane pitch	$m_n = 4.5$
pressure angle	$\alpha_n = 20°$
profile offset	$X \cdot m = 0.818$
Spur gear	$\beta = 0$

Fig.2. Dimensions of the standard gear.

MATERIAL DATA, MICROSTRUCTURE, SPECIMENS AND TESTING

Table 1 contains the data of the investigated material, which was manufactured in the single pressing and sintering technique. The specimens used for the study are presented in Fig.3. All critical fatigue surfaces of the gears and specimens were in the as sintered state. The bainitic microstructure of the gear is displayed in Fig.4; the notched specimens as well as the rollers reveal the same microstructure [1].

Tab.1. Material data.

Material	t[min]/T[°C]	ρ [g/cm^3]	HV 10	R_m [MPa]	$R_{po.2}$ [MPa]	A_5 [%]	μ	E [GPa]
(Fe-1.5Mo) +0.5 C, quenched and tempered	1250°C/40 min 90 N_2/10H_2, 875°C/30 min Oil/60°C 200°C/60 min	7.15	400-430	1411	1286	0.5	0.26	165

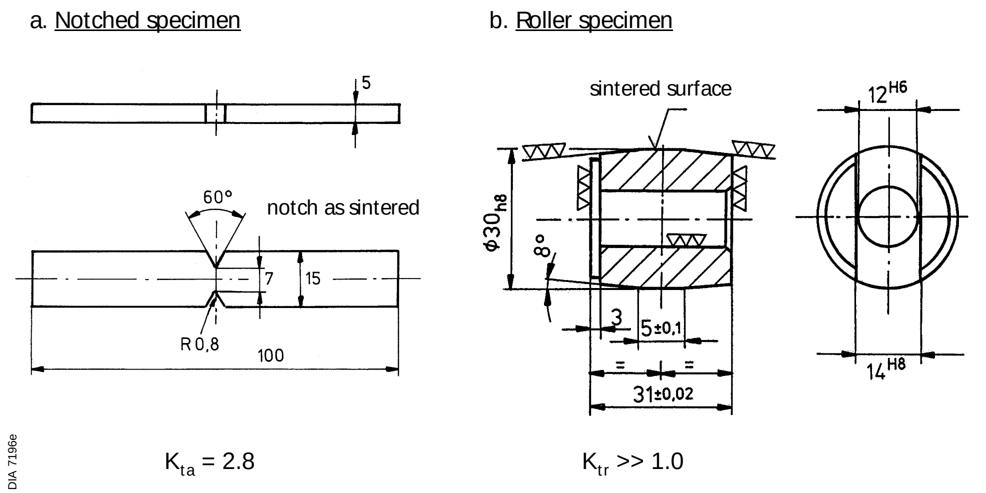


Fig.3. Notched and roller specimens.

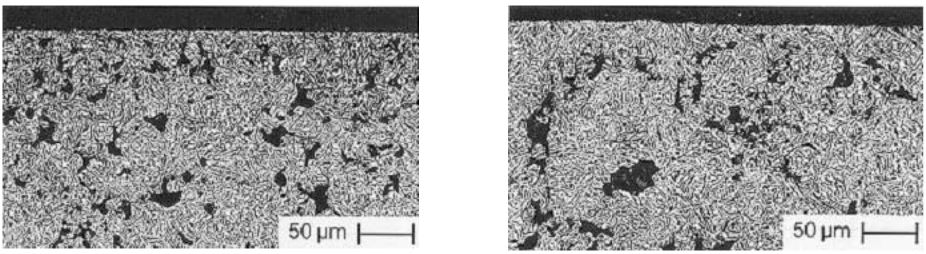
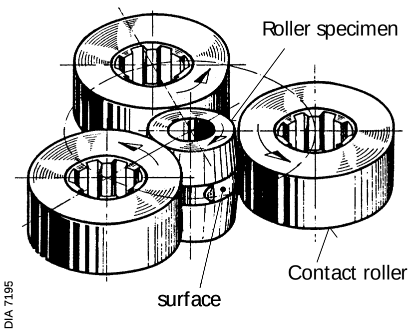


Fig.4. Microstructures of a gear tooth and of a gear flank.

To determine the fatigue properties, the following test series were conducted simultaneously:

- Pulsating axial loading (R=0) of the notched specimens,
- rolling contact fatigue tests of the roller specimens in a RCF-test bench, Fig.5, with a sliding of S = -24 %,
- gear tooth pulsating bending (R=0), Fig.6, and finally,
- simultaneous gear testing under real loading conditions, Fig.7.



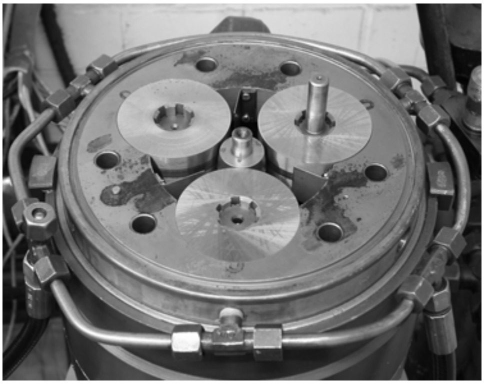


Fig.5. Rolling contact fatigue test principle according to ZF.

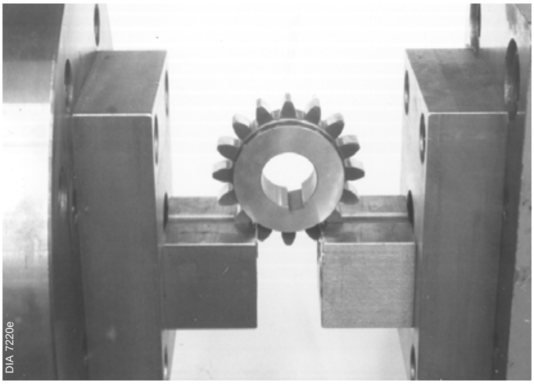


Fig.6. Bending fatigue test of gear teeth.

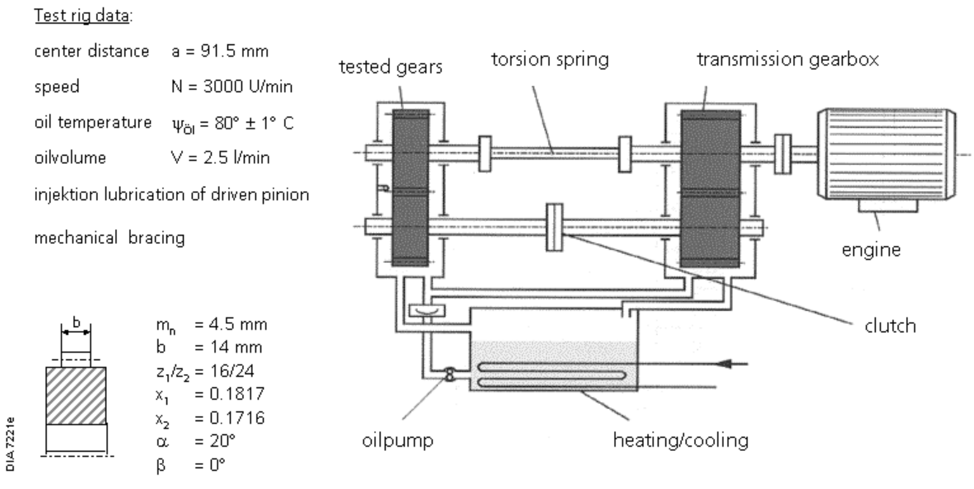


Fig.7. Back-to-back gear testing.

EXPERIMENTAL RESULTS

As damage is a local event, and must be assessed using local properties, in the following, all test results will be presented in the local stress system. In the case of axial fatigue tests with notched specimens, the local equivalent stresses in the notch root are determined by $\sigma_{eq} = \sigma_{1,max} = K_{ta} \cdot \sigma_{nom}$, as the equivalent stress for sintered steels up to ρ = 7.50 g.cm^{-3} can be calculated by the principal stress hypothesis [4]. This also applies for the gear tooth bending tests, where the equivalent stresses were calculated from local measured strains in the roots by $\sigma_{eq} = \sigma_{1,max} = (\varepsilon_{1.max} + \mu\ \varepsilon_{2.max}) \cdot E/(1-\mu^2)$. However, if the local multiaxial stress state is caused by a surface pressure, i.e. for rolling contact fatigue, then the equivalent stress is calculated by the von Mises hypothesis [5].

In Figure 8, the test results are presented for the notched specimens and for the gear tooth under bending. Local supportable stresses of the notched specimens are higher than the local tooth root stresses, due to the smaller radius of the notched bars. The highly stressed volume in the notch is much smaller, by a factor of 13, than the volume in the gear tooth roots. If this volume difference is compensated, considering the size effect [1] by $\sigma_{a.2}/\sigma_{a.1} = (V_{90\%,1}/V_{90\%,2})^{0.06}$, then the SN-curve of the gears falls within the scatter of T_σ = 1:1.35 [3] quite well. The difference of not more then 10 % between the two curves is mainly a consequence of differing batches and the effect of geometry during compaction and sintering.

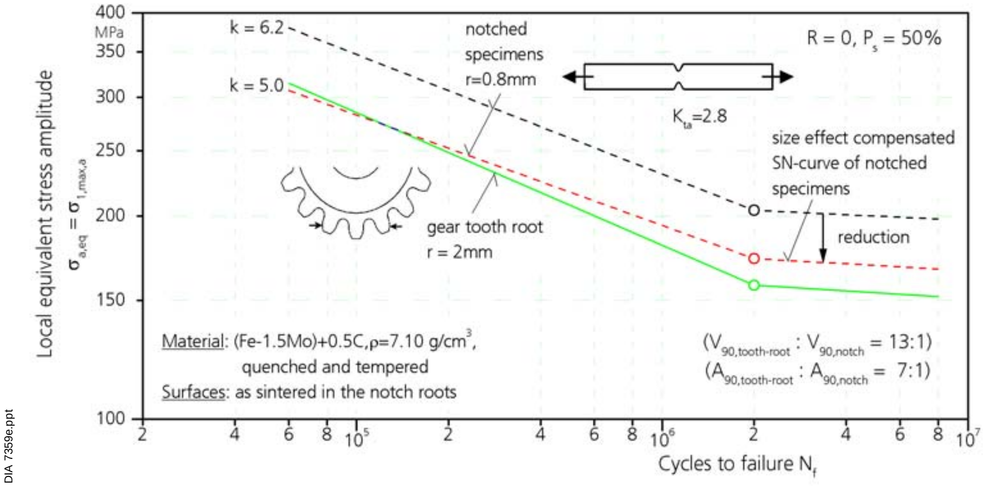


Fig.8. Local SN-curves of notched specimens and gear tooth roots.

The comparison of rolling contact fatigue behaviour between the gears and roller specimens is displayed in Fig.9 on the basis of Hertzian pressure. The Hertzian pressure is related to the equivalent von Mises stress [5]; on the roller specimens and gear flanks the maximum equivalent stresses are identical, Fig.10. However, the site of maximum stress and the stress distribution are not identical, due to the particular geometries.

For both the rollers and the gears, the crack initiation occurred below the surface in the area of the maximum equivalent stress [3,5]. The difference between the SN-curve of the specimens and gears is again less then 10 %, which is within the range of the occurring scatters. For the gear flanks and the test rollers, the curvatures and therefore also the stress distributions below the surface, as well as the equivalent highly stressed volumes, are comparable.

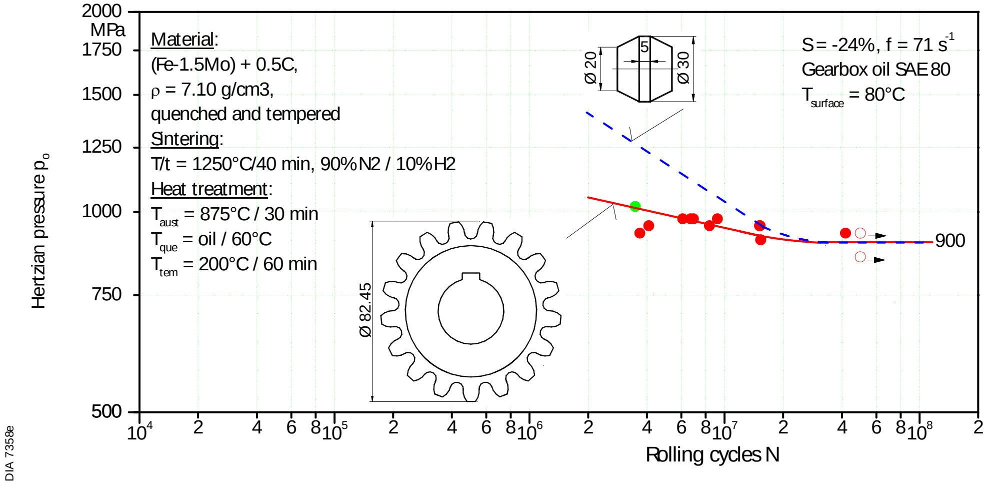


Fig.9. Comparison of rolling contact behaviour of specimens and gears.

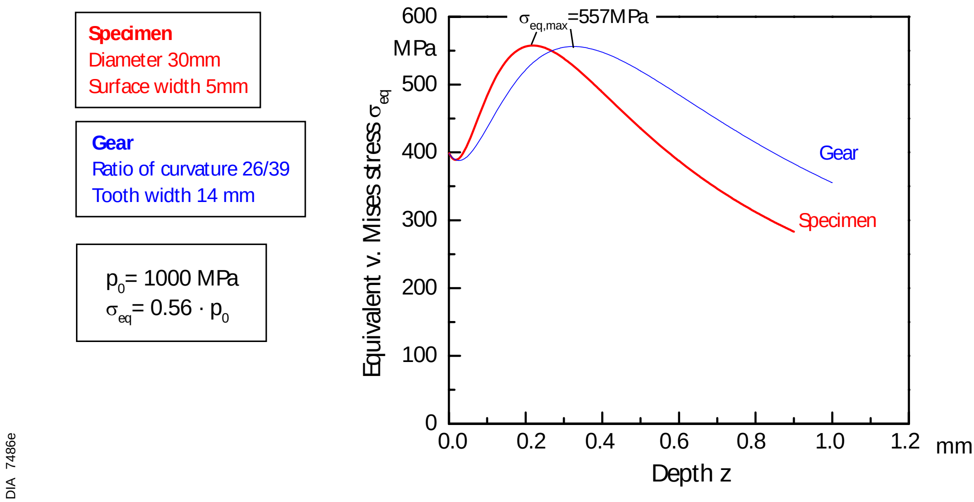


Fig.10. Distribution of equivalent stresses on the gear flank and the roller specimen.

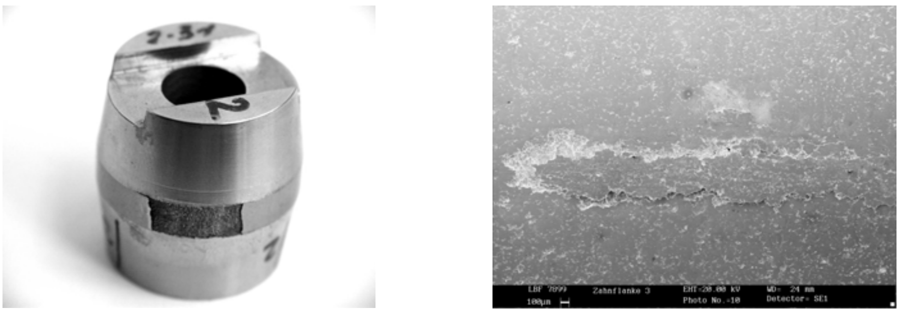


Fig.11. Failure appearances on test roller surfaces and gear flanks.

While in the case of the notched specimens and gear tooth bending the failures always started from the roots, in the case of gear testing in the back-to-back gear testing and the roller specimens, the observed failures were spallings, Fig.11; the tooth roots were not critical for the integrity of the gears during back-to-back gear testing.

CALCULATION OF LOCAL STRESSES

After the proof of the local stress concept as a good engineering tool, which enables an approach of the component's behaviour by specimen, a numerical assessment of the component's fatigue behaviour will be carried out. For a fatigue life of $N=10^9$ cycles and a theoretical probability of failure $P_f=10^{-6}$, corresponding to a safety factor of j=2.0 for a material, and a production scatter of $T_\sigma = 1 : 1.45$ [1] the allowable local notch root stress and the allowable Hertzian pressure have been derived, Fig.12.

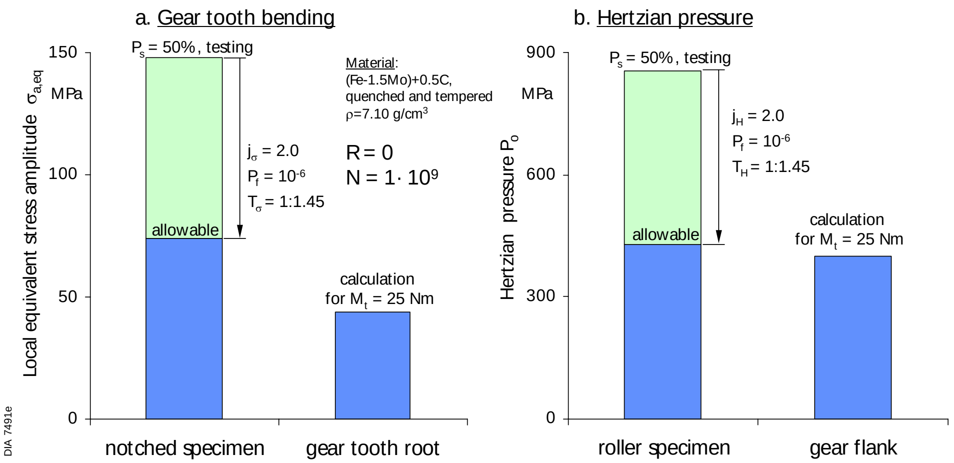


Fig.12. Local supportable and local occurring stresses for a transmission torque of M_t = 25 Nm for $N = 1 \cdot 10^9$ cycles.

For a transmission torque of M_t = 25 Nm the calculated local root stress and the Hertzian pressure for both possible failure areas are below the allowable values; the gear flank is for the selected part more endangered by rolling contact fatigue than the tooth root by bending. Thus, a fatigue life of more than $N = 1 \cdot 10^9$ cycles can be expected for the given torque.

CONCLUSIONS AND OUTLOOK

By the example of standard gears manufactured from sintered steel (Fe-1.5Mo) + 0.5C, ρ=7.10 g.cm^{-3}, quenched and tempered, and specimens of the same material, it could be demonstrated that a fatigue design using particular local material data obtained with notched and roller specimens can be applied. In the literature a good data base already exists for the application of the local stress concept [1-3, 5-8].

However, the concept has been proved until now on gears without significant residual stresses caused by post sintering treatments like carbonitriding, induction hardening, or surface rolling. It will be a big challenge to extend the applicability of the local stress concept to PM components with such complex surface states.

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