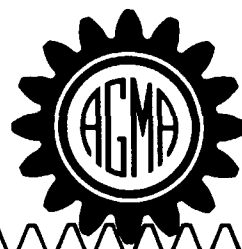


Bending Fatigue Investigation Under Variable Load Conditions on Case Carburized Gears

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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

Carburized spur gears were tested to determine bending fatigue life under variable loads. Fatigue life in random tests is shorter than in block programmed tests. However, chronological order of loads in block programmed tests has insignificant influence. Fatigue life in block programmed tests is decreased, if sequence length is shortened. Fatigue life is similar to random load tests, if a few hundred sequences are repeated until tooth breakage. Loads below 50% of the fatigue limit can be eliminated without changing test results. Fatigue life can be calculated by Miner's Rule as modified by Haibach using a damage ratio of $D = 0,5$. Single loads applied early decrease fatigue life up to 65%. The greater the single load the greater the life reduction. Even single loads on reverse sides of teeth significantly reduce fatigue life.

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BENDING FATIGUE INVESTIGATIONS UNDER VARIABLE LOAD CONDITIONS ON CASE CARBURIZED GEARS

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Nomenclature

b	gear face width	mm
d	pitch circle diameter	mm
d_b	base diameter	mm
h_{Fn}	lever height at clamping in the pulsator	mm
k	gradient of S-N-curve	-
m_n	normal module	mm
n_i	load cycle number on level i	-
q	damage parameter by Haibach	-
s	logarithmic standard deviation	-
s_{Fn}	chordal tooth thickness at 30°	mm
x	addendum modification factor	-
z	number of teeth	-
D	cumulative damage ratio	-
E_{ht}	case depth	mm
F_n	normal load on tooth flank	N
F_t	nominal tangential load	N
N_i	achieved load cycle number at load level i	-
R_z	roughness	μm
Y_S	stress correction factor	-
Y_β	helix angle factor	-
α_n	normal pressure angle	$^\circ$
α_{Fn}	pressure angle in pulsator	$^\circ$
σ_D	actual fatigue limit	N/mm^2
σ_{D0}	fatigue limit	N/mm^2
σ_{F0}	nominal tooth root stress (DIN 3990)	N/mm^2

1 Introduction

Gears in practice are mostly operated under variable loads. Even in a continuous process the load can fluctuate due to acceleration, malfunction, emergency stops or operating errors. Under these variable loads a tooth breakage, which mostly results in a total gear failure, must be avoided with high reliability. Additionally, demands on modern gears, regarding costs and weight, are increasing. With classic sizing of gears, where loads above the fatigue limit are not allowed, the above goals cannot be achieved. Using a calculation method, where loads above the fatigue limit are taken adequately into account, the operational stability without tooth breakage can be ensured with predictable safety.

To evaluate tooth root fatigue tests with variable load amplitude, the applied spectrum of load levels and the tooth strength in terms of the S-N-curve is required. The expected spectrum of load levels during the life cycle can be evaluated by measurement, simulation or estimation. The S-N-curve can either be experimentally derived or standardized curves as ISO 6336 [10] can be used.

For safe and operational stable sizing of variably loaded gears an experimentally verified and easily applicable calculation method is required. Therefore tooth breakage fatigue tests on spur, case carburized gears are carried out in hydraulic pulsators. Influence of load sequence and load distribution on the life cycle is examined.

Additionally, a possible damaging influence of load levels below fatigue limit is evaluated.

Besides fluctuations of gear load, which appear during standard operation and are recorded in the load distribution, singular events, due to malfunctions or operating errors, can occur and cause additional loads on gears. In several test series singular events are applied on the test gears, in addition to the variable amplitude load according to the standard load distribution. The influence of load level and temporal occurrence of singular events is examined.

2 Test conditions

2.1 Test program

Fig. 1 shows the test program for the constant amplitude and variable load amplitude tests within the scope of the present investigations.

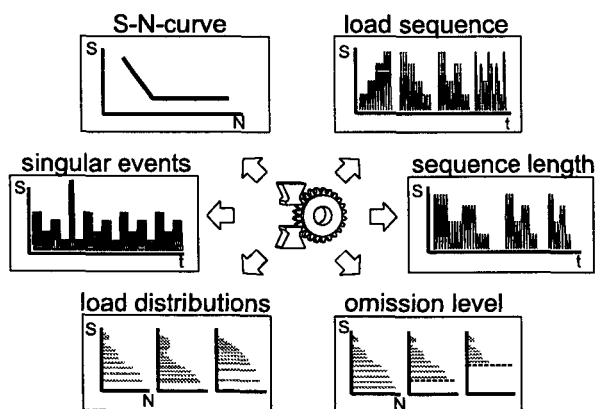


Fig. 1: Test program: tooth root bending fatigue under constant and variable load amplitude

The tooth bending strength of the test gears in terms of the S-N-curve is needed to evaluate variable load amplitude tests. The S-N-curve is determined in constant load amplitude tests with an adequate statistical verification in the range of low cycle and

high cycle fatigue.

Influence of the load sequence is determined in block programmed tests, where one single sequence is repeated until tooth breakage. The chronological order of the load levels in the sequence is varied to ascending, descending and mixed load order. Results of these tests are compared to results of random tests with stochastic load sequence. The number of repeated sequences until tooth breakage is varied by variation of the sequence length in block programmed tests. Results are compared to the results of random tests as well.

The omission level is determined in block programmed tests. Below this load level, cycles can be left out without an influence on test results. Running time of variable load amplitude tests can be considerably shortened, if loads below the omission level with high cycle numbers are left out.

Influence of the load distribution on fatigue life is examined with three different load distributions. Load distribution "B2" is derived from measurements of tooth root stress in practical gears and is typical for large scale gear units [18]. Load collective type "EK" has a load spectrum, according to the Gaussian normal distribution [5, 8], which can be found in applications with continuous processes [1]. Load collective type "C2" is a high load distribution and corresponds to the load spectrum of vehicle gear units. Achieved fatigue life with these three different load distributions is evaluated with different calculation methods based on linear fatigue accumulation according to Miner's theorem [14].

Singular events due to malfunctions or operating errors can cause additional loads on gears. Influence of load level and temporal occurrence in a chronological sequence of singular events on tooth root fatigue are examined.

2.2 Test rigs

The objective of this project is experimental investigations of carburized gears with regard to tooth root fatigue under variable loads. If tooth root fatigue tests are performed in running tests in gear test rigs, only one test result is obtained with each gear pair. Considering the great number of required tests, the experiments were performed in hydraulic pulsator test rigs, instead. Clamping the test gear along four teeth between two clamping jaws, as shown in **fig. 2**, it is possible to obtain up to 12 test results per one single gear with 24 teeth. Systematic differences of tooth root strain in pulsators and running test rigs have no influence on a relative comparison.

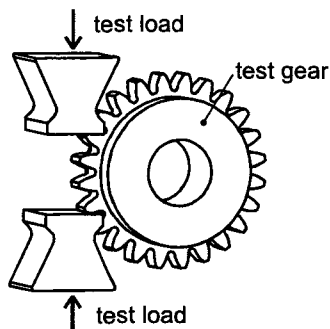


Fig. 2: Clamping of test gear performed in hydraulic pulsator test rigs, instead. Clamping the test gear along four teeth between two clamping jaws, as shown in **fig. 2**, it is possible to obtain up to 12 test results per one single gear with 24 teeth. Systematic differences of tooth root strain in pulsators and running test rigs have no influence on a relative comparison.

Fig. 3 shows a schematic view of the hydraulic pulsator test rig. The upper clamping jaw is connected to the load cell and the lower one is connected to the piston of the hydraulic system. Variable load tests are controlled by the external, computer-based control unit "MASLINK". With this unit, variable load tests in shape of block programmed and random loading tests are possible. Any discrepancy of achieved and

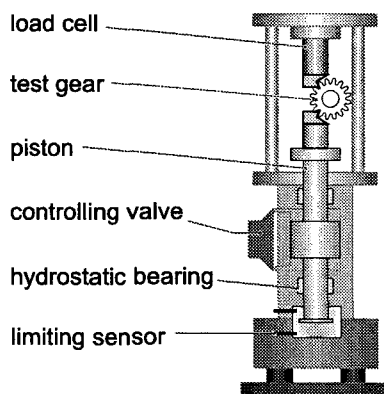


Fig. 3: Hydraulic pulsator test rig

"MASLINK". With this unit, variable load tests in shape of block programmed and random loading tests are possible. Any discrepancy of achieved and

demanded load level is detected and immediately corrected by the controlling unit.

2.3 Test gears

Investigations were carried out on test gears, according to the FZG test gear type C. Essential gear data are given in **table 1**.

normal module	m_n	4,5 mm
number of teeth	z	24
normal pressure angle	α_n	20°
helix angle	β	0°
face width	b	14 mm
addendum mod. factor	x	0,172
pitch circle diameter	d	108 mm
base diameter	d_b	101,5 mm
tip diameter	d_a	118,4 mm

Table 1: Essential test gear data

The test gears are manufactured from case carburized material 16MnCr5 comparable to SAE 5115. After heat treatment the gears are shot peened and ground. Mean peak-to-valley-roughness R_z in the tooth root is $R_z = 7 \mu\text{m}$. Case depth is $E_{ht} = 0,85 \text{ mm}$, corresponding to $E_{ht} = 0,17 \cdot m_n$.

2.4 Calculation of tooth root stress

For the tooth bending fatigue calculation according to ISO 6336 [10], bending strength of gear teeth is related to the resistance to cracking at the tooth root fillet. Cracks typically initiate in the area of the 30°

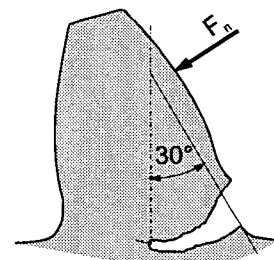
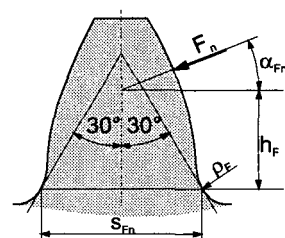


Fig. 4: Typical tooth crack

tangent to the tooth root fillet, as pictured in **fig. 4**. After the crack initiation, the crack grows during further load cycles until the tooth breaks off.

The nominal value for tooth root strain is calculated as the nominal tooth root stress at the tangent point of the 30° tangent to the root fillet. For calculation of the nominal tooth root stress of test gears in pulsators, the nominal tangential load in the equations of ISO 6336 is replaced by the pulsator load, as shown in **fig. 5**.



$$\sigma_{F0} = \frac{F_n \cdot \cos(\alpha_n)}{b \cdot m_n} \cdot Y_F \cdot Y_S$$

Fig. 5: Calculation of nominal tooth root stress σ_{F0} according to DIN 3990 / ISO 6336

2.5 Fatigue life calculation

To evaluate achieved fatigue life in variable load amplitude tests, different calculation methods, based on linear fatigue accumulation according to Miner's theorem [14], are applied. The fundamental idea of Miner's theory is that any load cycle causes damage, which accumulates during the life cycle up to a critical value. According to equation (1), cumulative damage D can be calculated as the sum of damage portions ΔD_i , with endured load cycles n_i and associated allowable cycle number N_i at any load level i .

$$D = \sum_i \Delta D_i = \sum_i \frac{n_i}{N_i} \quad (1)$$

Different fatigue accumulation hypotheses rate actual damage with regard to the real damaging process by

differently assigning allowable cycle numbers N_i . The best known fatigue accumulation hypothesis is the Palmgren-Miner-rule, derived in 1924 by Palmgren [15] for Hertzian pressure in ball bearings, and applied in 1945 by Miner in his often cited work [14]. In the Palmgren-Miner-rule, allowable cycle numbers are assigned according to the S-N-curve and loads below fatigue limit are ignored. However, variable load amplitude tests showed that loads below fatigue limit can damage as well. Hence, the Palmgren-Miner-rule has been modified. Corten and Dolan [2] modified the consideration of loads below fatigue limit by linearly extending the S-N-curve to the range of high cycle fatigue below fatigue limit. Allowable cycle numbers are assigned according to this straight line in double logarithmic scale. A modified form of the fatigue accumulation was suggested by Haibach using fracture mechanics [7]. He specifies the decline of the fatigue limit σ_{D0} in terms of the cumulative damage ratio D . The value of the actual fatigue limit σ_D is calculated with equation (2).

$$\sigma_D = \sigma_{D0} \cdot (1 - D)^{\frac{1}{q}} \quad (2)$$

Load cycles below fatigue limit σ_D cause no damage, only higher load levels cause damage, according to Palmgren-Miner-rule. The slope of fatigue limit decline is given by the parameter q , which can be approximated in terms of the gradient k of the S-N-curve to $q = k - 1$. In **fig. 6** different fatigue accumulation hypotheses are shown together with an example load distribution.