

Investigations on the Micropitting Load Capacity of Case Carburized Gears

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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

The load capacity of power transmitting gears can be limited by different failure modes. Standardized calculation methods acc. to German (DIN) or International (ISO) standard are available for rating the pitting resistance and bending strength of gear teeth. A further kind of fatigue damage is micropitting that is most frequently observed on case carburized gears.

Micropitting is controlled by the conditions of the tribological system of tooth flank surface and lubricant. The oil film thickness has been found to be a dominant parameter. Lubricant of base oil and additive, operating conditions, surface roughness and gear geometry are known as important influence factors on the micropitting load capacity.

In continuous work over several research projects major influences on the micropitting load capacity of gears were systematically investigated.

For evaluating the influence of lubricants the FZG micropitting test was developed. Results on the influence of certain parameters such as oil temperature, surface roughness or material were determined by variation of the test conditions.

Within the scope of actual research work some basic influences of gear geometry, gear size and operating conditions were investigated. For this purpose an extensive test program on spur and helical gears of different sizes and different gear geometry has been carried out. Based on the results of the previous and actual investigations an enhanced calculation method to determine the micropitting load capacity of practical gear units was developed.

In accordance to the existing standardized calculation methods regarding pitting resistance and bending strength the proposed rating formulas can be used to evaluate the risk of micropitting respectively to determine a safety factor for micropitting on case carburized gears.

The calculation method is based on the result of the micropitting test as a tribological parameter for the lubricant in use but enables the gear designer furthermore to take major influences as operating conditions, gear geometry and gear size of the actual application into consideration if rating the micropitting load capacity of a gear.

The paper summarizes important results of the continuous experimental investigations and introduces the proposed calculation method for rating the micropitting load capacity of case carburized gears.

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Nomenclature

A	start of line of contact		-
B	lowest point of single tooth contact		-
C	pitch point	.....	-
D	highest point of single tooth contact	.....	-
E	end of line of contact	.....	-
C_a	amount of tip relief	.....	μm
$E_{1,2}$	Young's modulus of pinion, gear	.....	\text{N/mm^2
E'	reduced Young's modulus	.....	\text{N/mm^2
R	radius of flank curvature	.....	\text{mm
R_a	mean value of tooth flank roughness	.....	μm
S_{GF}	micropitting safety factor	.....	-
S_{GFmin}	minimum demanded safety factor	.....	-
a	center distance	.....	\text{mm
b	gear face width	.....	\text{mm
f_{fm}	mean profile deviation	.....	μm
h_c	film thickness at pitch point (isotherm)	..	μm
h_{min}	local minimum oil film thickness	.....	μm
m_n	normal module	.....	\text{mm
p	Hertzian contact pressure	.....	\text{N/mm^2
p_e	normal base pitch	.....	\text{mm
u	tangential velocity	.....	\text{m/s
$x_{1,2}$	addendum modification factor	.....	-
$z_{1,2}$	number of teeth	.....	-
β	helix angle	.....	$^\circ$
ε_α	transverse contact ratio	.....	-
ε_β	overlap ratio	.....	-
ζ	coordinate in the direction of contact line	mm	
η	coordinate in the direction of face width	mm	
η	dynamic viscosity	.....	\text{Pas
η_M	dynamic viscosity at bulk temperature	..	Pas
Θ_M	bulk temperature	.....	$^\circ\text{C}$
λ_{GF}	effective rel. minimum oil film thickness	..	-
λ_{GFP}	permissible rel. minimum oil film thickness	-	
ρ	relative radius of flank curvature	.....	\text{mm

1 Introduction

The load capacity of power transmitting gears can be limited by different failure modes. Standardized calculation methods acc. to [1, 2, 12] are available for rating the pitting resistance and bending strength of gear teeth. A further kind of fatigue damage is micropitting that is most frequently observed on case carburized gears (**Fig. 1**).

Micropitting firstly has been noticed on high power transmitting gears operated with low viscosity lubricants at high temperatures.

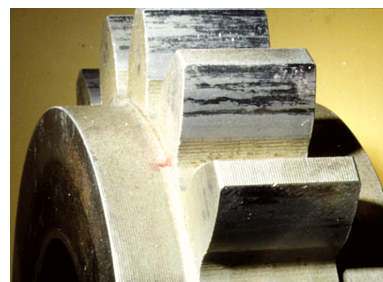


Fig. 1: Severe micropitting on the teeth of a test pinion

The increasing use of lubricants with EP additives has led to a decrease of the scuffing risk and an increase of the transmitted power. As a consequence micropitting has been observed in recent years on a diversity of different gear applications.

It is the state of knowledge that micropitting on gears is controlled by the conditions of the tribological system of tooth flank surface and lubricant. The oil film thickness has been found to be a dominant parameter.

In continuous work over several research projects major influences on the micropitting load capacity of gears were systematically investigated. For evaluating the influence of lubricant the FZG micropitting test was developed. Results on the

influence of several further parameters such as oil temperature, surface roughness or gear material were determined by variation of the test conditions.

For a safe and reliable rating of the micropitting load capacity of gears an experimentally verified calculation method to evaluate the risk of micropitting of gears in practice is required. Therefore some more basic influences such as gear geometry, gear size and operating conditions has to be known. For this purpose an extensive test program on spur and helical gears has been carried out. Gears with different sizes and different gear geometry were included in the test program in order to develop an enhanced calculation method that is based on the result of the micropitting test as a tribological parameter for the lubricant in use but taking also further major influences into consideration when rating the micropitting load capacity of a gear.

2 Characteristics of Micropitting

Micropitting occurs most frequently on tooth flanks with a high surface hardness under unfavorable lubrication conditions. Several parameters influence the damage occurrence, development and local intensity on a tooth flank. First indications of the occurrence of micropitting are determined often after few load cycles at very low loads; that indicates the beginning of damages of wear type. Cracks and material pits in the further damage progression point out the fatigue character of the micropitting failure. Micropitting on the flank surfaces normally occurs first on the dedendum flank of the driving gear, i.e. in the area of negative specific sliding. It propagates gradually over the flank and covers in extreme cases the whole active flank surface.

Forms of micropitting failure and consequential damages:

- Micropitting is a surface damage. It can cause profile deviations of wear type on the active flanks (**Fig. 2**). In this case the dynamical

additional forces and the gear noise can increase.

- The immediately resulted small pits, that give the flank its grey appearance, can build large flat pits.
- Some of the many small cracks can propagate and ramify. As a result large deep triangular particles can break out. That is the way of occurrence of pitting and spalling, that in many cases can reach the tip edge of the gear.

Typical changes in the involute profile diagram of a tooth flank caused by progressing profile deviations due to micropitting are shown in **Fig. 2** as a function of the number of load cycles. These profile deviations in Fig. 2 are located in section A-C on the line of contact and are correlated to the closed grey area on the tooth flank.

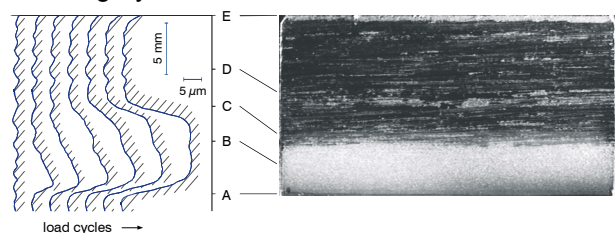


Fig. 2: Changes of the involute profile of a gear tooth caused by progressing profile deviations due to micropitting and correlation to the tooth flank

A more detailed description of the damage pattern as well as of some effects of micropitting on operating characteristics and gear life are to be found in [10].

3 Influences on the Micropitting Load Capacity

Micropitting is controlled by the conditions of a tribological system consisting of the tooth flank surface and the lubricant (base oil and additives). The relationship of oil film thickness to surface roughness of tooth flank ($h_{\min}/R_a$) is a dominant parameter. The oil film thickness depends on the lubricant viscosity and the operating conditions and can be calculated according to the rules of elastohydrodynamic (EHD) theory.

Fig. 3 shows a differentiation of basic influences

on the micropitting load capacity of gears into three main categories: lubricant, tooth flank and operating conditions.

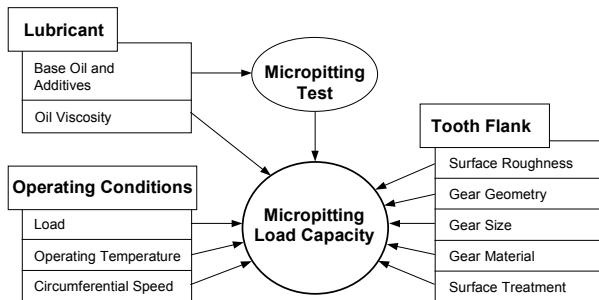


Fig. 3: Influences on the micropitting load capacity

Influences of lubricant

It is well known that the chemistry of base oil and especially additives has a large influence on the micropitting load capacity of gears. As the chemical interaction of base oil and additives with the material of the tooth flank is normally not predictable the influence of lubricant on the micropitting load capacity has to be determined by an experimental test method as the FZG-micropitting test [7, 8]. This is also due to different additive performance at different operating temperatures.

The influence of oil viscosity is calculable but minor compared to the influence of chemistry of the lubricant. A higher viscosity of the lubricant normally reduces micropitting due to higher oil film thickness [10].

FZG micropitting test

The FZG-micropitting test provides a quantitative evaluation of the influence of lubricant (especially additives), lubricant temperature and other parameters on the occurrence of micropitting. The micropitting test differentiates oils according to their micropitting load capacity and enables the choice of a lubricant with a sufficient micropitting resistance. The FZG-micropitting test consists of a load stage test with incremental increasing of the contact stress and an endurance test.

In the load stage test the micropitting load capacity of a lubricant is determined for specified test

conditions in form of a failure load stage. The failure load stage is reached, if the tooth profile has changed by a mean profile deviation of $7.5 \mu\text{m}$ (corresponding to a change of gear accuracy from DIN 5 to DIN 6). The endurance test provides additional information on the damage progression with higher numbers of load cycles. **Fig. 4** shows typical examples of lubricants with different micropitting load capacity. A detailed description of the test procedure is to be found in [8].

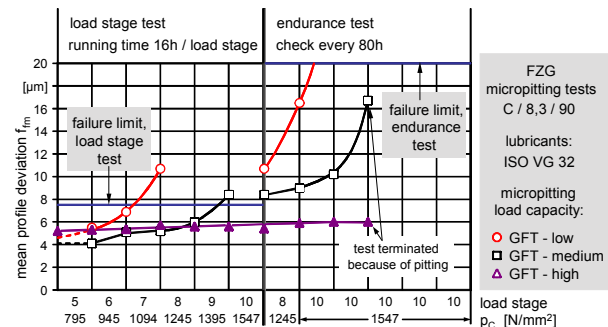


Fig. 4: Typical micropitting test results for lubricants with different micropitting load capacity

In order to allow a transfer of the test result on practical gear sets an adequate calculation method to compare the conditions of the tribological system in the practical application to the test conditions is necessary. For reliable results the test conditions should be as close as possible to the operating conditions of the application. As the effect of the additives on the micropitting load capacity depends on the lubricant temperature it is particularly recommended to run the micropitting test in the temperature range of the application.

Influences of tooth flank and operating conditions

Several influences on the micropitting load capacity of gears were systematically investigated in former research projects by variation of the test conditions [5, 6, 14, 15, 16]. Some of the basic results acc. to [10] can be summarized as followed:

- Surface roughness is one of the major influences on the micropitting load capacity. An increase of the surface roughness of the tooth flank leads for almost all operating conditions to a decrease of the micropitting load capacity.