Applied Mechanics and Materials Vol 86 (2011) pp 898-903 *Online: 2011-08-16*
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doi:10.4028/www.scientific.net/AMM.86.898

Micropitting in Wind Turbine Gearboxes: Calculation of the Safety Factor And Optimization of the Gear Geometry

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Keywords: Micropitting, Profile Correction, Lead Correction, Lubricant, Wind.

Abstract. If the contact pressure between mating flanks of a gear set is increased, the lubricant film thickness in between is reduced to a level where the asperities of the flanks start to touch. This case where the surface roughness is of similar value as the EHD film thickness is called “mixed friction”. Due to the metallic contact of the asperities and the movement of the flanks with respect to each other, the flanks are damaged. The damaged flanks appear dull or greyish, hence the name “grey-staining” (or “Graufleckigkeit” in German), see e.g. [4] or [1]. Micropitting are small cracks on the surface of the gears (as opposed to pitting, where the cracks form below the surface), which grow into the material. The size of the damages is about 10-20 μm depth, 25-100 μm length and 10-20 μm width. Micropitting is mainly observed with case carburized gears but may also be found in nitrided, induction hardened or through hardened gears. Micropitting mainly occurs in areas of negative specific sliding. Negative specific sliding is to be found along the path of contact between point A and C on the driving gear and between point C and E on the driven gear.

Introduction

Today, an analysis of the gearing in terms of micropitting should be considered state of the art and is typically required as part of the certification process of wind turbine gearboxes. The calculation against micropitting should be used as a design criterion for the gear macro geometry, the gear micro geometry and the lubricant.

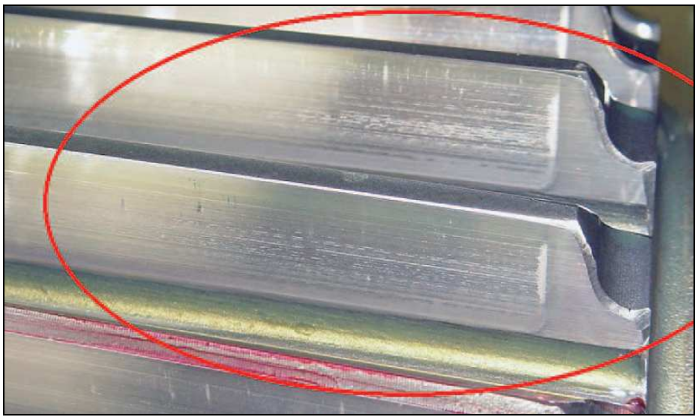


Fig. 1 Micropitting on a sun gear of a wind turbine gearbox [1]

Means to reduce the risk of micropitting

To assess the risk of micropitting, the specific film thickness λ or, using the ISO/TR 15144:2010 nomenclature, λGF, (the ratio between lubricant film thickness and surface roughness), is considered. The area of interest for micropitting is the domain of $0.7<\lambda<2.0$, where micropitting may occur. This area is the so called mixed lubrication domain.

For the gearbox designer, the question remains on how he can reduce the risk of micropitting. Different approaches are listed in the literature [6] as shown below:

Table 1. Means to influence the risk of micropitting

	Action	Effect	Comments
Material, Surface	**Reduce flank roughness to 1/16**	**1:2**	**See use of super finishing of gears in wind industry**
	Gears with run-in vs. without run-in	1:3	Running in of gears may be done during serial testing of gearboxes. The effectiveness may be lower for super finished gears and gears with micro geometry modifications
	Case carburizing vs. Nitriding vs. Phosphating vs. Use of copper plating	*1:2:1.4 :3*	*Seems to be impractical as only case carburized gears are used for external gears in wind industry*
	Normal vs. stainless steel	*1:0.3*	*The use of stainless steel in is limited*
Lubricant	Use of EP additives	1:5	The use of lubricants with EP additives and other additives is considered state of the art in wind industry
	Double the viscosity	1:1.15	The viscosity of the lubricants as used in wind industry is typically v40=320mm^2/s
Gear design	**Change in gear macro geometry**	**1:6**	**Optimised gear design is in the responsibility of the gear designer**
	Change in gear micro geometry	**1:2**	**Suitable modifications of the gear geometry should be applied by the gear designer**
	Spur vs. helical gears	*1:0.75*	*Typically, helical gears are used due to the high requirements in terms of noise levels*
Operation	*High vs. Low circumferential speeds*	*1:8*	*Circumferential speed is determined by the rotor speed and gear size and is hence difficult to change*

Relevant and may be applied by gear designer
Partly relevant as already state of the art in wind industry
Not applicable in wind industry

The other parameters are either limited in their effectiveness, not feasible in wind industry or already optimised/state of the art. Own studies as listed below show that optimisation of gear macro geometry (module, profile shift, reference profile, pressure angle, …), optimisation of gear micro geometry (profile and lead modifications) do influence the specific film thickness considerably. The effectiveness of certain approaches as listed in the table above are questionable, the results of the studies shown below show less influence e.g. of gear macro geometry optimisation.

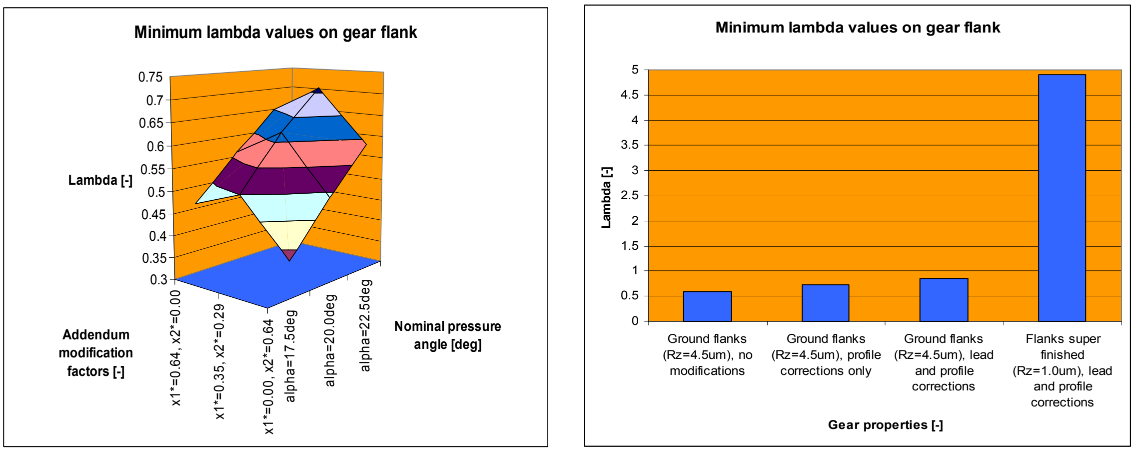


Fig. 2. Left: Influence of gear macro geometry on λGF,min. Right: Influence of gear micro geometry on λGF,min. Also shown is the influence of a reduced surface roughness

Micropitting calculation, introduction

The main factors influencing the risk of micropitting are the local contact pressure between the mating flanks, the temperature and viscosity of the lubricant film, the surface roughness of the flanks and the additives of the lubricant. Based on the above, the minimum specific film thickness between the flanks of the gears is calculated and compared to a required specific film thickness. It has to be noted that not all aspects can be considered in the calculation methods directly. The calculation method gets its effectiveness only through the definition of the required values based on test results. The result of the procedure is a safety factor which needs to be higher than a required safety factor:

$$S_\lambda = \frac{\lambda_{GF,min}}{\lambda_{GFP}} \geq S_{\lambda,min}$$

$\lambda_{GF,min} = \min(\lambda_{GF,Y})$	minimum specific lubricant film thickness in the contact point Y
λ_{GFP}	permissible specific lubricant film thickness
$S_{\lambda,min}$	minimum required safety factor

ISO/TR 15144:2010

The calculation procedure is based on the concept of a safety factor that needs to be higher than a required safety factor as shown above, where as the safety factor is the result of a comparison of a specific lubricant film thickness compared to a required specific lubricant film thickness.

The local specific lubricant film thickness in the contact is calculated along Dowson/Higginson as the relation between the local lubricant film thickness hy in Point Y divided by the effective arithmetic mean roughness value Ra:

$$Ra = 0{,}5 \cdot (Ra_1 + Ra_2)$$

$$\lambda_{GF,Y} = \frac{h_Y}{Ra} \quad \text{and} \quad h_Y = 1600 \cdot \rho_{n,Y} \cdot G_M{}^{0,6} \cdot U_Y{}^{0,7} \cdot W_Y{}^{-0,13} \cdot S_{GF,Y}{}^{0,22}$$

Y	point of calculation
$\rho_{n,Y}$	normal radius of relative curvature at point Y
G_M	is the material parameter
U_Y	local velocity parameter
W_Y	local load parameter
$S_{GF,Y}$	local sliding parameter

Method A:

The local load parameter WY is a function of the contact stress (and the reduced modulus of elasticity). In case of method A, the local contact stress is computed based on a detailed tooth contact analysis, taking into account all gear corrections, deformations and misalignment. Therefore, for method A, the basis of the local micropitting risk calculation is the tooth contact analysis. How this tooth contact analysis is to be done is not documented in the ISO/TR 15144:2010. However, it may be implemented as follows according to [12] as shown in the figure below. This will then yield a contact stress for each point of the flank surface, and therefore, the safety factor for micropitting can be computed for each point on the flank (as opposed to method B below, where only seven points are considered).

Method B:

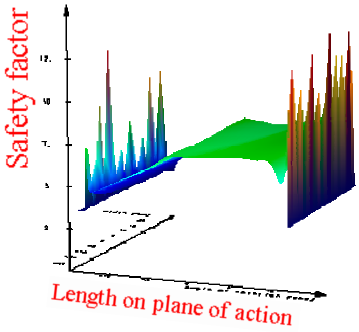
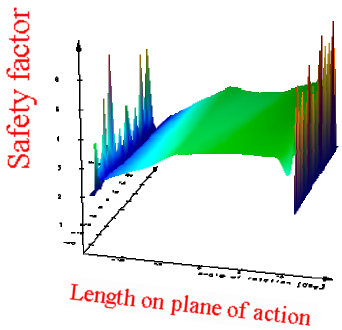
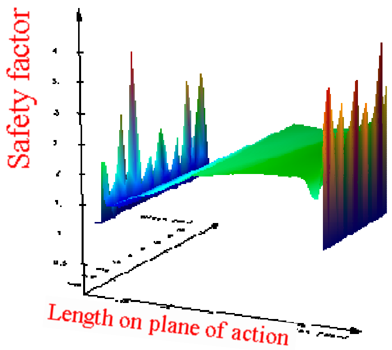
In method B, the calculation of the local load parameter is much simplified compared to method A. The lead direction is not considered at all (the gear is considered as perfectly aligned and no deformation in lead direction are considered) and in profile direction, only seven points (A, E, B, D, C and two more points) Y are considered. At each of these points, the factors ρn,Y, GM, UY, WY, SGF,Y are calculated as per section 6 to 10 of the ISO/TR 15144:2010. This then yields much less information compared to method A. Field experience shows that effects leading to micropitting often are related to profile and lead modifications as well as component deformations. These effects can not be considered by method B though.

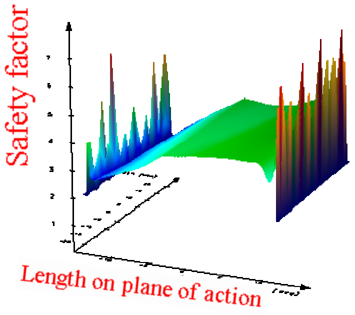
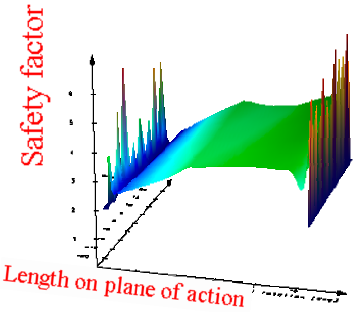
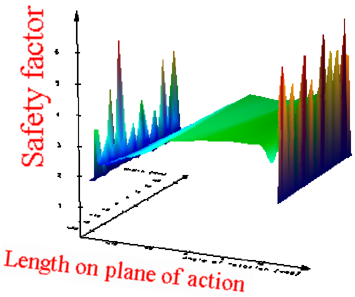
Permissible specific film thickness and required safety factor:
The minimum permissible specific film thickness is based on measurements of the load capacity of the lubricant according to [7]. It is given as a function of the above mentioned load capacity SKS (a number between 5 and 10) and the lubricant base viscosity. Note that no required safety factors are given in ISO/TR 15144:2010 but recommendations on additional considerations are listed.

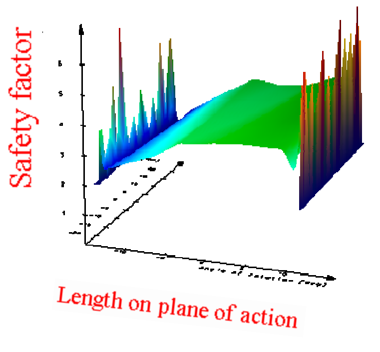
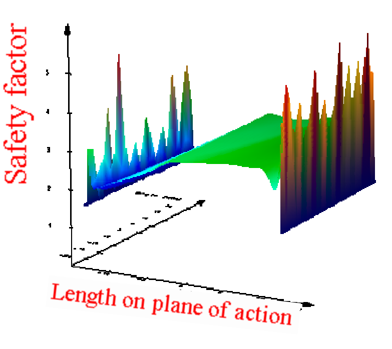
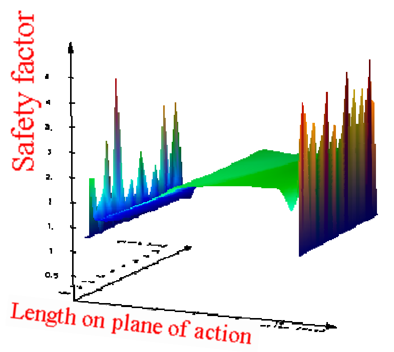
However, in particular for the wind gearbox industry, other sources may be used to define a required safety factor, e.g. the GL guidelines or IEC 61400-4. In the GL guidelines, section 7.4.5, Calculation of load capacity of gears, a required safety factor of Sλ,min=1.20 at nominal load is given.

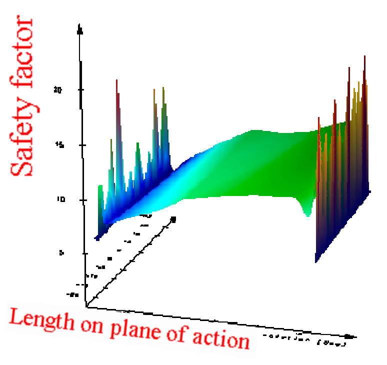
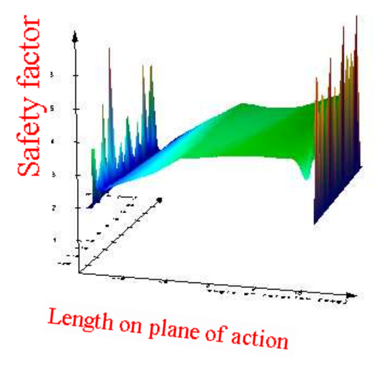
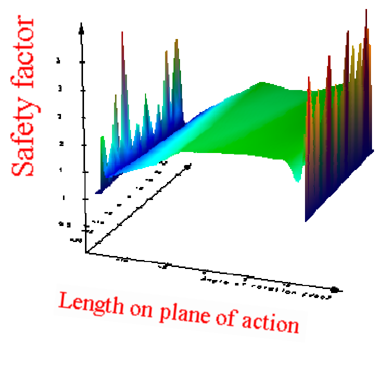
Sensitivity analysis

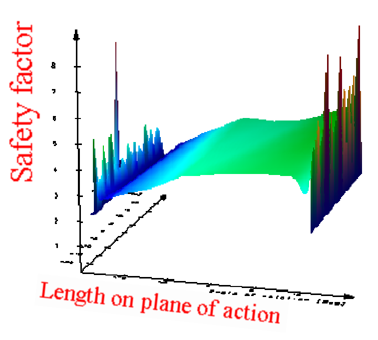
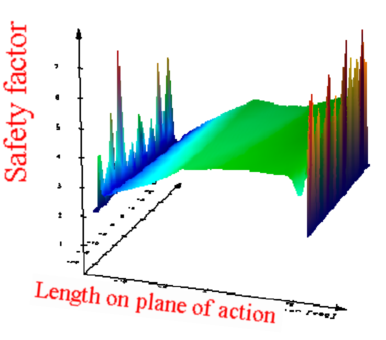
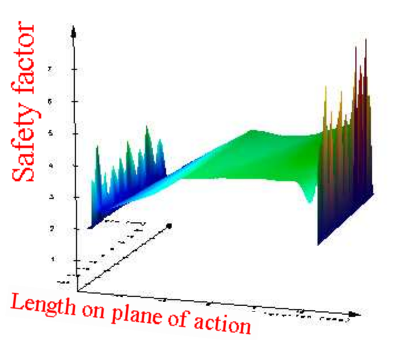
The below sensitivity analysis is based on the sun-planet contact of a 2.5MW wind turbine gearbox. Below, the influence of basic operating data as well of gear properties on the calculated safety factor Sλ is shown. Note that in the graphical display of the calculated safety factor over the whole plane of contact, numerical peaks at the start and end of mesh occur. However, it is noted that at the start of mesh (near point A for the driving gear), the lowest safety factors occur, which corresponds to the observation in reality that micropitting typically occurs in the root of the driving gear.

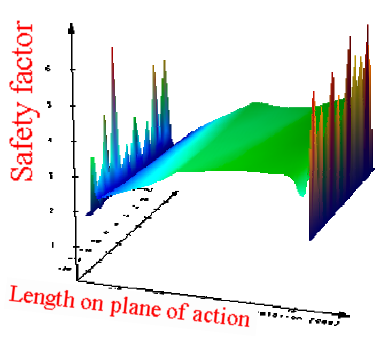
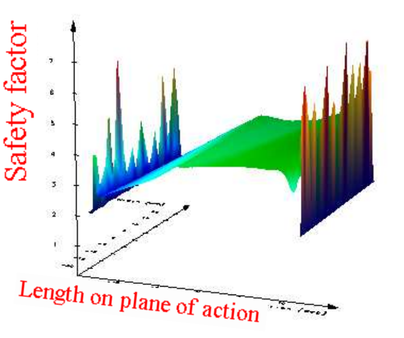
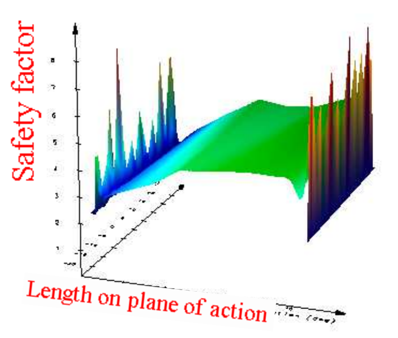
Influence of lubricant temperature, ISO VG 220, SKS=10, Rz=4.8		
T=50C	T=70C	T=90C
		
Sλ=3.360	Sλ=1.813	Sλ=1.098

Influence of lubricant viscosity, T=70C, SKS=10 , Rz=4.8		
VG320	VG220	VG150
		
Sλ=1.894	Sλ=1.813	Sλ=1.715

Influence of the load stage capacity, T=70C, ISO VG200 , Rz=4.8		
SKS=10	SKS=9	SKS=8
		
Sλ=1.813	Sλ=1.478	Sλ=1.207

Influence of flank roughness, T=70C, ISO VG200, SKS 10		
Rz=2.0um	Rz=4.8um	Rz=8.0um
		
Sλ=5.660	Sλ=1.813	Sλ=0.982

Influence of load level, T=70C, ISO VG200, SKS 10		
Torque=80% of nominal torque	Torque=100% of nominal torque	Torque=120% of nominal torque
		
Sλ=2.026	Sλ=1.917	Sλ=1.827

Influence of speed, T=70C, ISO VG200, SKS 10		
Speed=80% of nominal speed	Speed=100% of nominal speed	Speed=120% of nominal speed
		
Sλ=1.699	Sλ=1.917	Sλ=2.112

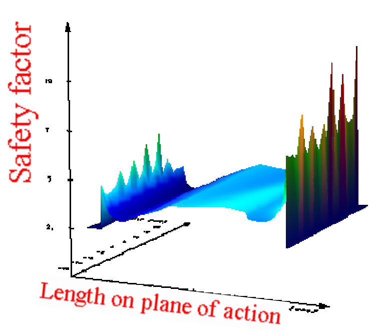
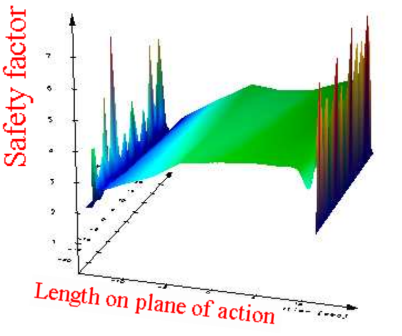
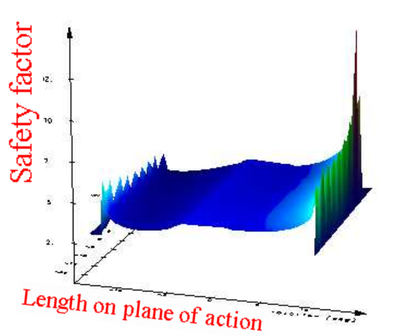
Influence of tip relief, T=70C, ISO VG200, SKS 10		
Short tip relief, Ca=25.0um	No tip relief, Ca=0.0um	Long tip relief, Ca=25.0um
		
Sλ=2.342	Sλ=1.917	Sλ=2.701

Fig. 3: Safety against micropitting as a function of different parameters

We observe that

- the load level of the lubricant is of relevance
- the temperature of the lubricant is of relevance
- the flank roughness is of particular relevance

While

- the applied torque and speed level seems to be of lesser relevance
- the viscosity grade seems to be of lesser relevance
- the profile correction seems to be is of lesser relevance

In the practical application of the calculation in the field of wind gearbox design however, all above aspects need to be considered in the gear design.

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