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Calculation of micropitting load capacity of cylindrical spur and helical gears

Part 2: Examples of calculation for micropitting

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National foreword

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TECHNICAL REPORT

ISO/TR 15144-2

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2014-10-01

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2015-01-15

Calculation of micropitting load capacity of cylindrical spur and helical gears —

Part 2:
Examples of calculation for micropitting

Calcul de la capacité de charge aux micropiqûres des engrenages cylindriques à dentures droite et hélicoïdale —

Partie 2: Exemples de calcul pour micropiqûres

Reference number
ISO/TR 15144-2:2014(E)

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information

The committee responsible for this document is ISO/TC 60, *Gears*, Subcommittee SC 2, *Gear capacity calculation*.

This corrected version of ISO/TR 15144-2:2014 incorporates the following corrections: errors in symbols and equations have been corrected.

ISO/TR 15144 consists of the following parts, under the general title *Calculation of micropitting load capacity of cylindrical spur and helical gears*:

— *Part 1: Introduction and basic principles*

— *Part 2: Examples of calculation for micropitting*

Introduction

This part of ISO/TR 15144 provides worked examples for the application of the calculation procedures defined in ISO/TR 15144-1. The example calculations cover the application to spur and helical cyclindrical involute gears for both high-speed and low-speed operating conditions, determining the micropitting safety factor for each gear pair. The calculation procedures used are consistent with those presented in ISO/TR 15144-1. No additional calculations are presented here that are outside of the technical report.

Four worked examples are presented with the necessary input data for each gear set provided at the beginning of the calculation. The worked examples are based on real gear pairs where either laboratory or operational field performance data has been established, with the examples covering several applications. When available, pictures and measurements are provided of the micropitting wear, experienced on the gear sets when run under the conditions used in the worked examples. Calculation details are presented in full for several of the initial calculations after which only summarized results data are included. For better applicability, the numbering of the formulae follows ISO/TR 15144-1. Several of the worked examples are presented with the calculation procedures performed in accordance with the application of both methods A and B.

Calculation of micropitting load capacity of cylindrical spur and helical gears —

Part 2:
Examples of calculation for micropitting

1 Scope

The example calculations presented here are provided for guidance on the application of the technical report ISO/TR 15144-1 only. Any of the values or the data presented should not be used as material or lubricant allowables or as recommendations for micro-geometry in real applications when applying this procedure. The necessary parameters and allowable film thickness values, λ_{GFP}, should be determined for a given application in accordance with the procedures defined in ISO/TR 15144-1.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 1122-1:1998, *Vocabulary of gear terms — Part 1: Definitions related to geometry*

ISO 6336-1:2006, *Calculation of load capacity of spur and helical gears — Part 1: Basic principles, introduction and general influence factors*

ISO 6336-2:2006, *Calculation of load capacity of spur and helical gears — Part 2: Calculation of surface durability (pitting)*

ISO 21771:2007, *Gears — Cylindrical involute gears and gear pairs — Concepts and geometry*

ISO/TR 15144-1:2014, *Calculation of micropitting load capacity of cylindrical spur and helical gears — Part 1: Introduction and basic principles*

3 Terms, definitions, symbols, and units

3.1 Terms and definitions

For the purpose of this document, the terms and definitions given in ISO 1122-1, ISO 6336-1, and ISO 6336-2 apply.

3.2 Symbols and units

The symbols used in this technical report are given in Table 1. The units of length metre, millimetre, and micrometre are chosen in accordance with common practice. The conversions of the units are already included in the given formulae.

Table 1 — Symbols and units

Symbol	Description	Unit
a	centre distance	mm
B_{M1}	thermal contact coefficient of pinion	$N/(m \cdot s^{0,5} \cdot K)$
B_{M2}	thermal contact coefficient of wheel	$N/(m \cdot s^{0,5} \cdot K)$
b	face width	mm
C_{a1}	tip relief of pinion	µm
C_{a2}	tip relief of wheel	µm
c_{M1}	specific heat per unit mass of pinion	J/(kg·K)
c_{M2}	specific heat per unit mass of wheel	J/(kg·K)
c'	maximum tooth stiffness per unit face width (single stiffness) of a tooth pair	N/(mm·µm)
$c_{\gamma\alpha}$	mean value of mesh stiffness per unit face width	N/(mm·µm)
d_{a1}	tip diameter of pinion	mm
d_{a2}	tip diameter of wheel	mm
d_{b1}	base diameter of pinion	mm
d_{b2}	base diameter of wheel	mm
d_{w1}	pitch diameter of pinion	mm
d_{w2}	pitch diameter of wheel	mm
d_{Y1}	Y-circle diameter of pinion	mm
d_{Y2}	Y-circle diameter of wheel	mm
E_r	reduced modulus of elasticity	N/mm^2
E_1	modulus of elasticity of pinion	N/mm^2
E_2	modulus of elasticity of wheel	N/mm^2
F_{bt}	nominal transverse load in plane of action (base tangent plane)	N
F_t	(nominal) transverse tangential load at reference cylinder per mesh	N
G_M	material parameter	-
g_Y	parameter on the path of contact (distance of point Y from point A)	mm
g_α	length of path of contact	mm
H_v	load losses factor	-
h_Y	local lubricant film thickness	µm
K_A	application factor	-
$K_{H\alpha}$	transverse load factor	-
$K_{H\beta}$	face load factor	-
K_v	dynamic factor	-
n_1	rotation speed of pinion	min^{-1}
P	transmitted power	kW
p_{et}	transverse base pitch on the path of contact	Mm
$p_{dyn,Y}$	local Hertzian contact stress including the load factors K	N/mm^2
$p_{H,Y}$	local nominal Hertzian contact stress	N/mm^2
Ra	effective arithmetic mean roughness value	µm
Ra_1	arithmetic mean roughness value of pinion	µm
Ra_2	arithmetic mean roughness value of wheel	µm
$S_{GF,Y}$	local sliding parameter	-

Table 1 *(continued)*

Symbol	Description	Unit
S_λ	safety factor against micropitting	-
$S_{\lambda,min}$	minimum required safety factor against micropitting	-
T_1	nominal torque at the pinion	Nm
U_Y	local velocity parameter	-
u	gear ratio	-
$v_{g,Y}$	local sliding velocity	m/s
$v_{r1,Y}$	local tangential velocity on pinion	m/s
$v_{r2,Y}$	local tangential velocity on wheel	m/s
$v_{\Sigma,C}$	sum of tangential velocities at pitch point	m/s
$v_{\Sigma,Y}$	sum of tangential velocities at point Y	m/s
W_W	material factor	-
W_Y	local load parameter	-
$X_{but,Y}$	local buttressing factor	-
X_{Ca}	tip relief factor	-
X_L	lubricant factor	-
X_R	roughness factor	-
X_S	lubrication factor	-
X_Y	local load sharing factor	-
Z_E	elasticity factor	$(N/mm^2)^{0,5}$
z_1	number of teeth of pinion	-
z_2	number of teeth of wheel	-
α_t	transverse pressure angle	°
α_{wt}	pressure angle at the pitch cylinder	°
$\alpha_{\theta B,Y}$	pressure-viscosity coefficient at local contact temperature	m^2/N
$\alpha_{\theta M}$	pressure-viscosity coefficient at bulk temperature	m^2/N
α_{38}	pressure-viscosity coefficient at 38 °C	m^2/N
β_b	base helix angle	°
ε_{max}	maximum addendum contact ratio	-
ε_α	transverse contact ratio	-
$\varepsilon_{\alpha n}$	virtual transverse contact ratio	-
ε_β	overlap ratio	-
ε_γ	total contact ratio	-
ε_1	addendum contact ratio of the pinion	-
ε_2	addendum contact ratio of the wheel	-
$\eta_{\theta B,Y}$	dynamic viscosity at local contact temperature	$N \cdot s/m^2$
$\eta_{\theta M}$	dynamic viscosity at bulk temperature	$N \cdot s/m^2$
$\eta_{\theta oil}$	dynamic viscosity at oil inlet/sump temperature	$N \cdot s/m^2$
η_{38}	dynamic viscosity at 38 °C	$N \cdot s/m^2$
$\theta_{B,Y}$	local contact temperature	°C
$\theta_{fl,Y}$	local flash temperature	°C
θ_M	bulk temperature	°C

Table 1 *(continued)*

Symbol	Description	Unit
θ_{oil}	oil inlet/sump temperature	°C
$\lambda_{GF,min}$	minimum specific lubricant film thickness in the contact area	-
$\lambda_{GF,Y}$	local specific lubricant film thickness	-
λ_{GFP}	permissible specific lubricant film thickness	-
λ_{GFT}	limiting specific lubricant film thickness of the test gears	-
λ_{M1}	specific heat conductivity of pinion	W/(m·K)
λ_{M2}	specific heat conductivity of wheel	W/(m·K)
μ_m	mean coefficient of friction	-
$\nu_{\theta B,Y}$	kinematic viscosity at local contact temperature	mm^2/s
$\nu_{\theta M}$	kinematic viscosity at bulk temperature	mm^2/s
ν_1	Poisson's ratio of pinion	-
ν_2	Poisson's ratio of wheel	-
ν_{100}	kinematic viscosity at 100 °C	mm^2/s
ν_{40}	kinematic viscosity at 40 °C	mm^2/s
ρ_{M1}	density of pinion	kg/m^3
ρ_{M2}	density of wheel	kg/m^3
$\rho_{n,C}$	normal radius of relative curvature at pitch diameter	mm
$\rho_{n,Y}$	normal radius of relative curvature at point Y	mm
$\rho_{t,Y}$	transverse radius of relative curvature at point Y	mm
$\rho_{t1,Y}$	transverse radius of curvature of pinion at point Y	mm
$\rho_{t2,Y}$	transverse radius of curvature of wheel at point Y	mm
$\rho_{\theta B,Y}$	density of lubricant at local contact temperature	kg/m^3
$\rho_{\theta M}$	density of lubricant at bulk temperature	kg/m^3
ρ_{15}	density of lubricant at 15 °C	kg/m^3
Subscripts to symbols		
Y	Parameter for any contact point Y in the contact area for method A and on the path of contact for method B (all parameters subscript Y has to be calculated with local values).	

4 Example calculation

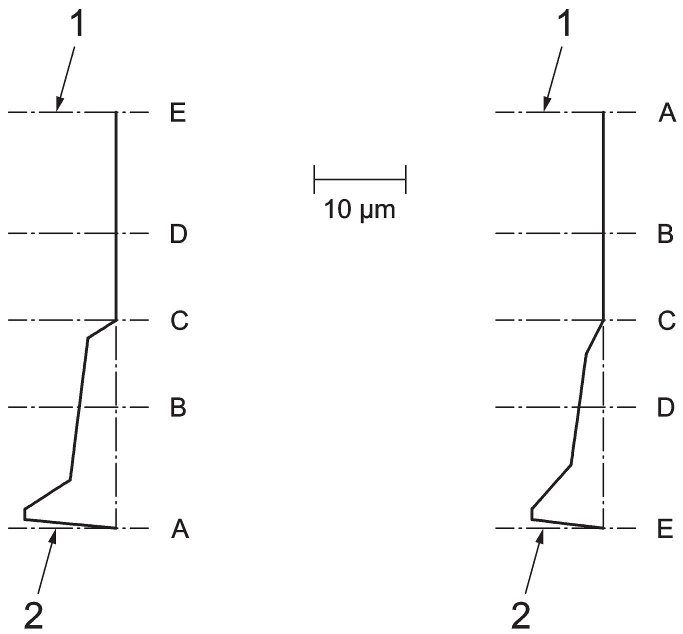
The following presents examples for the calculation of the safety factor against micropitting, S_λ. Each example is first calculated according to method B and examples 1, 3, and 4 subsequently calculated according to method A. The calculation sequence for method B has been provided to follow a logical approach in relation to the input data. Beside the formulae itself, the formula numbers related to ISO/TR 15144-1 are given.

The examples calculate the safety factor S_λ of a specific gear set when compared to an allowable λ_{GFP} value. For the examples 1, 2, and 4, the permissible specific oil film thickness, λ_{GFP}, was determined from the test result of the lubricant in the FZG-FVA micropitting test.[1] For these calculations medium values for the standard FZG back-to-back test rig and standard test conditions for $K_{H\beta}$ and K_v were used ($K_{H\beta}$ = 1,10 and K_v = 1,05). The calculation of the λ_{GFP} value from the test result of the FZG-FVA micropitting test[1] (method B) is shown exemplary on the basis of the first example. For example 3, the permissible specific oil film thickness, λ_{GFP}, was determined from a bench test.

NOTE The calculations were performed computer-based. If the calculations are performed manually, small differences between the results can appear.

4.1 Example 1 — Spur gear

The result of this example is confirmed by experimental investigations. The gears were obviously micropitted and had profile deviations of approximately 8 to 10 µm. Figure 1 shows a diagram of the observed location and severity of micropitting for pinion and wheel of example 1.



a) pinion **b) wheel**

Key

1 tip

2 root

Figure 1 — Diagram of schematic profile deviations of pinion and wheel for example 1

4.1.1 Input data

Table 2 — Input data for Example 1

	Symbol	Description	Unit	Example 1 pinion	Example 1 wheel
				comb.	
Geometry	z	number of teeth	-	18	18
	-	driving gear	-	x	
	m_n	normal module	mm	10,93	
	α_n	normal pressure angle	°	20	
	β	helix angle	°	0	
	b	face width	mm	21,4	
	a	centre distance	mm	200	
	x	addendum modification factor	-	0,158	0,158
	d_a	tip diameter of pinion	mm	221,4	221,4
	-	tooth flank modifications	-	no modifications	
	Q	gear quality	-	5	5
	Ra	arithmetic mean roughness value	µm	0,90	0,90
Material	-	material	-	Eh	Eh
	E	modulus of elasticity	N/mm^2	206 000	206 000
	ν	Poisson's ratio	-	0,3	0,3
	λ_M	specific heat conductivity	W/(m·K)	45	45
	c_M	specific heat per unit mass	J/(kg·K)	440	440
	ρ_M	density	kg/m^3	7 800	7 800
	W_W	material factor according to ISO/TR 15144-1:2014, Table A.1 (for matching case carburised/case carburised)	-	1,0	
Application	K_A	application factor	-	1,0	
	K_v	dynamic factor	-	1,15	
	$K_{H\alpha}$	transverse load factor	-	1,0	
	$K_{H\beta}$	face load factor	-	1,10	
Load	T_1	nominal torque at the pinion	Nm	1 878	
	n_1	rotation speed of the pinion	min^{-1}	3 000	
Lubricant	θ_{oil}	oil inlet temperature (injection lubrication)	°C	90	
	ν_{40}	kinematic viscosity at 40 °C	mm^2/s	210	
	ν_{100}	kinematic viscosity at 100 °C	mm^2/s	18,5	
	ρ_{15}	density of the lubricant at 15 °C	kg/m^3	895	
	-	oil type	-	mineral oil	
	-	failure load stage at test temperature (90 °C) according to FVA 54/7	-	SKS 8	
	λ_{GFP}	permissible lubricant film thickness (see 4.1.4 for calculation)	-	0,211	

4.1.2 Calculation according to method B

4.1.2.1 Calculation of gear geometry (according to ISO 21771)

Basic values:

$$m_t = \frac{m_n}{\cos\beta}$$ m_t = 10,93 mm

$d_1 = z_1 \cdot m_t$ d_1 = 196,74 mm

$d_2 = z_2 \cdot m_t$ d_2 = 196,74 mm

$$u = \frac{z_2}{z_1}$$ u = 1

$$\alpha_t = \arctan\left(\frac{\tan\alpha_n}{\cos\beta}\right)$$ α_t = 20 °

$d_{b1} = d_1 \cos\alpha_t$ d_{b1} = 184,875 mm

$d_{b2} = d_2 \cos\alpha_t$ d_{b2} = 184,875 mm

$$d_{w1} = \frac{2 \cdot a}{u+1}$$ d_{w1} = 200 mm

$$d_{w2} = 2 \cdot a - d_{w1}$$ d_{w2} = 200 mm

$$\alpha_{wt} = \arccos\left[\frac{(z_1 + z_2) \cdot m_t \cdot \cos\alpha_t}{2 \cdot a}\right]$$ α_{wt} = 22,426 °

$$\beta_b = \arcsin(\sin\beta \cdot \cos\alpha_n)$$ β_b = 0 ° $\beta_b = 0\,^\circ$

$$p_{et} = m_t \cdot \pi \cdot \cos\alpha_t$$ p_{et} = 32,267 mm

$$\varepsilon_1 = \frac{z_1}{2 \cdot \pi} \cdot \left[\sqrt{\left(\frac{d_{a1}}{d_{b1}}\right)^2 - 1} - \tan\alpha_{wt}\right]$$ ε_1 = 0,705

$$\varepsilon_2 = \frac{z_2}{2 \cdot \pi} \cdot \left[\sqrt{\left(\frac{d_{a2}}{d_{b2}}\right)^2 - 1} - \tan\alpha_{wt}\right]$$ ε_2 = 0,705

$$\varepsilon_\alpha = \frac{1}{p_{et}} \cdot \left(\sqrt{\frac{{d_{a1}}^2}{4} - \frac{{d_{b1}}^2}{4}} + \sqrt{\frac{{d_{a2}}^2}{4} - \frac{{d_{b2}}^2}{4}} - a \cdot \sin\alpha_{wt}\right)$$ ε_α = 1,411

$$\varepsilon_\beta = \frac{b \cdot \sin\beta}{m_n \cdot \pi}$$ $\varepsilon_\beta = 0$

$$\varepsilon_\gamma = \varepsilon_\alpha + \varepsilon_\beta$$ $\varepsilon_\gamma = 1{,}411$

$$g_\alpha = 0{,}5 \cdot \left(\sqrt{d_{a1}^{\,2} - d_{b1}^{\,2}} + \sqrt{d_{a2}^{\,2} - d_{b2}^{\,2}} \right) - a \cdot \sin\alpha_{wt}$$ $g_\alpha = 45{,}519$ mm

Coordinates of the basic points (A, AB, B, C, D, DE, E) on the line of action:

$$g_A = 0 \text{ mm} \quad (34)$$ $g_A = 0$ mm

$$g_{AB} = \frac{g_\alpha - p_{et}}{2} \quad (35)$$ $g_{AB} = 6{,}626$ mm

$$g_B = g_\alpha - p_{et} \quad (36)$$ $g_B = 13{,}253$ mm

$$g_C = \frac{d_{b1}}{2} \cdot \tan\alpha_{wt} - \sqrt{\frac{d_{a1}^{\,2}}{4} - \frac{d_{b1}^{\,2}}{4}} + g_\alpha \quad (37)$$ $g_C = 22{,}760$ mm

$$g_D = p_{et} \quad (38)$$ $g_D = 32{,}267$ mm

$$g_{DE} = \frac{g_\alpha - p_{et}}{2} + p_{et} \quad (39)$$ $g_{DE} = 38{,}893$ mm

$$g_E = g_\alpha \quad (40)$$ $g_E = 45{,}519$ mm

$$d_{A1} = 2 \cdot \sqrt{\frac{d_{b1}^{\,2}}{4} + \left(\sqrt{\frac{d_{a1}^{\,2}}{4} - \frac{d_{b1}^{\,2}}{4}} - g_\alpha + g_A \right)^2} \quad (41)$$ $d_{A1} = 187{,}419$ mm

$d_{AB1} = 190{,}046$ mm $d_{B1} = 193{,}546$ mm $d_{C1} = 200{,}000$ mm

$d_{D1} = 207{,}998$ mm $d_{DE1} = 214{,}394$ mm $d_{E1} = 221{,}400$ mm

$$d_{A2} = 2 \cdot \sqrt{\frac{d_{b2}^{\,2}}{4} + \left(\sqrt{\frac{d_{a2}^{\,2}}{4} - \frac{d_{b2}^{\,2}}{4}} - g_A \right)^2} \quad (42)$$ $d_{A2} = 221{,}400$ mm

$d_{AB2} = 214{,}394$ mm $d_{B2} = 207{,}998$ mm $d_{C2} = 200{,}000$ mm

$d_{D2} = 193{,}546$ mm $d_{DE2} = 190{,} 046$ mm $d_{E2} = 187{,}419$ mm

Normal radius of relative curvature:

$$\rho_{n,A} = \frac{\rho_{t,A}}{\cos\beta_b} \quad (45)$$ $\rho_{n,A} = 12{,}285$ mm

$\rho_{n,AB} = 15{,}663$ mm $\rho_{n,B} = 17{,}890$ mm $\rho_{n,C} = 19{,}074$ mm

$\rho_{n,D} = 17{,}890$ $\rho_{n,DE} = 15{,}663$ mm $\rho_{n,E} = 12{,}285$ mm

4.1.2.2 Calculation of material data

$$E_r = 2 \cdot \left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right)^{-1} \quad (6) \qquad E_r = 226\ 374\ \text{N/mm}^2$$

$$B_{M1} = \sqrt{\lambda_{M1} \cdot \rho_{M1} \cdot c_{M1}} \quad (82) \qquad B_{M1} = 12\ 427{,}4\ \text{N/(ms}^{0{,}5}\text{K)}$$

$$B_{M2} = \sqrt{\lambda_{M2} \cdot \rho_{M2} \cdot c_{M2}} \quad (83) \qquad B_{M2} = 12\ 427{,}4\ \text{N/(ms}^{0{,}5}\text{K)}$$

4.1.2.3 Calculation of operating conditions

Loading:

$$P = 2 \cdot \pi \cdot \frac{n_1}{60} \cdot \frac{T_1}{1\ 000} \quad (85) \qquad P = 590\ \text{kW}$$

$$F_t = 2\ 000 \cdot \frac{T_1}{d_1} \qquad F_t = 19\ 091\ \text{N}$$

$$F_{bt} = 2\ 000 \cdot \frac{T_1}{d_{b1}} \qquad F_{bt} = 20\ 316\ \text{N}$$

Local load sharing factor:

NOTE No tooth flank modifications, spur gears, gear quality ≤7 (see ISO/TR 15144-1:2014, Figure 2).

$$X_A = \frac{Q-2}{15} + \frac{1}{3} \cdot \frac{g_A}{g_B} \quad (46) \qquad X_A = 0{,}333$$

$X_{AB} = 0{,}500$ $X_B = 1{,}000$ $X_C = 1{,}000$

$X_D = 1{,}000$ $X_{DE} = 0{,}500$ $X_E = 0{,}333$

Elasticity factor:

$$Z_E = \sqrt{\frac{E_r}{2 \cdot \pi}} \quad (26) \qquad Z_E = 189{,}812\ (\text{N/mm}^2)^{0{,}5}$$

Local Hertzian contact stress:

$$p_{H,A,B} = Z_E \cdot \sqrt{\frac{F_t \cdot X_A}{b \cdot \rho_{n,A} \cdot \cos\alpha_t \cdot \cos\beta_b}} \quad (25) \qquad p_{H,A,B} = 963\ \text{N/mm}^2$$

$p_{H,AB,B} = 1\ 045\ \text{N/mm}^2$ $p_{H,B,B} = 1\ 383\ \text{N/mm}^2$ $p_{H,C,B} = 1\ 339\ \text{N/mm}^2$

$p_{H,D,B} = 1\ 383\ \text{N/mm}^2$ $p_{H,DE,B} = 1\ 045\ \text{N/mm}^2$ $p_{H,E,B} = 963\ \text{N/mm}^2$

$$p_{dyn,A,B} = p_{H,A,B} \cdot \sqrt{K_A \cdot K_V \cdot K_{H\alpha} \cdot K_{H\beta}} \quad (24) \qquad p_{dyn,A,B} = 1\ 084\ \text{N/mm}^2$$

$p_{dyn,AB,B} = 1\ 175\ \text{N/mm}^2$ $p_{dyn,B,B} = 1\ 555\ \text{N/mm}^2$ $p_{dyn,C,B} = 1\ 506\ \text{N/mm}^2$

$p_{dyn,D,B}$ = 1 555 N/mm² $\quad$ $p_{dyn,DE,B}$ = 1 175 N/mm² $\quad$ $p_{dyn,E,B}$ = 1 084 N/mm²

Velocity:

$v_{g,A} = v_{r1,A} - v_{r2,A}$ (81) $\quad$ $v_{g,A} = -14{,}300$ m/s

$v_{g,AB} = -10{,}137$ m/s $\quad$ $v_{g,B} = -5{,}974$ m/s $\quad$ $v_{g,C} = 0$ m/s

$v_{g,D} = 5{,}974$ m/s $\quad$ $v_{g,DE} = 10{,}137$ m/s $\quad$ $v_{g,E} = 14{,}300$ m/s

$v_{\Sigma,A} = v_{r1,A} + v_{r2,A}$ (13) $\quad$ $v_{\Sigma,A} = 23{,}969$ m/s

$v_{\Sigma,AB} = 23{,}969$ m/s $\quad$ $v_{\Sigma,B} = 23{,}969$ m/s $\quad$ $v_{\Sigma,C} = 23{,}969$ m/s

$v_{\Sigma,D} = 23{,}969$ m/s $\quad$ $v_{\Sigma,DE} = 23{,}969$ m/s $\quad$ $v_{\Sigma,E} = 23{,}969$ m/s

Effective arithmetic mean roughness value:

$$Ra = 0{,}5 \cdot \left(Ra_1 + Ra_2 \right) \quad (3) \qquad Ra = 0{,}90\ \mu\text{m}$$

4.1.2.4 Calculation of lubricant data

X_L = 1,0 for mineral oil (see ISO/TR 15144-1:2014, Table 3)

$$\alpha_{38} = 2{,}657 \cdot 10^{-8} \cdot \eta_{38}^{\ 0{,}134\,8} \quad (9) \qquad \alpha_{38} = 2{,}15 \cdot 10^{-8}\ \text{m}^2/\text{N}$$

X_S = 1,2 for injection lubrication

4.1.2.5 Calculation of the material parameter

Mean coefficient of friction:

$$X_R = 2{,}2 \cdot \left(\frac{Ra}{\rho_{n,C}} \right)^{0{,}25} \quad (87) \qquad X_R = 1{,}025$$

$K_{B\gamma}$ = 1,0 for $\varepsilon_\gamma < 2$

$$\mu_m = 0{,}045 \cdot \left(\frac{K_A \cdot K_v \cdot K_{H\alpha} \cdot K_{H\beta} \cdot F_{bt} \cdot K_{B\gamma}}{b \cdot v_{\Sigma,C} \cdot \rho_{n,C}} \right)^{0{,}2} \cdot \left(10^3 \cdot \eta_{\theta oil} \right)^{-0{,}05} \cdot X_R \cdot X_L \quad (86) \qquad \mu_m = 0{,}048$$

Bulk temperature:

$$H_v = \left(\varepsilon_1^{\,2} + \varepsilon_2^{\,2} + 1 - \varepsilon_\alpha \right) \cdot \left(\frac{1}{z_1} + \frac{1}{z_2} \right) \cdot \frac{\pi}{\cos \beta_b} \text{ for } \varepsilon_\alpha < 2 \quad (91) \qquad H_v = 0{,}204$$

$\varepsilon_{max} = \varepsilon_1 = \varepsilon_2$

X_{CA} = 1,0 for no profile modification (method B) (101)

$$\theta_M = \theta_{oil} + 7\,400 \cdot \left(\frac{P \cdot \mu_m \cdot H_v}{a \cdot b} \right)^{0{,}72} \cdot \frac{X_S}{1{,}2 \cdot X_{Ca}} \quad (84) \qquad \theta_M = 153{,}6°\ \text{C}$$

Material parameter:

$G_M = 10^6 \cdot \alpha_{\theta M} \cdot E_r$ (5) $G_M = 2\,678{,}6$

4.1.2.6 Calculation of the velocity parameter

$$U_A = \eta_{\theta M} \cdot \frac{v_{\Sigma,A}}{2\,000 \cdot E_r \cdot \rho_{n,A}} \quad (12) \qquad U_A = 2{,}005 \cdot 10^{-11}$$

$U_{AB} = 1{,}572 \cdot 10^{-11}$ $U_B = 1{,}377 \cdot 10^{-11}$ $U_C = 1{,}291 \cdot 10^{-11}$

$U_D = 1{,}377 \cdot 10^{-11}$ $U_{DE} = 1{,}572 \cdot 10^{-11}$ $U_E = 2{,}005 \cdot 10^{-11}$

4.1.2.7 Calculation of the load parameter

$$W_A = \frac{2 \cdot \pi \cdot p_{dyn,A}{}^2}{E_r{}^2} \quad (22) \qquad W_A = 1{,}440 \cdot 10^{-4}$$

$W_{AB} = 1{,}694 \cdot 10^{-4}$ $W_B = 2{,}966 \cdot 10^{-4}$ $W_C = 2{,}781 \cdot 10^{-4}$

$W_D = 2{,}966 \cdot 10^{-4}$ $W_{DE} = 1{,}694 \cdot 10^{-4}$ $W_E = 1{,}440 \cdot 10^{-4}$

4.1.2.8 Calculation of the sliding parameter

Local flash temperature:

$$\theta_{fl,A} = \frac{\sqrt{\pi}}{2} \cdot \frac{10^6 \cdot \mu_m \cdot p_{dyn,A} \cdot \left|v_{g,A}\right|}{B_{M1}\sqrt{v_{r1,A}} + B_{M2}\sqrt{v_{r2,A}}} \cdot \sqrt{8 \cdot \rho_{n,A} \cdot \frac{p_{dyn,A}}{1\,000 \cdot E_r}} \quad (80) \qquad \theta_{fl,A} = 175{,}3° \text{ C}$$

$\theta_{fl,AB} = 154{,}1°$ C $\theta_{fl,B} = 145{,}4°$ C $\theta_{fl,C} = 0°$ C

$\theta_{fl,D} = 145{,}4°$ C $\theta_{fl,DE} = 154{,}1°$ C $\theta_{fl,E} = 175{,}3°$ C

Local contact temperature as sum of bulk and local flash temperature:

$\theta_{B,A} = \theta_M + \theta_{fl,A}$ (79) $\theta_{B,A} = 328{,}9°$ C

$\theta_{B,AB} = 307{,}7°$ C $\theta_{B,B} = 299{,}0°$ C $\theta_{B,C} = 153{,}6°$ C

$\theta_{B,D} = 299{,}0°$ C $\theta_{B,DE} = 307{,}7°$ C $\theta_{B,E} = 328{,}9°$ C

Local sliding parameter:

$$S_{GF,A} = \frac{\alpha_{\theta B,A} \cdot \eta_{\theta B,A}}{\alpha_{\theta M} \cdot \eta_{\theta M}} \quad (27) \qquad S_{GF,A} = 0{,}057$$

$S_{GF,AB} = 0{,}076$ $S_{GF,B} = 0{,}086$ $S_{GF,C} = 1{,}000$

$S_{GF,D} = 0{,}086$ $S_{GF,DE} = 0{,}076$ $S_{GF,E} = 0{,}057$

4.1.2.9 Calculation of the lubricant film thickness

$$h_A = 1600 \cdot \rho_{n,A} \cdot G_M{}^{0,6} \cdot U_A{}^{0,7} \cdot W_A{}^{-0,13} \cdot S_{GF,A}{}^{0,22} \quad (4) \qquad h_A = 0{,}122\ \mu\text{m}$$

h_{AB} = 0,137 µm	h_B = 0,136 µm	h_C = 0,241 µm
h_D = 0,136 µm	h_{DE} = 0,137 µm	h_E = 0,122 µm

4.1.2.10 Calculation of the specific lubricant film thickness

$$\lambda_{GF,A} = \frac{h_A}{Ra} \quad (2) \qquad \lambda_{GF,A} = 0{,}136$$

$\lambda_{GF,AB}$ =0,153	$\lambda_{GF,B}$ = 0,152	$\lambda_{GF,C}$ = 0,267
$\lambda_{GF,D}$ = 0,152	$\lambda_{GF,DE}$ = 0,153	$\lambda_{GF,E}$ = 0,136

$\lambda_{GF,min} = \lambda_{GF,A} = \lambda_{GF,E}$ $\qquad$ $\lambda_{GF,min}$ = 0,136

4.1.2.11 Calculation of the micropitting safety factor

$$S_\lambda = \frac{\lambda_{GF,min}}{\lambda_{GFP}} \quad (1) \qquad S_\lambda = 0{,}644$$

The calculation of the permissible specific lubricant film thickness, λ_{GFP}, for example 1 is shown exemplary in 4.1.4.

The final results for the calculation of the safety factor against micropitting, S_λ, for example 1 are shown in Table 3.

Table 3 — Results of calculation according to method B — Example 1

Point	A	AB	B	C	D	DE	E
$\lambda_{GF,Y}$	0,136	0,153	0,152	0,267	0,152	0,153	0,136
$\lambda_{GF,min}$	0,136						
λ_{GFP}	0,211						
S_λ	**0,644**						

4.1.3 Calculation according to method A

The calculation of example 1 according to method A was carried out by a 3D-calculation programme. Calculated results during method A will vary depending on the method of determining load distribution. The load distribution, on which the following calculation according to method A is based, is shown in Table 4. The maximum values are printed in bold.

Table 4 — Matrix of pressure distribution — $p_{H,Y,A}$ in N/mm²

	Width in mm			
	0,0	7,6	13,8	21,4
A	**1 115**	1 110	1 110	1 114
AB	**1 048**	1 044	1 044	1 047
B	**1 375**	1 373	1 373	1 375
C	**1 342**	1 339	1 339	1 342
D	**1 048**	1 045	1 045	1 048
DE	**1 050**	1 046	1 046	1 050
E	**1 099**	1 094	1 094	1 099

The resulting matrix of specific lubricant film thickness according to method A is shown in Table 5. The minimum value is printed in bold.

Table 5 — Matrix of resulting specific lubricant film thickness $\lambda_{GF,Y}$

	Width in mm			
	0,0	7,6	13,8	21,4
A	**0,122**	0,123	0,123	0,122
AB	0,159	0,160	0,160	0,159
B	0,159	0,159	0,159	0,159
C	0,270	0,271	0,271	0,270
D	0,197	0,198	0,198	0,197
DE	0,159	0,159	0,159	0,159
E	0,124	0,125	0,125	0,124

For the calculation of the micropitting safety factor according to method A, the minimum value of the matrix of resulting specific lubricant film thickness, shown in Table 5, was used.

$$S_{\lambda} = \frac{\lambda_{GF,min}}{\lambda_{GFP}} \quad (1) \qquad S_{\lambda} = 0,577$$

NOTE The difference in safety factor calculated between methods A and B in the above example 1 results from the simplified calculation of load distribution according to method B.

4.1.4 Calculation of the permissible lubricant film thickness

Calculation of the permissible specific lubricant film thickness from the test result of the FZG-FVA micropitting test[1] (Method B) with the reference test gears type C-GF.

The calculation of the reference value, λ_{GFT}, is done for point A because the minimum specific lubricant film thickness for gear type C is always at point A. All data of the reference test gears type C-GF have the subscript “Ref”.

Table 6 — Input data for calculation of the permissible lubricant film thickness

	Symbol	Description	Unit	C-GF pinion	C-GF wheel
				comb.	
Geometry	z_{Ref}	number of teeth	-	16	24
	m_{tRef}	transverse module ($m_{nRef} = m_{tRef}$)	mm	4,5	
	α_{nRef}	transverse pressure angle ($\alpha_{nRef} = \alpha_{tRef}$)	°	20	
	β_{bRef}	base helix angle ($\beta_{bRef} = \beta_{Ref}$)	°	0	
	b_{Ref}	face width	mm	14	
	a_{Ref}	centre distance	mm	91,5	
	x_{Ref}	addendum modification factor	-	0,1817	0,1716
	d_{aRef}	tip diameter of pinion	mm	82,45	118,35
	-	tooth flank modifications	-	no modifications	
	Ra_{Ref}	arithmetic mean roughness value	µm	0,50	0,50
	E_{Ref}	modulus of elasticity	N/mm^2	206 000	206 000
	ν_{Ref}	Poisson's ratio	-	0,3	0,3
	λ_{MRef}	specific heat conductivity	W/(m·K)	45	45
	c_{MRef}	specific heat per unit mass	J/(kg·K)	440	440
	ρ_{MRef}	density	kg/m^3	7 800	7 800
	W_w	material factor according to ISO/TR 15144-1:2014, Table A.1 (for matching case carburised/case carburised)	-	1,0	
Application	K_{ARef}	application factor	-	1,0	
	K_{vRef}	dynamic factor	-	1,05	
	$K_{H\alpha Ref}$	transverse load factor	-	1,0	
	$K_{H\beta Ref}$	face load factor	-	1,10	
Load	T_{1Ref}	nominal torque at the pinion for SKS 8	Nm	171,6	
	n_{1Ref}	rotation speed of the pinion	min^{-1}	2 250	
	$p_{H,A,A}$	nominal Hertzian contact stress at point A according to method A for SKS 8 (see Table 6)	N/mm^2	1 191	
	–	lubrication	-	injection lubrication	

NOTE The used values for K_{vRef} and $K_{H\beta Ref}$ are valid for the standard FZG back-to-back test rig and standard conditions.

Table 7 gives the nominal Hertzian contact stress at point A for the reference test gears type C-GF as a function of the reached failure load stage (SKS) in the FZG-FVA micropitting test.[1]

Table 7 — Relation between failure load stage according to FZG-FVA micropitting test[1] and nominal Hertzian contact stress at point A

SKS	Nominal torque at the pinion in Nm	Hertzian contact stress at point C in N/mm²	Nominal Hertzian contact stress at point A according to method A
5	70,0	795,1	764
6	98,9	945,1	906
7	132,5	1 093,9	1 048
8	171,6	1 244,9	1 191
9	215,6	1 395,4	1 333
10	265,1	1 547,3	1 476

4.1.4.1 Calculation of gear geometry

$$d_{1\text{Ref}} = z_{1\text{Ref}} \cdot m_{\text{tRef}}$$ $d_{1\text{Ref}}$ = 72,00 mm

$$d_{2\text{Ref}} = z_{2\text{Ref}} \cdot m_{\text{tRef}}$$ $d_{2\text{Ref}}$ = 108,00 mm

$$u_{\text{Ref}} = \frac{z_{2\text{Ref}}}{z_{1\text{Ref}}}$$ u_{Ref} = 1,5

$$d_{\text{b1Ref}} = d_{1\text{Ref}} \cdot \cos\alpha_{\text{tRef}}$$ d_{b1Ref} = 67,658 mm

$$d_{\text{b2Ref}} = d_{2\text{Ref}} \cdot \cos\alpha_{\text{tRef}}$$ d_{b2Ref} = 101,487 mm

$$d_{\text{w1Ref}} = \frac{2 \cdot a_{\text{Ref}}}{u_{\text{Ref}} + 1}$$ d_{w1Ref} = 73,20 mm

$$d_{\text{w2Ref}} = 2 \cdot a_{\text{Ref}} - d_{\text{w1Ref}}$$ d_{w2Ref} = 109,80 mm

$$\alpha_{\text{wtRef}} = \arccos\left[\frac{\left(z_{1\text{Ref}} + z_{2\text{Ref}}\right) \cdot m_{\text{tRef}} \cdot \cos\alpha_{\text{tRef}}}{2 \cdot a_{\text{Ref}}}\right]$$ α_{wtRef} = 22,439 °

$$p_{\text{etRef}} = m_{\text{tRef}} \cdot \pi \cdot \cos\alpha_{\text{tRef}}$$ p_{etRef} = 13,285 mm

$$\varepsilon_{1\text{Ref}} = \frac{z_{1\text{Ref}}}{2 \cdot \pi} \cdot \left[\sqrt{\left(\frac{d_{\text{a1Ref}}}{d_{\text{b1Ref}}}\right)^2 - 1} - \tan\alpha_{\text{wtRef}}\right]$$ $\varepsilon_{1\text{Ref}}$ = 0,722

$$\varepsilon_{2\text{Ref}} = \frac{z_{2\text{Ref}}}{2 \cdot \pi} \cdot \left[\sqrt{\left(\frac{d_{\text{a2Ref}}}{d_{\text{b2Ref}}}\right)^2 - 1} - \tan\alpha_{\text{wtRef}}\right]$$ $\varepsilon_{2\text{Ref}}$ = 0,714

$$\varepsilon_{\alpha\mathrm{Ref}} = \frac{1}{p_{\mathrm{etRef}}} \cdot \left(\sqrt{\frac{d_{\mathrm{a1Ref}}^2}{4} - \frac{d_{\mathrm{b1Ref}}^2}{4}} + \sqrt{\frac{d_{\mathrm{a2Ref}}^2}{4} - \frac{d_{\mathrm{b2Ref}}^2}{4}} - a_{\mathrm{Ref}} \cdot \sin\alpha_{\mathrm{wtRef}} \right)$$ $\varepsilon_{\alpha\mathrm{Ref}} = 1{,}436$

$$\varepsilon_{\beta\mathrm{Ref}} = \frac{b_{\mathrm{Ref}} \cdot \sin\beta_{\mathrm{Ref}}}{m_{\mathrm{nRef}} \cdot \pi}$$ $\varepsilon_{\mathrm{Ref}} = 0$

$$\varepsilon_{\gamma\mathrm{Ref}} = \varepsilon_{\alpha\mathrm{Ref}} + \varepsilon_{\beta\mathrm{Ref}}$$ $\varepsilon_{\gamma\mathrm{Ref}} = 1{,}436$

$$g_{\alpha\mathrm{Ref}} = 0{,}5 \cdot \left(\sqrt{d_{\mathrm{a1Ref}}^2 - d_{\mathrm{b1Ref}}^2} + \sqrt{d_{\mathrm{a2Ref}}^2 - d_{\mathrm{b2Ref}}^2} \right) - a_{\mathrm{Ref}} \cdot \sin\alpha_{\mathrm{wtRef}}$$ $g_{\alpha\mathrm{Ref}} = 19{,}079\ \mathrm{mm}$

$g_{\mathrm{ARef}} = 0\ \mathrm{mm}$ (34) $g_{\mathrm{ARef}} = 0\ \mathrm{mm}$

$$d_{\mathrm{A1Ref}} = 2 \cdot \sqrt{\frac{d_{\mathrm{b1Ref}}^2}{4} + \left(\sqrt{\frac{d_{\mathrm{a1Ref}}^2}{4} - \frac{d_{\mathrm{b1Ref}}^2}{4}} - g_{\alpha\mathrm{Ref}} + g_{\mathrm{ARef}} \right)^2}$$ (41) $d_{\mathrm{A1Ref}} = 68{,}249\ \mathrm{mm}$

$$d_{\mathrm{A2Ref}} = 2 \cdot \sqrt{\frac{d_{\mathrm{b2Ref}}^2}{4} + \left(\sqrt{\frac{d_{\mathrm{a2Ref}}^2}{4} - \frac{d_{\mathrm{b2Ref}}^2}{4}} - g_{\mathrm{ARef}} \right)^2}$$ (42) $d_{\mathrm{A2Ref}} = 118{,}350\ \mathrm{mm}$

$$\rho_{\mathrm{t1,ARef}} = \sqrt{\frac{d_{\mathrm{A1Ref}}^2 - d_{\mathrm{b1Ref}}^2}{4}}$$ (44) $\rho_{\mathrm{t1,ARef}} = 4{,}482\ \mathrm{mm}$

$$\rho_{\mathrm{t1,CRef}} = \sqrt{\frac{d_{\mathrm{w1Ref}}^2 - d_{\mathrm{b1Ref}}^2}{4}}$$ (44) $\rho_{\mathrm{t1,CRef}} = 13{,}970\ \mathrm{mm}$

$$\rho_{\mathrm{t2,ARef}} = \sqrt{\frac{d_{\mathrm{A2Ref}}^2 - d_{\mathrm{b2Ref}}^2}{4}}$$ (44) $\rho_{\mathrm{t2,ARef}} = 30{,}443\ \mathrm{mm}$

$$\rho_{\mathrm{t2,CRef}} = \sqrt{\frac{d_{\mathrm{w2Ref}}^2 - d_{\mathrm{b2Ref}}^2}{4}}$$ (44) $\rho_{\mathrm{t2,CRef}} = 20{,}955\ \mathrm{mm}$

$$\rho_{\mathrm{t,ARef}} = \frac{\rho_{\mathrm{t1,ARef}} \cdot \rho_{\mathrm{t2,ARef}}}{\rho_{\mathrm{t1,ARef}} + \rho_{\mathrm{t2,ARef}}}$$ (43) $\rho_{\mathrm{t,ARef}} = \rho_{\mathrm{n,ARef}} = 3{,}907\ \mathrm{mm}$

$$\rho_{\mathrm{t,CRef}} = \frac{\rho_{\mathrm{t1,CRef}} \cdot \rho_{\mathrm{t2,CRef}}}{\rho_{\mathrm{t1,CRef}} + \rho_{\mathrm{t2,CRef}}}$$ (43) $\rho_{\mathrm{t,CRef}} = \rho_{\mathrm{n,CRef}} = 8{,}382\ \mathrm{mm}$

4.1.4.2 Calculation of material data type C-GF

$$E_{\text{rRef}} = 2 \cdot \left(\frac{1 - \nu_{1\text{Ref}}^{2}}{E_{1\text{Ref}}} + \frac{1 - \nu_{2\text{Ref}}^{2}}{E_{2\text{Ref}}} \right)^{-1} \quad (6) \quad E_{\text{rRef}} = 226\ 374\ \text{N/mm}^2$$

$$B_{\text{M1Ref}} = \sqrt{\lambda_{\text{M1Ref}} \cdot \rho_{\text{M1Ref}} \cdot c_{\text{M1Ref}}} \quad (82) \quad B_{\text{M1Ref}} = 12\ 427{,}4\ \text{N/(ms}^{0{,}5}\text{K)}$$

$$B_{\text{M2Ref}} = \sqrt{\lambda_{\text{M2Ref}} \cdot \rho_{\text{M2Ref}} \cdot c_{\text{M2Ref}}} \quad (83) \quad B_{\text{M2Ref}} = 12\ 427{,}4\ \text{N/(ms}^{0{,}5}\text{K)}$$

4.1.4.3 Calculation of operating conditions of FVA-FZG micropitting test

$$P_{\text{Ref}} = 2 \cdot \pi \cdot \frac{n_{1\text{Ref}}}{60} \cdot \frac{T_{1\text{Ref}}}{1000} \quad (85) \quad P_{\text{Ref}} = 40{,}43\ \text{kW}$$

$$F_{\text{btRef}} = 2000 \cdot \frac{T_{1\text{Ref}}}{d_{\text{b1Ref}}} \quad F_{\text{btRef}} = 5\ 072{,}6\ \text{N}$$

$$p_{\text{dyn,A,ARef}} = p_{\text{H,A,ARef}} \cdot \sqrt{K_{\text{ARef}} \cdot K_{\text{vRef}}} \quad (24) \quad p_{\text{dyn,A,ARef}} = 1\ 220\ \text{N/mm}^2$$

$$v_{\text{r1,ARef}} = 2 \cdot \pi \cdot \frac{n_{1\text{Ref}}}{60} \cdot \frac{d_{\text{w1Ref}}}{2000} \cdot \sin \alpha_{\text{wtRef}} \cdot \sqrt{\frac{d_{\text{A1Ref}}^{2} - d_{\text{b1Ref}}^{2}}{d_{\text{w1Ref}}^{2} - d_{\text{b1Ref}}^{2}}} \quad (14) \quad v_{\text{r1,ARef}} = 1{,}056\ \text{m/s}$$

$$v_{\text{r1,CRef}} = 2 \cdot \pi \cdot \frac{n_{1\text{Ref}}}{60} \cdot \frac{d_{\text{w1Ref}}}{2000} \cdot \sin \alpha_{\text{wtRef}} \quad (14) \quad v_{\text{r1,CRef}} = 3{,}292\ \text{m/s}$$

$$v_{\text{r2,ARef}} = 2 \cdot \pi \cdot \frac{n_{1\text{Ref}}}{60 \cdot u_{\text{Ref}}} \cdot \frac{d_{\text{w2Ref}}}{2000} \cdot \sin \alpha_{\text{wtRef}} \cdot \sqrt{\frac{d_{\text{A2Ref}}^{2} - d_{\text{b2Ref}}^{2}}{d_{\text{w2Ref}}^{2} - d_{\text{b2Ref}}^{2}}} \quad (15) \quad v_{\text{r2,ARef}} = 4{,}782\ \text{m/s}$$

$$v_{\text{r2,CRef}} = 2 \cdot \pi \cdot \frac{n_{1\text{Ref}}}{60 \cdot u_{\text{Ref}}} \cdot \frac{d_{\text{w2Ref}}}{2000} \cdot \sin \alpha_{\text{wtRef}} \quad (15) \quad v_{\text{r2,CRef}} = 3{,}292\ \text{m/s}$$

$$v_{\text{g,ARef}} = v_{\text{r1,ARef}} - v_{\text{r2,ARef}} \quad (81) \quad v_{\text{g,ARef}} = -3{,}726\ \text{m/s}$$

$$v_{\Sigma,\text{ARef}} = v_{\text{r1,ARef}} + v_{\text{r2,ARef}} \quad (13) \quad v_{\Sigma,\text{ARef}} = 5{,}838\ \text{m/s}$$

$$v_{\Sigma,\text{CRef}} = v_{\text{r1,CRef}} + v_{\text{r2,CRef}} \quad (13) \quad v_{\Sigma,\text{CRef}} = 6{,}583\ \text{m/s}$$

$$Ra_{\text{Ref}} = 0{,}5 \cdot \left(Ra_{1\text{Ref}} + Ra_{2\text{Ref}} \right) \quad (3) \quad Ra_{\text{Ref}} = 0{,}50\ \mu\text{m}$$

4.1.4.4 Calculation of lubricant data

$\theta_{\text{oilRef}} = \theta_{\text{oil}} = 90\ °\text{C}$

$\eta_{\theta\text{oilRef}} = \eta_{\theta\text{oil}} = 0{,}021\ \text{N·s/m}^2$

X_{SRef} = 1,2 for injection lubrication

4.1.4.5 Calculation of the permissible specific lubricant film thickness

$$X_{RRef} = 2{,}2 \cdot \left(\frac{Ra_{Ref}}{\rho_{n,CRef}} \right)^{0{,}25}$$ (87) X_{RRef} = 1,087

$K_{B\gamma Ref}$ = 1,0 for ε_γ <2 (88)

$\Pi K_{Ref} = K_{ARef} \cdot K_{vRef} \cdot K_{H\alpha Ref} \cdot K_{H\beta Ref} \cdot K_{B\gamma Ref}$ ΠK_{Ref} = 1,155

$$\mu_{mRef} = 0{,}045 \cdot \left(\frac{\prod K_{Ref} \cdot F_{btRef}}{b_{Ref} \cdot v_{\Sigma,CRef} \cdot \rho_{n,CRef}} \right)^{0{,}2} \cdot \left(10^3 \cdot \eta_{\theta oilRef}\right)^{-0{,}05} \cdot X_{RRef} \cdot X_L$$ (86) μ_{mRef} = 0,063

$$H_{vRef} = \left(\varepsilon_{1Ref}{}^2 + \varepsilon_{2Ref}{}^2 + 1 - \varepsilon_{\alpha Ref}\right) \cdot \left(\frac{1}{z_{1Ref}} + \frac{1}{z_{2Ref}} \right) \cdot \frac{\pi}{\cos \beta_{bRef}} \text{ for } \varepsilon_\alpha < 2$$ (91) H_{vRef} = 0,195

X_{CaRef} = 1,0 for no profile modification (method B) (101)

$$\theta_{MRef} = \theta_{oilRef} + 7400 \cdot \left(\frac{P_{Ref} \cdot \mu_{mRef} \cdot H_{vRef}}{a_{Ref} \cdot b_{Ref}} \right)^{0{,}72} \cdot \frac{X_{SRef}}{1{,}2 \cdot X_{CaRef}}$$ (84) θ_{MRef} = 115,9 °C

$$\log[\log(\nu_{\theta MRef} + 0{,}7)] = A \cdot \log(\theta_{MRef} + 273) + B$$ (17) $\nu_{\theta MRef}$ = 12,317 mm²/s

$$\rho_{\theta MRef} = \rho_{15} \cdot \left[1 - 0{,}7 \cdot \frac{(\theta_{MRef} + 273) - 289}{\rho_{15}} \right]$$ (20) $\rho_{\theta MRef}$ = 825,1 kg/m³

$$\eta_{\theta MRef} = 10^{-6} \cdot \nu_{\theta MRef} \cdot \rho_{\theta MRef}$$ (16) $\eta_{\theta MRef}$ = 0,010 N·s/m²

$$\alpha_{\theta MRef} = \alpha_{38} \cdot \left[1 + 516 \cdot \left(\frac{1}{\theta_{MRef} + 273} - \frac{1}{311} \right) \right]$$ (8) $\alpha_{\theta MRef}$ = $1{,}436 \cdot 10^{-8}$ m²/N

$$G_{MRef} = 10^6 \cdot \alpha_{\theta MRef} \cdot E_{rRef}$$ (5) G_{MRef} = 3 249,9

$$U_{ARef} = \eta_{\theta MRef} \cdot \frac{v_{\Sigma,ARef}}{2000 \cdot E_{rRef} \cdot \rho_{n,ARef}}$$ (12) U_{ARef} = $3{,}354 \cdot 10^{-11}$

$$W_{ARef} = \frac{2 \cdot \pi \cdot p_{dyn,ARef}{}^2}{E_{rRef}{}^2}$$ (22) W_{ARef} = $1{,}825 \cdot 10^{-4}$

$$\theta_{\text{fl,ARef}} = \frac{\sqrt{\pi}}{2} \cdot \frac{10^6 \cdot \mu_{\text{mRef}} \cdot p_{\text{dyn,ARef}} \cdot \left|v_{\text{g,ARef}}\right|}{B_{\text{M1Ref}} \sqrt{v_{\text{r1,ARef}}} + B_{\text{M2Ref}} \sqrt{v_{\text{r2,ARef}}}} \cdot \sqrt{8 \cdot \rho_{\text{n,ARef}} \cdot \frac{p_{\text{dyn,ARef}}}{1000 \cdot E_{\text{rRef}}}}$$ (80) $\theta_{\text{fl,ARef}} = 82{,}5\ °\text{C}$

$$\theta_{\text{B,ARef}} = \theta_{\text{MRef}} + \theta_{\text{fl,ARef}}$$ (79) $\theta_{\text{B,ARef}} = 198{,}3\ °\text{C}$

$$\log[\log(\nu_{\theta\text{B,ARef}} + 0{,}7)] = A \cdot \log(\theta_{\text{B,ARef}} + 273) + B$$ (30) $\nu_{\theta\text{B,ARef}} = 3{,}112\ \text{mm}^2/\text{s}$

$$\rho_{\theta\text{B,ARef}} = \rho_{15} \cdot \left[1 - 0{,}7 \cdot \frac{\left(\theta_{\text{B,ARef}} + 273\right) - 289}{\rho_{15}}\right]$$ (33) $\rho_{\theta\text{B,ARef}} = 767{,}4\ \text{kg/m}^3$

$$\eta_{\theta\text{B,ARef}} = 10^{-6} \cdot \nu_{\theta\text{B,ARef}} \cdot \rho_{\theta\text{B,ARef}}$$ (29) $\eta_{\theta\text{B,ARef}} = 0{,}002\ \text{N·s/m}^2$

$$\alpha_{\theta\text{B,ARef}} = \alpha_{38} \cdot \left[1 + 516 \cdot \left(\frac{1}{\theta_{\text{B,ARef}} + 273} - \frac{1}{311}\right)\right]$$ (28) $\alpha_{\theta\text{B,ARef}} = 9{,}364 \cdot 10^{-9}\ \text{m}^2/\text{N}$

$$S_{\text{GF,ARef}} = \frac{\alpha_{\theta\text{B,ARef}} \cdot \eta_{\theta\text{B,ARef}}}{\alpha_{\theta\text{MRef}} \cdot \eta_{\theta\text{MRef}}}$$ (27) $S_{\text{GF,ARef}} = 0{,}153$

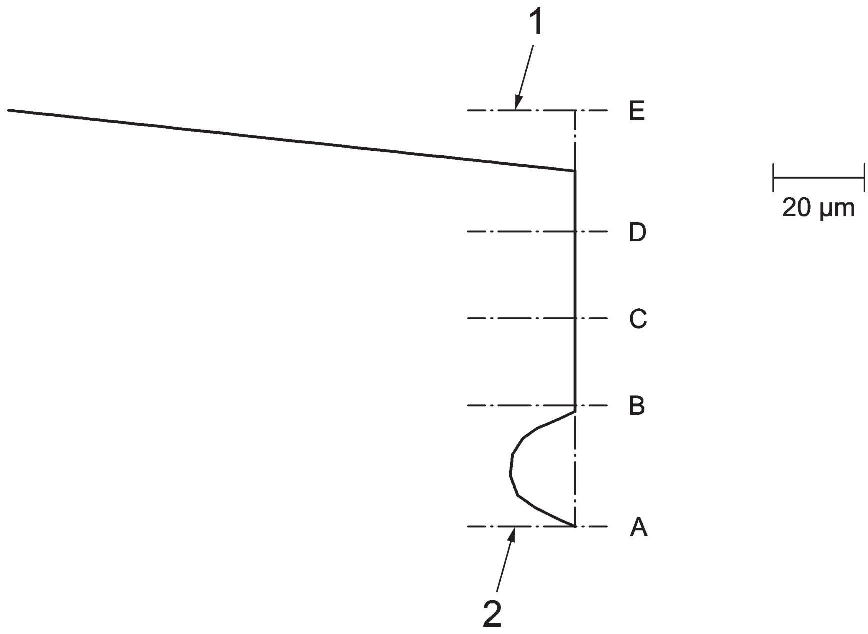
$$h_{\text{ARef}} = 1600 \cdot \rho_{\text{n,ARef}} \cdot G_{\text{MRef}}^{0{,}6} \cdot U_{\text{ARef}}^{0{,}7} \cdot W_{\text{ARef}}^{-0{,}13} \cdot S_{\text{GF,ARef}}^{0{,}22}$$ (4) $h_{\text{ARef}} = 0{,}075\ \mu\text{m}$

$$\lambda_{\text{GFT}} = \lambda_{\text{GF,ARef}} = \frac{h_{\text{ARef}}}{Ra_{\text{Ref}}}$$ (2) $\lambda_{\text{GFT}} = 0{,}151$

$$\lambda_{\text{GFP}} = 1{,}4 \cdot W_{\text{W}} \cdot \lambda_{\text{GFT}}$$ $\lambda_{\text{GFP}} = 0{,}211$

4.2 Example 2 — Spur gear

The result of this example is confirmed by experimental investigations. The gears were obviously micropitted and had profile deviations of approximately 15 µm. Figure 2 shows a diagram of the observed location and severity of micropitting for the pinion of example 2.



Key

1 tip

2 root

Figure 2 — Diagram of schematic profile deviations of the pinion for example 2

NOTE Example 2 is only calculated according to method B. Furthermore, no modifications for the calculation according to method B were considered.

4.2.1 Input data

Table 8 — Input data for Example 2

	Symbol	Description	Unit	Example 2	
				pinion	wheel
				comb.	
Geometry	z	number of teeth	-	20	20
	-	driving gear	-	x	
	m_n	normal module	mm	10,0	
	α_n	normal pressure angle	°	20	
	β	helix angle	°	0	
	b	face width	mm	15	
	a	centre distance	mm	200	
	x	addendum modification factor	-	0,0	0,0
	d_a	tip diameter of pinion	mm	220,0	220,0
	-	tooth flank modifications	-	no adequate tip relief	
	Q	gear quality	-	6	6
	Ra	arithmetic mean roughness value	μm	0,80	0,80

Table 8 *(continued)*

	Symbol	Description	Unit	Example 2	
				pinion	wheel
				comb.	
Material	-	material	-	Eh	Eh
	E	modulus of elasticity	N/mm^2	206 000	206 000
	ν	Poisson's ratio	-	0,3	0,3
	λ_M	specific heat conductivity	W/(m·K)	45	45
	C_M	specific heat per unit mass	J/(kg·K)	440	440
	ρ_M	density	kg/m^3	7 800	7 800
	W_w	material factor according to ISO/TR 15144-1:2014, Table A.1 (for matching case carburised/case carburised)	-	1,0	
Application	K_A	application factor	-	1,0	
	K_v	dynamic factor	-	1,038	
	$K_{H\alpha}$	transverse load factor	-	1,0	
	$K_{H\beta}$	face load factor	-	1,05	
Load	T_1	nominal torque at the pinion	Nm	2 400	
	n_1	rotation speed of the pinion	min^{-1}	1 000	
Lubricant	θ_{oil}	oil inlet temperature (injection lubrication)	° C	70	
	ν_{40}	kinematic viscosity at 40 ° C	mm^2/s	150	
	ν_{100}	kinematic viscosity at 100 ° C	mm^2/s	14,7	
	ρ_{15}	density of the lubricant at 15 ° C	kg/m^3	890	
	-	oil type	-	mineral oil	
	-	failure load stage at test temperature (70 ° C) according to FVA 54/7	-	SKS 10	
	λ_{GFP}	permissible lubricant film thickness	-	0,171	

4.2.2 Calculation according to method B

4.2.2.1 Calculation of gear geometry (according to ISO 21771)

Basic values:

$$m_t = \frac{m_n}{\cos\beta}$$ m_t = 10,000 mm

$$d_1 = z_1 \cdot m_t$$ d_1 = 200,000 mm

$$d_2 = z_2 \cdot m_t$$ d_2 = 200,000 mm

$$u = \frac{z_2}{z_1}$$ u = 1,00

$$\alpha_t = \arctan\left(\frac{\tan\alpha_n}{\cos\beta}\right)$$ $\alpha_t = 20{,}000\ °$

$$d_{b1} = d_1 \cdot \cos\alpha_t$$ $d_{b1} = 187{,}939$ mm

$$d_{b2} = d_2 \cdot \cos\alpha_t$$ $d_{b2} = 187{,}939$ mm

$$d_{w1} = \frac{2\cdot a}{u+1}$$ $d_{w1} = 200{,}000$ mm

$$d_{w2} = 2\cdot a - d_{w1}$$ $d_{w2} = 200{,}000$ mm

$$\alpha_{wt} = \arccos\left[\frac{(z_1+z_2)\cdot m_t \cdot \cos\alpha_t}{2\cdot a}\right]$$ $\alpha_{wt} = 20{,}000\ °$

$$\beta_b = \arcsin(\sin\beta \cdot \cos\alpha_n)$$ $\beta_b = 0\ °$

$$p_{et} = m_t \cdot \pi \cdot \cos\alpha_t$$ $p_{et} = 29{,}521$ mm

$$\varepsilon_1 = \frac{z_1}{2\cdot\pi}\cdot\left[\sqrt{\left(\frac{d_{a1}}{d_{b1}}\right)^2 - 1} - \tan\alpha_{wt}\right]$$ $\varepsilon_1 = 0{,}778$

$$\varepsilon_2 = \frac{z_2}{2\cdot\pi}\cdot\left[\sqrt{\left(\frac{d_{a2}}{d_{b2}}\right)^2 - 1} - \tan\alpha_{wt}\right]$$ $\varepsilon_2 = 0{,}778$

$$\varepsilon_\alpha = \frac{1}{p_{et}}\cdot\left(\sqrt{\frac{{d_{a1}}^2}{4} - \frac{{d_{b1}}^2}{4}} + \sqrt{\frac{{d_{a2}}^2}{4} - \frac{{d_{b2}}^2}{4}} - a\cdot\sin\alpha_{wt}\right)$$ $\varepsilon_\alpha = 1{,}557$

$$\varepsilon_\beta = \frac{b\cdot\sin\beta}{m_n\cdot\pi}$$ $\varepsilon_\beta = 0$

$$\varepsilon_\gamma = \varepsilon_\alpha + \varepsilon_\beta$$ $\varepsilon_\gamma = 1{,}557$

$$g_\alpha = 0{,}5\cdot\left(\sqrt{{d_{a1}}^2 - {d_{b1}}^2} + \sqrt{{d_{a2}}^2 - {d_{b2}}^2}\right) - a\cdot\sin\alpha_{wt}$$ $g_\alpha = 45{,}960$ mm

Coordinates of the basic points (A, AB, B, C, D, DE, E) on the line of action:

$g_A = 0$ mm (34) $g_A = 0$ mm

$$g_{AB} = \frac{g_\alpha - p_{et}}{2} \quad (35)$$ $g_{AB} = 8{,}219$ mm

$$g_B = g_\alpha - p_{et} \quad (36) \qquad g_B = 16{,}439 \text{ mm}$$

$$g_C = \frac{d_{b1}}{2} \cdot \tan\alpha_{wt} - \sqrt{\frac{d_{a1}^2}{4} - \frac{d_{b1}^2}{4}} + g_\alpha \quad (37) \qquad g_C = 22{,}980 \text{ mm}$$

$$g_D = p_{et} \quad (38) \qquad g_D = 29{,}521 \text{ mm}$$

$$g_{DE} = \frac{g_\alpha - p_{et}}{2} + p_{et} \quad (39) \qquad g_{DE} = 37{,}741 \text{ mm}$$

$$g_E = g_\alpha \quad (40) \qquad g_E = 45{,}960 \text{ mm}$$

$$d_{A1} = 2 \cdot \sqrt{\frac{d_{b1}^2}{4} + \left(\sqrt{\frac{d_{a1}^2}{4} - \frac{d_{b1}^2}{4}} - g_\alpha + g_A\right)^2} \quad (41) \qquad d_{A1} = 189{,}274 \text{ mm}$$

d_{AB1} = 191,919 mm d_{B1} = 195,912 mm d_{C1} = 200,00 mm

d_{D1} = 204,844 mm d_{DE1} = 211,920 mm d_{E1} = 220,000 mm

$$d_{A2} = 2 \cdot \sqrt{\frac{d_{b2}^2}{4} + \left(\sqrt{\frac{d_{a2}^2}{4} - \frac{d_{b2}^2}{4}} - g_A\right)^2} \quad (42) \qquad d_{A2} = 220{,}000 \text{ mm}$$

d_{AB2} = 211,920 mm d_{B2} = 204,844 mm d_{C2} = 200,000 mm

d_{D2} = 195,912 mm d_{DE2} = 191,919 mm d_{E2} = 189,274 mm

Normal radius of relative curvature:

$$\rho_{n,A} = \frac{\rho_{t,A}}{\cos\beta_b} \quad (45) \qquad \rho_{n,A} = 9{,}381 \text{ mm}$$

$\rho_{n,AB}$ = 13,916 mm $\rho_{n,B}$ = 16,475 mm $\rho_{n,C}$ = 17,101 mm

$\rho_{n,D}$ = 16,475 mm $\rho_{n,DE}$ = 13,916 mm $\rho_{n,E}$ = 9,381 mm

4.2.2.2 Calculation of material data

$$E_r = 2 \cdot \left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right)^{-1} \quad (6) \qquad E_r = 226\,374 \text{ N/mm}^2$$

$$B_{M1} = \sqrt{\lambda_{M1} \cdot \rho_{M1} \cdot c_{M1}} \quad (82) \qquad B_{M1} = 12\,427{,}4 \text{ N/(ms}^{0{,}5}\text{K)}$$

$$B_{M2} = \sqrt{\lambda_{M2} \cdot \rho_{M2} \cdot c_{M2}} \quad (83) \qquad B_{M2} = 12\,427{,}4 \text{ N/(ms}^{0{,}5}\text{K)}$$

4.2.2.3 Calculation of operating conditions

Loading:

$$P = 2 \cdot \pi \cdot \frac{n_1}{60} \cdot \frac{T_1}{1\,000} \qquad (85) \qquad P = 251 \text{ kW}$$

$$F_t = 2\,000 \cdot \frac{T_1}{d_1} \qquad F_t = 24\,000 \text{ N}$$

$$F_{bt} = 2\,000 \cdot \frac{T_1}{d_{b1}} \qquad F_{bt} = 25\,540 \text{ N}$$

Local load sharing factor:

NOTE No tooth flank modifications, spur gears, gear quality ≤ 7 (see ISO/TR 15144-1:2014, Figure 2).

$$X_A = \frac{Q-2}{15} + \frac{1}{3} \cdot \frac{g_A}{g_B} \qquad (46) \qquad X_A = 0{,}333$$

$X_{AB} = 0{,}500$ $X_B = 1{,}000$ $X_C = 1{,}000$

$X_D = 1{,}000$ $X_{DE} = 0{,}500$ $X_E = 0{,}333$

Elasticity factor:

$$Z_E = \sqrt{\frac{E_r}{2 \cdot \pi}} \qquad (26) \qquad Z_E = 189{,}812 \text{ (N/mm}^2)^{0,5}$$

Local Hertzian contact stress:

$$p_{H,A,B} = Z_E \cdot \sqrt{\frac{F_t \cdot X_A}{b \cdot \rho_{n,A} \cdot \cos\alpha_t \cdot \cos\beta_b}} \qquad (25) \qquad p_{H,A,B} = 1\,476 \text{ N/mm}^2$$

$p_{H,AB,B} = 1\,485$ N/mm^2 $p_{H,B,B} = 1\,930$ N/mm^2 $p_{H,C,B} = 1\,894$ N/mm^2

$p_{H,D,B} = 1\,930$ N/mm^2 $p_{H,DE,B} = 1\,485$ N/mm^2 $p_{H,E,B} = 1\,476$ N/mm^2

$$p_{dyn,A,B} = p_{H,A,B} \cdot \sqrt{K_A \cdot K_v \cdot K_{H\alpha} \cdot K_{H\beta}} \qquad (24) \qquad p_{dyn,A,B} = 1\,541 \text{ N/mm}^2$$

$p_{dyn,AB,B} = 1\,550$ N/mm^2 $p_{dyn,B,B} = 2\,014$ N/mm^2 $p_{dyn,C,B} = 1\,977$ N/mm^2

$p_{dyn,D,B} = 2\,014$ N/mm^2 $p_{dyn,DE,B} = 1\,550$ N/mm^2 $p_{dyn,E,B} = 1\,541$ N/mm^2

Velocity:

$$v_{g,A} = v_{r1,A} - v_{r2,A} \qquad (81) \qquad v_{g,A} = -4{,}813 \text{ m/s}$$

$v_{g,AB} = -3{,}091$ m/s $v_{g,B} = -1{,}370$ m/s $v_{g,C} = 0$ m/s

$v_{g,D} = 1{,}370$ m/s $v_{g,DE} = 3{,}091$ m/s $v_{g,E} = 4{,}813$ m/s

$$v_{\Sigma,A} = v_{r1,A} + v_{r2,A} \qquad (13) \qquad v_{\Sigma,A} = 7{,}163 \text{ m/s}$$

$v_{\Sigma,AB}$ = 7,163 m/s $v_{\Sigma,B}$ = 7,163 m/s $v_{\Sigma,C}$ = 7,163 m/s

$v_{\Sigma,D}$ = 7,163 m/s $v_{\Sigma,DE}$ = 7,163 m/s $v_{\Sigma,E}$ = 7,163 m/s

Effective arithmetic mean roughness value:

$$Ra = 0{,}5 \cdot \left(Ra_1 + Ra_2 \right) \quad (3) \qquad Ra = 0{,}80\ \mu\text{m}$$

4.2.2.4 Calculation of lubricant data

X_L = 1,0 for mineral oil (see ISO/TR 15144-1:2014, Table 3)

$$\alpha_{38} = 2{,}657 \cdot 10^{-8} \cdot \eta_{38}{}^{0{,}1348} \quad (9) \qquad \alpha_{38} = 2{,}05 \cdot 10^{-8}\ \text{m}^2/\text{N}$$

X_S = 1,2 for injection lubrication

4.2.2.5 Calculation of the material parameter

Mean coefficient of friction:

$$X_R = 2{,}2 \cdot \left(\frac{Ra}{\rho_{n,C}} \right)^{0{,}25} \quad (87) \qquad X_R = 1{,}023$$

$K_{B\gamma}$ = 1,0 for $\varepsilon_\gamma < 2$ (88)

$$\mu_m = 0{,}045 \cdot \left(\frac{K_A \cdot K_v \cdot K_{H\alpha} \cdot K_{H\beta} \cdot F_{bt} \cdot K_{B\gamma}}{b \cdot v_{\Sigma,C} \cdot \rho_{n,C}} \right)^{0{,}2} \cdot \left(10^3 \cdot \eta_{\theta oil} \right)^{-0{,}05} \cdot X_R \cdot X_L \quad (86) \qquad \mu_m = 0{,}067$$

Bulk temperature:

$$H_v = \left(\varepsilon_1{}^2 + \varepsilon_2{}^2 + 1 - \varepsilon_\alpha \right) \cdot \left(\frac{1}{z_1} + \frac{1}{z_2} \right) \cdot \frac{\pi}{\cos \beta_b} \text{ for } \varepsilon_\alpha < 2 \quad (91) \qquad H_v = 0{,}206$$

$$\varepsilon_{max} = \varepsilon_1 = \varepsilon_2$$

X_{Ca} = 1,0 for no adequate profile modification (method B) (101)

$$\theta_M = \theta_{oil} + 7\,400 \cdot \left(\frac{P \cdot \mu_m \cdot H_v}{a \cdot b} \right)^{0{,}72} \cdot \frac{X_s}{1{,}2 \cdot X_{Ca}} \quad (84) \qquad \theta_M = 126{,}6\ ^\circ\text{C}$$

Material parameter:

$$G_M = 10^6 \cdot \alpha_{\theta M} \cdot E_r \quad (5) \qquad G_M = 2\,936{,}2$$

4.2.2.6 Calculation of the velocity parameter

$$U_A = \eta_{\theta M} \cdot \frac{v_{\Sigma,A}}{2000 \cdot E_r \cdot \rho_{n,A}} \quad (12) \qquad U_A = 1{,}087 \cdot 10^{-11}$$

$U_{AB} = 7{,}325 \cdot 10^{-12}$	$U_B = 6{,}187 \cdot 10^{-12}$	$U_C = 5{,}961 \cdot 10^{-12}$
$U_D = 6{,}187 \cdot 10^{-12}$	$U_{DE} = 7{,}325 \cdot 10^{-12}$	$U_E = 1{,}087 \cdot 10^{-11}$

4.2.2.7 Calculation of the load parameter

$$W_A = \frac{2 \cdot \pi \cdot {p_{dyn,A}}^2}{{E_r}^2} \qquad (22) \qquad W_A = 2{,}913 \cdot 10^{-4}$$

$W_{AB} = 2{,}946 \cdot 10^{-4}$	$W_B = 4{,}976 \cdot 10^{-4}$	$W_C = 4{,}794 \cdot 10^{-4}$
$W_D = 4{,}976 \cdot 10^{-4}$	$W_{DE} = 2{,}946 \cdot 10^{-4}$	$W_E = 2{,}913 \cdot 10^{-4}$

4.2.2.8 Calculation of the sliding parameter

Local flash temperature:

$$\theta_{fl,A} = \frac{\sqrt{\pi}}{2} \cdot \frac{10^6 \cdot \mu_m \cdot p_{dyn,A} \cdot \left| v_{g,A} \right|}{B_{M1}\sqrt{v_{r1,A}} + B_{M2}\sqrt{v_{r2,A}}} \cdot \sqrt{8 \cdot \rho_{n,A} \cdot \frac{p_{dyn,A}}{1000 \cdot E_r}} \qquad (80) \qquad \theta_{fl,A} = 225{,}7\ ^\circ\mathrm{C}$$

$\theta_{fl,AB} = 170{,}3\ ^\circ\mathrm{C}$	$\theta_{fl,B} = 119{,}2\ ^\circ\mathrm{C}$	$\theta_{fl,C} = 0\ ^\circ\mathrm{C}$
$\theta_{fl,D} = 119{,}2\ ^\circ\mathrm{C}$	$\theta_{fl,DE} = 170{,}3\ ^\circ\mathrm{C}$	$\theta_{fl,E} = 225{,}7\ ^\circ\mathrm{C}$

Local contact temperature as sum of bulk and local flash temperature:

$$\theta_{B,A} = \theta_M + \theta_{fl,A} \qquad (79) \qquad \theta_{B,A} = 352{,}3\ ^\circ\mathrm{C}$$

$\theta_{B,AB} = 296{,}9\ ^\circ\mathrm{C}$	$\theta_{B,B} = 245{,}8\ ^\circ\mathrm{C}$	$\theta_{B,C} = 126{,}6\ ^\circ\mathrm{C}$
$\theta_{B,D} = 245{,}8\ ^\circ\mathrm{C}$	$\theta_{B,DE} = 296{,}9\ ^\circ\mathrm{C}$	$\theta_{B,E} = 352{,}3\ ^\circ\mathrm{C}$

Local sliding parameter:

$$S_{GF,A} = \frac{\alpha_{\theta B,A} \cdot \eta_{\theta B,A}}{\alpha_{\theta M} \cdot \eta_{\theta M}} \qquad (27) \qquad S_{GF,A} = 0{,}024$$

$S_{GF,AB} = 0{,}049$	$S_{GF,B} = 0{,}102$	$S_{GF,C} = 1{,}000$
$S_{GF,D} = 0{,}102$	$S_{GF,DE} = 0{,}049$	$S_{GF,E} = 0{,}024$

4.2.2.9 Calculation of the lubricant film thickness

$$h_A = 1600 \cdot \rho_{n,A} \cdot {G_M}^{0,6} \cdot {U_A}^{0,7} \cdot {W_A}^{-0,13} \cdot {S_{GF,A}}^{0,22} \qquad (4) \qquad h_A = 0{,}048\ \mu\mathrm{m}$$

$h_{AB} = 0{,}064\ \mu\mathrm{m}$	$h_B = 0{,}074\ \mu\mathrm{m}$	$h_C = 0{,}124\ \mu\mathrm{m}$
$h_D = 0{,}074\ \mu\mathrm{m}$	$h_{DE} = 0{,}064\ \mu\mathrm{m}$	$h_E = 0{,}048\ \mu\mathrm{m}$

4.2.2.10 Calculation of the specific lubricant film thickness

$$\lambda_{GF,A} = \frac{h_A}{Ra} \quad (2) \qquad \lambda_{GF,A} = 0{,}060$$

$\lambda_{GF,AB} = 0{,}080$ $\lambda_{GF,B} = 0{,}092$ $\lambda_{GF,C} = 0{,}155$

$\lambda_{GF,D} = 0{,}092$ $\lambda_{GF,DE} = 0{,}080$ $\lambda_{GF,E} = 0{,}060$

$$\lambda_{GF,min} = \lambda_{GF,A} \qquad \lambda_{GF,min} = 0{,}060$$

4.2.2.11 Calculation of the micropitting safety factor

$$S_\lambda = \frac{\lambda_{GF,min}}{\lambda_{GFP}} \quad (1) \qquad S_\lambda = 0{,}353$$

The final results for the calculation of the safety factor against micropitting, S_λ, for example 2 are shown in Table 9.

Table 9 — Results of calculation according to method B — Example 2

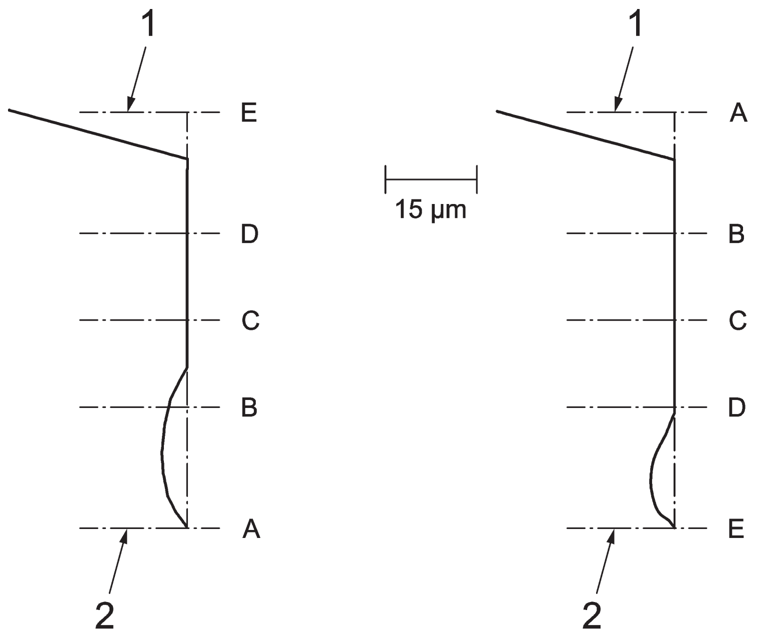
Point	A	AB	B	C	D	DE	E
$\lambda_{GF,Y}$	0,060	0,080	0,092	0,155	0,092	0,080	0,060
$\lambda_{GF,min}$	0,060						
λ_{GFP}	0,171						
S_λ	**0,353**						

NOTE With reference to ISO 15144-1, 5.4, for θ_{oilRef} the oil temperature, at which the test was performed, has to be used. Micropitting load capacity is significantly influenced by additives, often more than by the viscosity. As the effectiveness of additives depends significantly on temperature, it is recommended to test the oil at the temperature used in the application.

Normally, the FZG-FVA micropitting test[1] is executed at 90 °C oil temperature. The data from oil providers should contain together with the failure load stage SKS also the test temperature.

4.3 Example 3 — Helical gear

The result of this example is confirmed by experimental investigations. The gears were obviously micropitted and had profile deviations of approximately 10 µm (pinion) and 5 µm (wheel). Figure 3 shows a diagram of the observed location and severity of micropitting for pinion and wheel of example 3.



a) pinion **b) wheel**

Key

1 tip

2 root

Figure 3 — Diagram of schematic profile deviations of pinion and wheel for example 3

NOTE For the calculation according to method B, no modifications were considered.

4.3.1 Input data

Table 10 — Input data for Example 3

	Symbol	Description	Unit	Example 3 pinion	Example 3 wheel
				comb.	
Geometry	z	number of teeth	-	33	34
	-	driving gear	-	X	
	m_n	normal module	°	4,5	
	α_n	normal pressure angle	°	20	
	β	helix angle (right-hand on pinion)	mm	19,578	
	b	face width	°	44	
	a	centre distance	°	160	
	x	addendum modification factor	mm	0,0	0,0
	d_a	tip diameter of pinion	mm	166,61	171,39
	-	tooth flank modifications[a]	-	linear tip relief C_{a1} = 50 µm, d_{End1} = 162,72 mm C_{a2} = 50 µm, d_{End2} = 162,52 mm	
	Q	gear quality	-	4	4
	Ra	arithmetic mean roughness value	µm	0,45	0,45
Material	-	material	-	Eh	Eh
	E	modulus of elasticity	N/mm^2	206 000	206 000
	ν	Poisson's ratio	-	0,3	0,3
	λ_M	specific heat conductivity	W/(m·K)	45	45
	c_M	specific heat per unit mass	J/(kg·K)	440	440
	ρ_M	density	kg/m^3	7 800	7 800
	W_w	material factor according to ISO/TR 15144-1:2014, Table A.1 (for matching case carburised/case carburised)	-	1,0	
Application	K_A	application factor	-	1,0	
	K_v	dynamic factor	-	1,05	
	$K_{H\alpha}$	transverse load factor	-	1,0	
	$K_{H\beta}$	face load factor	-	1,10	
Load	T_1	nominal torque at the pinion	Nm	4 000	
	n_1	rotation speed of the pinion	min^{-1}	3 000	

[a] Calculation according to method B: modifications assumed as not adequate; calculation according to method A: modifications recognized during calculation of pressure distribution.

Table 10 *(continued)*

	Symbol	Description	Unit	Example 3	
				pinion	wheel
				comb.	
Lubricant	θ_{oil}	oil inlet temperature (injection lubrication)	° C	90	
	ν_{40}	kinematic viscosity at 40 °C	mm^2/s	76,5	
	ν_{100}	kinematic viscosity at 100 °C	mm^2/s	8,0	
	ρ_{15}	density of the lubricant at 15 °C	kg/m^3	895	
	-	oil type	-	mineral oil	
	λ_{GFP}	permissible lubricant film thickness determined from a representative bench test	-	0,112	

[a] Calculation according to method B: modifications assumed as not adequate; calculation according to method A: modifications recognized during calculation of pressure distribution.

4.3.2 Calculation according to method B

4.3.2.1 Calculation of gear geometry (according to ISO 21771)

Basic values:

$$m_t = \frac{m_n}{\cos\beta}$$ m_t = 4,776 mm

$$d_1 = z_1 \cdot m_t$$ d_1 = 157,612 mm

$$d_2 = z_2 \cdot m_t$$ d_2 = 162,388 mm

$$u = \frac{z_2}{z_1}$$ u = 1,03

$$\alpha_t = \arctan\left(\frac{\tan\alpha_n}{\cos\beta}\right)$$ α_t = 21,122 °

$$d_{b1} = d_1 \cdot \cos\alpha_t$$ d_{b1} = 147,023 mm

$$d_{b2} = d_2 \cdot \cos\alpha_t$$ d_{b2} = 151,479 mm

$$d_{w1} = \frac{2 \cdot a}{u+1}$$ d_{w1} = 157,612 mm

$$d_{w2} = 2 \cdot a - d_{w1}$$ d_{w2} = 162,388 mm

$$\alpha_{wt} = \arccos\left[\frac{(z_1+z_2) \cdot m_t \cdot \cos\alpha_t}{2 \cdot a}\right]$$ α_{wt} = 21,122 °

$$\beta_b = \arcsin(\sin\beta \cdot \cos\alpha_n)$$ β_b = 18,354 °

$$p_{et} = m_t \cdot \pi \cdot \cos\alpha_t$$ p_{et} = 13,997 mm

$$\varepsilon_1 = \frac{z_1}{2\cdot\pi}\cdot\left[\sqrt{\left(\frac{d_{a1}}{d_{b1}}\right)^2 - 1} - \tan\alpha_{wt}\right]$$ ε_1 = 0,771

$$\varepsilon_2 = \frac{z_2}{2\cdot\pi}\cdot\left[\sqrt{\left(\frac{d_{a2}}{d_{b2}}\right)^2 - 1} - \tan\alpha_{wt}\right]$$ ε_2 = 0,774

$$\varepsilon_\alpha = \frac{1}{p_{et}}\cdot\left(\sqrt{\frac{d_{a1}^2}{4} - \frac{d_{b1}^2}{4}} + \sqrt{\frac{d_{a2}^2}{4} - \frac{d_{b2}^2}{4}} - a\cdot\sin\alpha_{wt}\right)$$ ε_α = 1,545

$$\varepsilon_\beta = \frac{b\cdot\sin\beta}{m_n\cdot\pi}$$ ε_β = 1,043

$$\varepsilon_\gamma = \varepsilon_\alpha + \varepsilon_\beta$$ ε_γ = 2,588

$$g_\alpha = 0{,}5\cdot\left(\sqrt{d_{a1}^2 - d_{b1}^2} + \sqrt{d_{a2}^2 - d_{b2}^2}\right) - a\cdot\sin\alpha_{wt}$$ g_α = 21,623 mm

Coordinates of the basic points (A, AB, B, C, D, DE, E) on the line of action:

g_A = 0 mm (34) g_A = 0 mm

$$g_{AB} = \frac{g_\alpha - p_{et}}{2} \quad (35)$$ g_{AB} = 3,813 mm

$$g_B = g_\alpha - p_{et} \quad (36)$$ g_B = 7,626 mm

$$g_C = \frac{d_{b1}}{2}\cdot\tan\alpha_{wt} - \sqrt{\frac{d_{a1}^2}{4} - \frac{d_{b1}^2}{4}} + g_\alpha \quad (37)$$ g_C = 10,832 mm

$$g_D = p_{et} \quad (38)$$ g_D = 13,997 mm

$$g_{DE} = \frac{g_\alpha - p_{et}}{2} + p_{et} \quad (39)$$ g_{DE} = 17,810 mm

$$g_E = g_\alpha \quad (40)$$ g_E = 21,623 mm

$$d_{A1} = 2\cdot\sqrt{\frac{d_{b1}^2}{4} + \left(\sqrt{\frac{d_{a1}^2}{4} - \frac{d_{b1}^2}{4}} - g_\alpha + g_A\right)^2} \quad (41)$$ d_{A1} = 151,162 mm

d_{AB1} = 153,115 mm d_{B1} = 155,417 mm d_{C1} = 157,612 mm

d_{D1} = 160,002 mm d_{DE1} = 163,161 mm d_{E1} = 166,610 mm

$$d_{A2} = 2 \cdot \sqrt{\frac{d_{b2}^2}{4} + \left(\sqrt{\frac{d_{a2}^2}{4} - \frac{d_{b2}^2}{4}} - g_A \right)^2} \quad (42)$$

d_{A2} = 171,390 mm

d_{AB2} = 167,957 mm d_{B2} = 164,807 mm d_{C2} = 162,388 mm

d_{D2} = 160,216 mm d_{DE2} = 157,897 mm d_{E2} = 155,916 mm

Normal radius of relative curvature:

$$\rho_{n,A} = \frac{\rho_{t,A}}{\cos \beta_b} \quad (45)$$

$\rho_{n,A}$ = 12,869 mm

$\rho_{n,AB}$ = 14,173 mm $\rho_{n,B}$ = 14,945 mm $\rho_{n,C}$ = 15,183 mm

$\rho_{n,D}$ = 15,050 mm $\rho_{n,DE}$ = 14,403 mm $\rho_{n,E}$ = 13,225 mm

4.3.2.2 Calculation of material data

$$E_r = 2 \cdot \left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right)^{-1} \quad (6)$$

E_r = 226 374 N/mm²

$$B_{M1} = \sqrt{\lambda_{M1} \cdot \rho_{M1} \cdot c_{M1}} \quad (82)$$

B_{M1} = 12 427,4 N/(ms^{0,5}K)

$$B_{M2} = \sqrt{\lambda_{M2} \cdot \rho_{M2} \cdot c_{M2}} \quad (83)$$

B_{M2} = 12 427,4 N/(ms^{0,5}K)

4.3.2.3 Calculation of operating conditions

Loading:

$$P = 2 \cdot \pi \cdot \frac{n_1}{60} \cdot \frac{T_1}{1\,000} \quad (85)$$

P = 1 257 kW

$$F_t = 2\,000 \cdot \frac{T_1}{d_1}$$

F_t = 50 758 N

$$F_{bt} = 2\,000 \cdot \frac{T_1}{d_{b1}}$$

F_{bt} = 54 413 N

Local load sharing factor:

NOTE Helical gears, $\varepsilon_\beta \geq 1$, unmodified profile (see ISO/TR 15144-1:2014, Figure 12).

$$X_A = \frac{1}{\varepsilon_\alpha} \cdot X_{but,A} \quad (69)$$

X_A = 0,841
($X_{but,A}$ = 1,3)

X_{AB} = 0,647	X_B = 0, 647	X_C = 0,647
($X_{but,AB}$ = 1,0)	($X_{but,B}$ = 1,0)	($X_{but,C}$ = 1,0)
X_D = 0,647	X_{DE} = 0,647	X_E = 0,841
($X_{but,D}$ = 1,0)	($X_{but,DE}$ = 1,0)	($X_{but,E}$ = 1,0)

Elasticity factor:

$$Z_E = \sqrt{\frac{E_r}{2 \cdot \pi}} \quad (26) \qquad Z_E = 189{,}812\ (\mathrm{N/mm^2})^{0,5}$$

Local Hertzian contact stress:

$$p_{H,A,B} = Z_E \cdot \sqrt{\frac{F_t \cdot X_A}{b \cdot \rho_{n,A} \cdot \cos\alpha_t \cdot \cos\beta_b}} \quad (25) \qquad p_{H,A,B} = 1\,752\ \mathrm{N/mm^2}$$

$p_{H,AB,B}$ = 1 464 N/mm^2	$p_{H,B,B}$ = 1 426N/mm^2	$p_{H,C,B}$ = 1 415 N/mm^2
$p_{H,D,B}$ = 1 421 N/mm^2	$p_{H,DE,B}$ = 1 452 N/mm^2	$p_{H,E,B}$ = 1 728 N/mm^2

$$p_{dyn,A,B} = p_{H,A,B} \cdot \sqrt{K_A \cdot K_v \cdot K_{H\alpha} \cdot K_{H\beta}} \quad (24) \qquad p_{dyn,A,B} = 1\,883\ \mathrm{N/mm^2}$$

$p_{dyn,AB,B}$ = 1 574 N/mm^2	$p_{dyn,B,B}$ = 1 532 N/mm^2	$p_{dyn,C,B}$ = 1 520 N/mm^2
$p_{dyn,D,B}$ = 1 527 N/mm^2	$p_{dyn,DE,B}$ = 1 561 N/mm^2	$p_{dyn,E,B}$ = 1 857 N/mm^2

Velocity:

$$v_{g,A} = v_{r1,A} - v_{r2,A} \quad (81) \qquad v_{g,A} = -6{,}706\ \mathrm{m/s}$$

$v_{g,AB}$ = −4,345 m/s	$v_{g,B}$ = −1,984 m/s	$v_{g,C}$ = 0 m/s
$v_{g,D}$ = 1,959 m/s	$v_{g,DE}$ = 4,320 m/s	$v_{g,E}$ = 6,681 m/s

$$v_{\Sigma,A} = v_{r1,A} + v_{r2,A} \quad (13) \qquad v_{\Sigma,A} = 17{,}743\ \mathrm{m/s}$$

$v_{\Sigma,AB}$ = 17,778 m/s	$v_{\Sigma,B}$ = 17,813 m/s	$v_{\Sigma,C}$ = 17,843 m/s
$v_{\Sigma,D}$ = 17,872 m/s	$v_{\Sigma,DE}$ = 17,907 m/s	$v_{\Sigma,E}$ = 17,942 m/s

Effective arithmetic mean roughness value:

$$Ra = 0{,}5 \cdot \left(Ra_1 + Ra_2\right) \quad (3) \qquad Ra = 0{,}45\ \mu\mathrm{m}$$

4.3.2.4 Calculation of lubricant data

X_L = 1,0 for mineral oil (see Table 3 in ISO/TR 15144 part 1)

$$\alpha_{38} = 2{,}657 \cdot 10^{-8} \cdot \eta_{38}^{\;0,1348} \quad (9) \qquad \alpha_{38} = 1{,}88 \cdot 10^{-8}\ \mathrm{m^2/N}$$

X_S = 1,2 for injection lubrication

4.3.2.5 Calculation of the material parameter

Mean coefficient of friction:

$$X_R = 2{,}2 \cdot \left(\frac{Ra}{\rho_{n,C}}\right)^{0{,}25} \quad (87) \qquad X_R = 0{,}913$$

$K_{B\gamma} = 1{,}238$ for $2 < \varepsilon_\gamma < 3{,}5$ (89)

$$\mu_m = 0{,}045 \cdot \left(\frac{K_A \cdot K_v \cdot K_{H\alpha} \cdot K_{H\beta} \cdot F_{bt} \cdot K_{B\gamma}}{b \cdot v_{\Sigma,C} \cdot \rho_{n,C}}\right)^{0{,}2} \cdot \left(10^3 \cdot \eta_{\theta oil}\right)^{-0{,}05} \cdot X_R \cdot X_L \quad (86) \qquad \mu_m = 0{,}054$$

Bulk temperature:

$$H_v = \left(\varepsilon_1{}^2 + \varepsilon_2{}^2 + 1 - \varepsilon_\alpha\right) \cdot \left(\frac{1}{z_1} + \frac{1}{z_2}\right) \cdot \frac{\pi}{\cos \beta_b} \text{ for } \varepsilon_\alpha < 2 \quad (91) \qquad H_v = 0{,}128$$

$$\varepsilon_{max} = \varepsilon_2$$

$X_{Ca} = 1{,}0$ for no adequate profile modification (method B) (101)

$$\theta_M = \theta_{oil} + 7\,400 \cdot \left(\frac{P \cdot \mu_m \cdot H_v}{a \cdot b}\right)^{0{,}72} \cdot \frac{X_S}{1{,}2 \cdot X_{Ca}} \quad (84) \qquad \theta_M = 149{,}3\ °C$$

Material parameter:

$$G_M = 10^6 \cdot \alpha_{\theta M} \cdot E_r \quad (5) \qquad G_M = 238\ 8{,}5$$

4.3.2.6 Calculation of the velocity parameter

$$U_A = \eta_{\theta M} \cdot \frac{V_{\Sigma,A}}{2\,000 \cdot E_r \cdot \rho_{n,A}} \quad (12) \qquad U_A = 7{,}431 \cdot 10^{-12}$$

$U_{AB} = 6{,}761 \cdot 10^{-12}$ $U_B = 6{,}424 \cdot 10^{-12}$ $U_C = 6{,}334 \cdot 10^{-12}$

$U_D = 6{,}400 \cdot 10^{-12}$ $U_{DE} = 6{,}701 \cdot 10^{-12}$ $U_E = 7{,}312 \cdot 10^{-12}$

4.3.2.7 Calculation of the load parameter

$$W_A = \frac{2 \cdot \pi \cdot p_{dyn,A}{}^2}{E_r{}^2} \quad (22) \qquad W_A = 4{,}347 \cdot 10^{-4}$$

$W_{AB} = 3{,}036 \cdot 10^{-4}$ $W_B = 2{,}879 \cdot 10^{-4}$ $W_C = 2{,}834 \cdot 10^{-4}$

$W_D = 2{,}859 \cdot 10^{-4}$ $W_{DE} = 2{,}988 \cdot 10^{-4}$ $W_E = 4{,}230 \cdot 10^{-4}$

4.3.2.8 Calculation of the sliding parameter

Local flash temperature:

$$\theta_{fl,A} = \frac{\sqrt{\pi}}{2} \cdot \frac{10^6 \cdot \mu_m \cdot p_{dyn,A} \cdot \left| v_{g,A} \right|}{B_{M1}\sqrt{v_{r1,A}} + B_{M2}\sqrt{v_{r2,A}}} \cdot \sqrt{8 \cdot \rho_{n,A} \cdot \frac{p_{dyn,A}}{1000 \cdot E_r}} \quad (80) \qquad \theta_{fl,A} = 241,7\ °C$$

$\theta_{fl,AB}$ = 124,0 °C	$\theta_{fl,B}$ = 55,5 °C	$\theta_{fl,C}$ = 0 °C
$\theta_{fl,D}$ = 54,6 °C	$\theta_{fl,DE}$ = 122,4 °C	$\theta_{fl,E}$ = 237,7 °C

Local contact temperature as sum of bulk and local flash temperature:

$$\theta_{B,A} = \theta_M + \theta_{fl,A} \quad (79) \qquad \theta_{B,A} = 391,0\ °C$$

$\theta_{B,AB}$ = 273,4 °C	$\theta_{B,B}$ = 204,8 °C	$\theta_{B,C}$ = 149,3 °C
$\theta_{B,D}$ = 203,9 °C	$\theta_{B,DE}$ = 271,7 °C	$\theta_{B,E}$ = 387,0 °C

Local sliding parameter:

$$S_{GF,A} = \frac{\alpha_{\theta B,A} \cdot \eta_{\theta B,A}}{\alpha_{\theta M} \cdot \eta_{\theta M}} \quad (27) \qquad S_{GF,A} = 0,030$$

$S_{GF,AB}$ = 0,135	$S_{GF,B}$ = 0,361	$S_{GF,C}$ = 1,000
$S_{GF,D}$ = 0,366	$S_{GF,DE}$ = 0,138	$S_{GF,E}$ = 0,031

4.3.2.9 Calculation of the lubricant film thickness

$$h_A = 1600 \cdot \rho_{n,A} \cdot G_M{}^{0,6} \cdot U_A{}^{0,7} \cdot W_A{}^{-0,13} \cdot S_{GF,A}{}^{0,22} \quad (4) \qquad h_A = 0,045\ \mu m$$

h_{AB} = 0,067 µm	h_B = 0,086 µm	h_C = 0,108 µm
h_D = 0,087 µm	h_{DE} = 0,069 µm	h_E = 0,046 µm

4.3.2.10 Calculation of the specific lubricant film thickness

$$\lambda_{GF,A} = \frac{h_A}{Ra} \quad (2) \qquad \lambda_{GF,A} = 0,099$$

$\lambda_{GF,AB}$ = 0,150	$\lambda_{GF,B}$ = 0,191	$\lambda_{GF,C}$ = 0,241
$\lambda_{GF,D}$ = 0,192	$\lambda_{GF,DE}$ = 0,152	$\lambda_{GF,E}$ = 0,103

$$\lambda_{GF,min} = \lambda_{GF,A} \qquad \lambda_{GF,min} = 0,099$$

4.3.2.11 Calculation of the micropitting safety factor

$$S_\lambda = \frac{\lambda_{GF,min}}{\lambda_{GFP}} \quad (1) \qquad S_\lambda = 0,884$$

The final results for the calculation of the safety factor against micropitting, S_λ, for example 3 are shown in Table 11.

Table 11 — Results of calculation according to method B — Example 3

Point	A	AB	B	C	D	DE	E
$\lambda_{GF,Y}$	0,099	0,150	0,191	0,241	0,192	0,152	0,103
$\lambda_{GF,min}$	0,099						
λ_{GFP}	0,112						
S_λ	**0,884**						

4.3.3 Calculation according to method A

The calculation of example 3 according to method A was carried out by a 3D-calculation programme. Calculated results during method A will vary depending on the method of determining load distribution. The load distribution, on which the following calculation according to method A is based, is shown in Table 12. The maximum values are printed in bold.

Table 12 — Matrix of pressure distribution — $p_{H,Y,A}$ in N/mm^2

	Width in mm			
	0,0	15,5	28,5	44,0
A	**1 205**	768	742	384
AB	**1 572**	1 456	1 457	1 273
B	1 568	1 560	1 550	**1 589**
C	1 518	1 510	1 530	**1 582**
D	1 516	1 529	1 574	**1 621**
DE	1 192	1 423	1 454	**1 623**
E	250	655	765	**1 513**

The resulting matrix of specific lubricant film thickness according to method A is shown in Table 13. The minimum value is printed in bold.

Table 13 — Matrix of resulting specific lubricant film thickness, $\lambda_{GF,Y}$

	Width in mm			
	0,0	15,5	28,5	44,0
A	0,198	0,274	0,280	0,391
AB	0,191	0,203	0,203	0,225
B	0,244	0,245	0,246	0,242
C	0,323	0,324	0,323	0,320
D	0,251	0,250	0,245	0,241
DE	0,238	0,209	0,205	0,188
E	0,467	0,306	0,279	**0,163**

For the calculation of the micropitting safety factor according to method A, the minimum value of the matrix of resulting specific lubricant film thickness, shown in Table 13, was used.

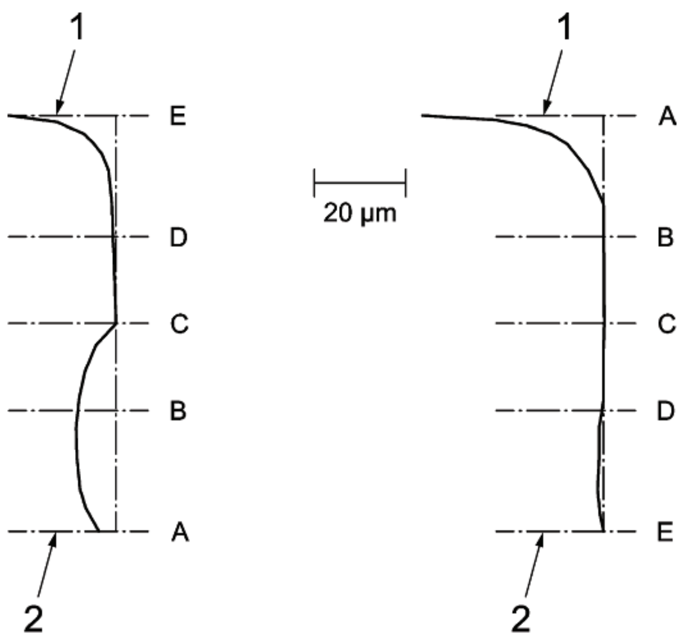
$$S_\lambda = \frac{\lambda_{\mathrm{GF,min}}}{\lambda_{\mathrm{GFP}}} \qquad S_\lambda = 1{,}124$$

NOTE The difference in safety factor calculated between methods A and B in the above example 3 results from the simplified analysis of method B, in relation to the account for profile modification. In example 3, the amount of tip relief is not calculated as being optimum for the specified load; therefore, the calculations for method B are based on contact conditions with no consideration for tip relief.

4.4 Example 4 — Speed increaser

The result of this example is confirmed by experimental investigations. The gears were obviously micropitted and had profile deviations of approximately 12 µm (pinion) and 3 µm (wheel). Figure 3 shows a diagram of the observed location and severity of micropitting for pinion and wheel of example 4.

NOTE It has to be considered that in example 4, the wheel is the driving gear. The beginning of tooth contact in this example is at the root of the wheel, point E.



a) pinion **b) wheel**

Key

1 tip

2 root

Figure 4 — Diagram of schematic profile deviations of pinion and wheel for example 4

NOTE For the calculation according to method B, no modifications were considered.

4.4.1 Input data

Table 14 — Input data for Example 4

	Symbol	Description	Unit	Example 4 pinion	Example 4 wheel
				comb.	
Geometry	z	number of teeth	-	21	67
	-	driving gear	-		x
	m_n	normal module	mm	8,0	
	α_n	normal pressure angle	°	20	
	β	helix angle (right-hand on pinion)	°	14,5	
	b	face width	mm	185	
	a	centre distance	mm	369	
	x	addendum modification factor	-	0,320 0	0,391 4
	d_a	tip diameter of pinion	mm	195,00	576,30
	-	tooth flank modifications[a]	-	linear tip relief pinion C_{a1} = 25 µm, d_{End1} = 188,07 mm linear tip relief wheel C_{a2} = 40 µm, d_{End2} = 570,69 mm symmetrical end relief wheel 50 µm, b = 35 mm	
	Q	gear quality	-	5	5
	Ra	arithmetic mean roughness value	µm	0,67	0,67
Material	-	material	-	Eh	Eh
	E	modulus of elasticity	N/mm²	210 000	210 000
	ν	Poisson's ratio	-	0,3	0,3
	λ_M	specific heat conductivity	W/(m·K)	33,7	33,7
	c_M	specific heat per unit mass	J/(kg·K)	461	461
	ρ_M	density	kg/m³	7 800	7 800
	W_W	material factor according to ISO/TR 15144-1:2014, Table A.1 (for matching case carburised/case carburised)	-	1,0	
Application	K_A	application factor	-	1,22	
	K_v	dynamic factor	-	1,015	
	$K_{H\alpha}$	transverse load factor	-	1,0	
	$K_{H\beta}$	face load factor	-	1,25	
Load	T_1	nominal torque at the pinion	Nm	16 817	
	n_1	rotation speed of the pinion	min⁻¹	530,9	

[a] Calculation according to method B: modifications assumed as not adequate; calculation according to method A: modifications recognized during calculation of pressure distribution.

Table 14 *(continued)*

	Symbol	Description	Unit	Example 4	
				pinion	wheel
				comb.	
Lubricant	θ_{oil}	oil inlet temperature (injection lubrication)	° C	70	
	ν_{40}	kinematic viscosity at 40° C	mm²/s	320	
	ν_{100}	kinematic viscosity at 100° C	mm²/s	24,5	
	ρ_{15}	density of the lubricant at 15° C	kg/m³	899	
	α_{38}	pressure-viscosity coefficient at 38° C	m²/N	$2{,}32 \cdot 10^{-8}$	
	-	oil type	-	mineral oil	
	-	failure load stage at test temperature (90° C) according to FVA 54/7	-	SKS 9	
	λ_{GFP}	permissible lubricant film thickness			

[a] Calculation according to method B: modifications assumed as not adequate; calculation according to method A: modifications recognized during calculation of pressure distribution.

NOTE With reference to ISO 15144-1, 5.4, for θ_{oilRef} the oil temperature, at which the test was performed, has to be used. Micropitting load capacity is significantly influenced by additives, often more than by the viscosity. As the effectiveness of additives depends significantly on temperature, it is recommended to test the oil at the temperature used in the application.

Normally the FZG-FVA micropitting test[1] is executed at 90 °C oil temperature. The data from oil providers should contain together with the failure load stage SKS also the test temperature.

4.4.2 Calculation according to method B

4.4.2.1 Calculation of gear geometry (according to ISO 21771)

Basic values:

$$m_t = \frac{m_n}{\cos\beta} \qquad m_t = 8{,}263 \text{ mm}$$

$$d_1 = z_1 \cdot m_t \qquad d_1 = 173{,}527 \text{ mm}$$

$$d_2 = z_2 \cdot m_t \qquad d_2 = 533{,}635 \text{ mm}$$

$$u = \frac{z_2}{z_1} \qquad u = 3{,}19$$

$$\alpha_t = \arctan\left(\frac{\tan\alpha_n}{\cos\beta}\right) \qquad \alpha_t = 20{,}603\ °$$

$$d_{b1} = d_1 \cdot \cos\alpha_t \qquad d_{b1} = 162{,}428 \text{ mm}$$

$$d_{b2} = d_2 \cdot \cos\alpha_t \qquad d_{b2} = 518{,}223 \text{ mm}$$

$$d_{w1} = \frac{2 \cdot a}{u+1}$$ d_{w1} = 176,114 mm

$$d_{w2} = 2 \cdot a - d_{w1}$$ d_{w2} = 561,886 mm

$$\alpha_{wt} = \arccos\left[\frac{(z_1 + z_2) \cdot m_t \cdot \cos\alpha_t}{2 \cdot a}\right]$$ α_{wt} = 22,737 °

$$\beta_b = \arcsin(\sin\beta \cdot \cos\alpha_n)$$ β_b = 13,608 °

$$p_{et} = m_t \cdot \pi \cdot \cos\alpha_t$$ p_{et} = 24,299 mm

$$\varepsilon_1 = \frac{z_1}{2 \cdot \pi} \cdot \left[\sqrt{\left(\frac{d_{a1}}{d_{b1}}\right)^2 - 1} - \tan\alpha_{wt}\right]$$ ε_1 = 0,820

$$\varepsilon_2 = \frac{z_2}{2 \cdot \pi} \cdot \left[\sqrt{\left(\frac{d_{a2}}{d_{b2}}\right)^2 - 1} - \tan\alpha_{wt}\right]$$ ε_2 = 0,719

$$\varepsilon_\alpha = \frac{1}{p_{et}} \cdot \left(\sqrt{\frac{d_{a1}^2}{4} - \frac{d_{b1}^2}{4}} + \sqrt{\frac{d_{a2}^2}{4} - \frac{d_{b2}^2}{4}} - a \cdot \sin\alpha_{wt}\right)$$ ε_α = 1,539

$$\varepsilon_\beta = \frac{b \cdot \sin\beta}{m_n \cdot \pi}$$ ε_β = 1,843

$$\varepsilon_\gamma = \varepsilon_\alpha + \varepsilon_\beta$$ ε_γ = 3,382

$$g_\alpha = 0{,}5 \cdot \left(\sqrt{d_{a1}^2 - d_{b1}^2} + \sqrt{d_{a2}^2 - d_{b2}^2}\right) - a \cdot \sin\alpha_{wt}$$ g_α = 37,395 mm

Coordinates of the basic points (A, AB, B, C, D, DE, E) on the line of action:

$$g_A = 0 \text{ mm} \quad (34)$$ g_A = 0 mm

$$g_{AB} = \frac{g_\alpha - p_{et}}{2} \quad (35)$$ g_{AB} = 6,548 mm

$$g_B = g_\alpha - p_{et} \quad (36)$$ g_B = 13,096 mm

$$g_C = \frac{d_{b1}}{2} \cdot \tan\alpha_{wt} - \sqrt{\frac{d_{a1}^2}{4} - \frac{d_{b1}^2}{4}} + g_\alpha \quad (37)$$ g_C = 17,479 mm

$$g_D = p_{et} \quad (38)$$ g_D = 24,299 mm

$$g_{DE} = \frac{g_\alpha - p_{et}}{2} + p_{et} \quad (39) \qquad g_{DE} = 30{,}847 \text{ mm}$$

$$g_E = g_\alpha \quad (40) \qquad g_E = 37{,}395 \text{ mm}$$

$$d_{A1} = 2 \cdot \sqrt{\frac{{d_{b1}}^2}{4} + \left(\sqrt{\frac{{d_{a1}}^2}{4} - \frac{{d_{b1}}^2}{4}} - g_\alpha + g_A \right)^2} \quad (41) \qquad d_{A1} = 165{,}768 \text{ mm}$$

d_{AB1} = 168,872 mm d_{B1} = 172,914 mm d_{C1} = 176,114 mm

d_{D1} = 181,821 mm d_{DE1} = 188,070 mm d_{E1} = 195,000 mm

$$d_{A2} = 2 \cdot \sqrt{\frac{{d_{b2}}^2}{4} + \left(\sqrt{\frac{{d_{a2}}^2}{4} - \frac{{d_{b2}}^2}{4}} - g_A \right)^2} \quad (42) \qquad d_{A2} = 576{,}300 \text{ mm}$$

d_{AB2} = 570,692 mm d_{B2} = 565,333 mm d_{C2} = 561,886 mm

d_{D2} = 556,757 mm d_{DE2} = 552,104 mm d_{E2} = 547,725 mm

Normal radius of relative curvature:

$$\rho_{n,A} = \frac{\rho_{t,A}}{\cos \beta_b} \quad (45) \qquad \rho_{n,A} = 15{,}057 \text{ mm}$$

$\rho_{n,AB}$ = 19,919 mm $\rho_{n,B}$ = 24,164 mm $\rho_{n,C}$ = 26,660 mm

$\rho_{n,D}$ = 29,993 mm $\rho_{n,DE}$ = 32,561 mm $\rho_{n,E}$ = 34,510 mm

4.4.2.2 Calculation of material data

$$E_r = 2 \cdot \left(\frac{1 - {\nu_1}^2}{E_1} + \frac{1 - {\nu_2}^2}{E_2} \right)^{-1} \quad (6) \qquad E_r = 230\ 769 \text{ N/mm}^2$$

$$B_{M1} = \sqrt{\lambda_{M1} \cdot \rho_{M1} \cdot c_{M1}} \quad (82) \qquad B_{M1} = 11\ 008{,}1 \text{ N/(ms}^{0,5}\text{K)}$$

$$B_{M2} = \sqrt{\lambda_{M2} \cdot \rho_{M2} \cdot c_{M2}} \quad (83) \qquad B_{M2} = 11\ 008{,}1 \text{ N/(ms}^{0,5}\text{K)}$$

4.4.2.3 Calculation of operating conditions

Loading:

$$P = 2 \cdot \pi \cdot \frac{n_1}{60} \cdot \frac{T_1}{1000} \quad (85) \qquad P = 935 \text{ kW}$$

$$F_t = 2000 \cdot \frac{T_1}{d_1} \qquad F_t = 193\ 825 \text{ N}$$

$$F_{\text{bt}} = 2000 \cdot \frac{T_1}{d_{\text{b1}}}$$ $F_{\text{bt}} = 207\ 070$ N

Local load sharing factor:

NOTE Helical gears, $\varepsilon_\beta \geq 1$, unmodified profile (see ISO/TR 15144-1:2014, Figure 12).

$$X_{\text{A}} = \frac{1}{\varepsilon_\alpha} \cdot X_{\text{but,A}} \quad (69)$$ $X_{\text{A}} = 0{,}845$

$X_{\text{AB}} = 0{,}650$	$X_{\text{B}} = 0{,}650$	$X_{\text{C}} = 0{,}650$
$X_{\text{D}} = 0{,}650$	$X_{\text{DE}} = 0{,}650$	$X_{\text{E}} = 0{,}845$

Elasticity factor:

$$Z_{\text{E}} = \sqrt{\frac{E_{\text{r}}}{2 \cdot \pi}} \quad (26)$$ $Z_{\text{E}} = 191{,}646\ (\text{N/mm}^2)^{0,5}$

Local Hertzian contact stress:

$$p_{\text{H,A,B}} = Z_{\text{E}} \cdot \sqrt{\frac{F_{\text{t}} \cdot X_{\text{A}}}{b \cdot \rho_{\text{n,A}} \cdot \cos\alpha_{\text{t}} \cdot \cos\beta_{\text{b}}}} \quad (25)$$ $p_{\text{H,A,B}} = 1\ 541\ \text{N/mm}^2$

$p_{\text{H,AB,B}} = 1\ 175\ \text{N/mm}^2$	$p_{\text{H,B,B}} = 1\ 066\ \text{N/mm}^2$	$p_{\text{H,C,B}} = 1\ 015\ \text{N/mm}^2$
$p_{\text{H,D,B}} = 957\ \text{N/mm}^2$	$p_{\text{H,DE,B}} = 919\ \text{N/mm}^2$	$p_{\text{H,E,B}} = 1\ 018\ \text{N/mm}^2$

$$p_{\text{dyn,A,B}} = p_{\text{H,A,B}} \cdot \sqrt{K_{\text{A}} \cdot K_{\text{v}} \cdot K_{\text{H}\alpha} \cdot K_{\text{H}\beta}} \quad (24)$$ $p_{\text{dyn,A,B}} = 1\ 917\ \text{N/mm}^2$

$p_{\text{dyn,AB,B}} = 1\ 461\ \text{N/mm}^2$	$p_{\text{dyn,B,B}} = 1\ 327\ \text{N/mm}^2$	$p_{\text{dyn,C,B}} = 1\ 263\ \text{N/mm}^2$
$p_{\text{dyn,D,B}} = 1\ 191\ \text{N/mm}^2$	$p_{\text{dyn,DE,B}} = 1\ 143\ \text{N/mm}^2$	$p_{\text{dyn,E,B}} = 1\ 266\ \text{N/mm}^2$

Velocity:

$$v_{\text{g,A}} = v_{\text{r1,A}} - v_{\text{r2,A}} \quad (81)$$ $v_{\text{g,A}} = -1{,}276$ m/s

$v_{\text{g,AB}} = -0{,}798$ m/s	$v_{\text{g,B}} = -0{,}320$ m/s	$v_{\text{g,C}} = 0$ m/s
$v_{\text{g,D}} = 0{,}498$ m/s	$v_{\text{g,DE}} = 0{,}976$ m/s	$v_{\text{g,E}} = 1{,}454$ m/s

$v_{\Sigma,\text{A}} = v_{\text{r1,A}} + v_{\text{r2,A}}$ $v_{\Sigma,\text{A}} = 3{,}117$ m/s

$v_{\Sigma,\text{AB}} = 3{,}367$ m/s	$v_{\Sigma,\text{B}} = 3{,}617$ m/s	$v_{\Sigma,\text{C}} = 3{,}784$ m/s
$v_{\Sigma,\text{D}} = 4{,}045$ m/s	$v_{\Sigma,\text{DE}} = 4{,}294$ m/s	$v_{\Sigma,\text{E}} = 4{,}544$ m/s

Effective arithmetic mean roughness value:

$$Ra = 0{,}5 \cdot \left(Ra_1 + Ra_2\right) \quad (3)$$ $Ra = 0{,}67$ µm

4.4.2.4 Calculation of lubricant data

$X_L = 1{,}0$ for mineral oil (see Table 3 in ISO/TR 15144 part 1)

$X_S = 1{,}2$ for injection lubrication

4.4.2.5 Calculation of the material parameter

Mean coefficient of friction:

$$X_R = 2{,}2 \cdot \left(\frac{Ra}{\rho_{n,C}} \right)^{0,25} \qquad (87) \quad X_R = 0{,}876$$

$K_{B\gamma} = 1{,}299$ for $2 < \varepsilon_\gamma < 3{,}5$

$$\mu_m = 0{,}045 \cdot \left(\frac{K_A \cdot K_v \cdot K_{H\alpha} \cdot K_{H\beta} \cdot F_{bt} \cdot K_{B\gamma}}{b \cdot v_{\Sigma,C} \cdot \rho_{n,C}} \right)^{0,2} \cdot \left(10^3 \cdot \eta_{\theta oil} \right)^{-0,05} \cdot X_R \cdot X_L \qquad (86) \quad \mu_m = 0{,}060$$

Bulk temperature:

$$H_v = \left(\varepsilon_1{}^2 + \varepsilon_2{}^2 + 1 - \varepsilon_\alpha \right) \cdot \left(\frac{1}{z_1} + \frac{1}{z_2} \right) \cdot \frac{\pi}{\cos \beta_b} \text{ for } \varepsilon_\alpha < 2 \qquad (91) \quad H_v = 0{,}131$$

$$\varepsilon_{max} = \varepsilon_1$$

$X_{Ca} = 1{,}0$ for no adequate profile modification (method B) (101)

$$\theta_M = \theta_{oil} + 7400 \cdot \left(\frac{P \cdot \mu_m \cdot H_v}{a \cdot b} \right)^{0,72} \cdot \frac{X_S}{1{,}2 \cdot X_{Ca}} \qquad (84) \quad \theta_M = 80{,}282\ °C$$

Material parameter:

$$G_M = 10^6 \cdot \alpha_{\theta M} \cdot E_r \qquad (5) \quad G_M = 4\,290{,}7$$

4.4.2.6 Calculation of the velocity parameter

$$U_A = \eta_{\theta M} \cdot \frac{v_{\Sigma,A}}{2000 \cdot E_r \cdot \rho_{n,A}} \qquad (12) \quad U_A = 1{,}798 \cdot 10^{-11}$$

$U_{AB} = 1{,}468 \cdot 10^{-11}$ $U_B = 1{,}300 \cdot 10^{-11}$ $U_C = 1{,}232 \cdot 10^{-11}$

$U_D = 1{,}171 \cdot 10^{-11}$ $U_{DE} = 1{,}145 \cdot 10^{-11}$ $U_E = 1{,}143 \cdot 10^{-11}$

4.4.2.7 Calculation of the load parameter

$$W_A = \frac{2 \cdot \pi \cdot p_{dyn,A}{}^2}{E_r{}^2} \qquad (22) \quad W_A = 4{,}334 \cdot 10^{-4}$$

$W_{AB} = 2{,}520 \cdot 10^{-4}$ $W_B = 2{,}077 \cdot 10^{-4}$ $W_C = 1{,}883 \cdot 10^{-4}$

W_D = 1,674·10^{-4} W_{DE} = 1,542·10^{-4} W_E = 1,891·10^{-4}

4.4.2.8 Calculation of the sliding parameter

Local flash temperature:

$$\theta_{fl,A} = \frac{\sqrt{\pi}}{2} \cdot \frac{10^6 \cdot \mu_m \cdot p_{dyn,A} \cdot \left|v_{g,A}\right|}{B_{M1}\sqrt{v_{r1,A}} + B_{M2}\sqrt{v_{r2,A}}} \cdot \sqrt{8 \cdot \rho_{n,A} \cdot \frac{p_{dyn,A}}{1000 \cdot E_r}} \quad (80)$$

$\theta_{fl,A}$ = 152,4 °C

$\theta_{fl,AB}$ = 69,2 °C $\theta_{fl,B}$ = 25,3 °C $\theta_{fl,C}$ = 0 °C

$\theta_{fl,D}$ = 35,4 °C $\theta_{fl,DE}$ = 66,2 °C $\theta_{fl,E}$ = 115,8 °C

Local contact temperature as sum of bulk and local flash temperature:

$$\theta_{B,A} = \theta_M + \theta_{fl,A} \quad (79)$$

$\theta_{B,A}$ = 232,7 °C

$\theta_{B,AB}$ = 149,5 °C $\theta_{B,B}$ = 105,6 °C $\theta_{B,C}$ = 80,3 °C

$\theta_{B,D}$ = 115,6 °C $\theta_{B,DE}$ = 146,5 °C $\theta_{B,E}$ = 196,1 °C

Local sliding parameter:

$$S_{GF,A} = \frac{\alpha_{\theta B,A} \cdot \eta_{\theta B,A}}{\alpha_{\theta M} \cdot \eta_{\theta M}} \quad (27)$$

$S_{GF,A}$ = 0,021

$S_{GF,AB}$ = 0,109 $S_{GF,B}$ = 0,382 $S_{GF,C}$ = 1,000

$S_{GF,D}$ = 0,276 $S_{GF,DE}$ = 0,118 $S_{GF,E}$ = 0,041

4.4.2.9 Calculation of the lubricant film thickness

$$h_A = 1\,600 \cdot \rho_{n,A} \cdot G_M{}^{0,6} \cdot U_A{}^{0,7} \cdot W_A{}^{-0,13} \cdot S_{GF,A}{}^{0,22} \quad (4)$$

h_A = 0,129 µm

h_{AB} = 0,227 µm h_B = 0,341 µm h_C = 0,454 µm

h_D = 0,377 µm h_{DE} = 0,338 µm h_E = 0,275 µm

4.4.2.10 Calculation of the specific lubricant film thickness

$$\lambda_{GF,A} = \frac{h_A}{Ra} \quad (2)$$

$\lambda_{GF,A}$ = 0,192

$\lambda_{GF,AB}$ = 0,339 $\lambda_{GF,B}$ = 0,510 $\lambda_{GF,C}$ = 0,678

$\lambda_{GF,D}$ = 0,563 $\lambda_{GF,DE}$ = 0,504 $\lambda_{GF,E}$ = 0,411

$$\lambda_{GF,min} = \lambda_{GF,A}$$

$\lambda_{GF,min}$ = 0,192

4.4.2.11 Calculation of the micropitting safety factor

$$S_\lambda = \frac{\lambda_{GF,min}}{\lambda_{GFP}} \qquad (1) \quad S_\lambda = 0{,}894$$

The final results for the calculation of the safety factor against micropitting, S_λ, for example 4 are shown in Table 15.

Table 15 — Results of calculation according to method B — Example 4

Point	A	AB	B	C	D	DE	E
$\lambda_{GF,Y}$	0,192	0,339	0,510	0,678	0,563	0,504	0,411
$\lambda_{GF,min}$	0,192						
λ_{GFP}	0,215						
S_λ	**0,894**						

4.4.3 Calculation according to method A

The calculation of example 1 according to method A was carried out by a 3D-calculation programme. Calculated results during method A will vary depending on the method of determining load distribution. The load distribution, on which the following calculation according to method A is based, is shown in Table 16. The maximum values are printed in bold.

Table 16 — Matrix of pressure distribution — $p_{H,Y,A}$ in N/mm²

	Width in mm			
	0,0	65,3	141,5	185,0
A	468	996	1 013	**1 412**
AB	641	1 151	**1 271**	1 012
B	640	1 106	**1 260**	871
C	579	1 082	**1 209**	850
D	543	1 039	**1 129**	822
DE	538	935	**1 013**	674
E	621	796	**1 002**	188

The resulting matrix of specific lubricant film thickness according to method A is shown in Table 17. The minimum value is printed in bold.

Table 17 — Matrix of resulting specific lubricant film thickness, $\lambda_{GF,Y}$

	Width in mm			
	0,0	65,3	141,5	185,0
A	0,557	0,340	0,335	**0,249**
AB	0,580	0,399	0,369	0,438
B	0,723	0,565	0,526	0,635
C	0,864	0,734	0,714	0,782
D	0,850	0,610	0,579	0,698
DE	0,825	0,576	0,541	0,723
E	0,724	0,599	0,491	1,323

For the calculation of the micropitting safety factor according to method A, the minimum value of the matrix of resulting specific lubricant film thickness, shown in Table 17, was used.

$$S_\lambda = \frac{\lambda_{GF,min}}{\lambda_{GFP}} \quad (1) \qquad S_\lambda = 1{,}158$$

NOTE The difference in safety factor calculated between methods A and B in the above example 4 results from the simplified analysis of method B with relation to the account for profile modification. In example 4, the amount of tip relief is not calculated as being optimum for the specified load and therefore the calculations for method B are based on contact conditions with no consideration for tip relief.

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[1] FVA-Information Sheet 54/7: Test procedure for the investigation of the micropitting capacity of gear lubricants. 1993

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