TECHNICAL REPORT

ISO/TR 15144-1

Second edition
2014-09-01

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

Part 1:
Introduction and basic principles

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

Partie 1: Introduction et principes fondamentaux

Reference number
ISO/TR 15144-1:2014(E)

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Published in Switzerland

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

This second edition cancels and replaces the first edition (ISO/TR 15144-1:2010), which has been technically revised.

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 principles for the calculation of the micropitting load capacity of cylindrical involute spur and helical gears with external teeth.

The basis for the calculation of the micropitting load capacity of a gear set is the model of the minimum operating specific lubricant film thickness in the contact zone. There are many influence parameters such as surface topology, contact stress level, and lubricant chemistry. While these parameters are known to affect the performance of micropitting for a gear set, the subject area remains a topic of research and, as such, the science has not yet developed to allow these specific parameters to be included directly in the calculation methods. Furthermore, the correct application of tip and root relief (involute modification) has been found to greatly influence micropitting; the suitable values should therefore be applied. Surface finish is another crucial parameter. At present, *R*a is used but other aspects such as *R*z or skewness have been observed to have significant effects which could be reflected in the finishing process applied.

Although the calculation of specific lubricant film thickness does not provide a direct method for assessing micropitting load capacity, it can serve as an evaluation criterion when applied as part of a suitable comparative procedure based on known gear performance.

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

Part 1:
Introduction and basic principles

1 Scope

This part of ISO/TR 15144 describes a procedure for the calculation of the micropitting load capacity of cylindrical gears with external teeth. It has been developed on the basis of testing and observation of oil-lubricated gear transmissions with modules between 3 mm and 11 mm and pitch line velocities of 8 m/s to 60 m/s. However, the procedure is applicable to any gear pair where suitable reference data are available, provided the criteria specified below are satisfied.

The formulae specified are applicable for driving, as well as for driven cylindrical gears with tooth profiles in accordance with the basic rack specified in ISO 53. They are also applicable for teeth conjugate to other basic racks where the virtual contact ratio is less than $\varepsilon_{\alpha n} = 2,5$. The results are in good agreement with other methods for normal working pressure angles up to 25°, reference helix angles up to 25°, and in cases where pitch line velocity is higher than 2 m/s.

This part of ISO/TR 15144 is not applicable for the assessment of types of gear tooth surface damage other than micropitting.

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 53, *Cylindrical gears for general and heavy engineering — Standard basic rack tooth profile*

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

ISO 1328-1, *Cylindrical gears — ISO system of flank tolerance classification — Part 1: Definitions and allowable values of deviations relevant to flanks of gear teeth*

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

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

3 Terms, definitions, symbols, and units

3.1 Terms and definitions

For the purposes 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 ISO/TR 15144 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 equations.

Table 1 — Symbols and units

Symbol	Description	Unit
a	centre distance	mm
B_{M1}	thermal contact coefficient of pinion	N/(m·s^{0,5}·K)
B_{M2}	thermal contact coefficient of wheel	N/(m·s^{0,5}·K)
b	face width	mm
C_{a1}	tip relief of pinion	µm
C_{a2}	tip relief of wheel	µm
C_{eff}	effective tip relief	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	—
$K_{\mathrm{H}\alpha}$	transverse load factor	—
$K_{\mathrm{H}\beta}$	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

Table 1 *(continued)*

Symbol	**Description**	**Unit**
$p_{\mathrm{dyn,Y}}$	local Hertzian contact stress including the load factors K	N/mm^2
$p_{\mathrm{H,Y}}$	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
$S_{\mathrm{GF,Y}}$	local sliding parameter	—
S_λ	safety factor against micropitting	—
$S_{\lambda,\mathrm{min}}$	minimum required safety factor against micropitting	—
T_1	nominal torque at the pinion	Nm
U_{Y}	local velocity parameter	—
u	gear ratio	—
$v_{\mathrm{g,Y}}$	local sliding velocity	m/s
VI	viscosity improver	—
$v_{\mathrm{r1,Y}}$	local tangential velocity on pinion	m/s
$v_{\mathrm{r2,Y}}$	local tangential velocity on wheel	m/s
$v_{\Sigma,\mathrm{C}}$	sum of tangential velocities at pitch point	m/s
$v_{\Sigma,\mathrm{Y}}$	sum of tangential velocities at point Y	m/s
W_{W}	material factor	—
W_{Y}	local load parameter	—
$X_{\mathrm{but,Y}}$	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	°
$\alpha_{\theta\mathrm{B,Y}}$	pressure-viscosity coefficient at local contact temperature	m^2/N
$\alpha_{\theta\mathrm{M}}$	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	°
$\varepsilon_{\mathrm{max}}$	maximum addendum contact ratio	—
ε_α	transverse contact ratio	—
$\varepsilon_{\alpha\mathrm{n}}$	virtual contact ratio, transverse contact ratio of a virtual spur gear	—
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	—

Table 1 *(continued)*

Symbol	Description	Unit
$\eta_{\theta B,Y}$	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
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	$W/(m \cdot K)$
λ_{M2}	specific heat conductivity of wheel	$W/(m \cdot K)$
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 have to be calculated with local values)	

4 Definition of micropitting

Micropitting is a phenomenon that occurs in Hertzian type of rolling and sliding contact that operates in elastohydrodynamic or boundary lubrication regimes. Micropitting is influenced by operating conditions such as load, speed, sliding, temperature, surface topography, specific lubricant film thickness, and chemical composition of the lubricant. Micropitting is more commonly observed on materials with a high surface hardness.

Micropitting is the generation of numerous surface cracks. The cracks grow at a shallow angle to the surface forming micropits. The micropits are small relative to the size of the contact zone, typically of the order 10 µm–20 µm deep. The micropits can coalesce to produce a continuous fractured surface which appears as a dull, matte surface during unmagnified visual inspection.

Micropitting is the preferred name for this phenomenon, but it has also been referred to as grey staining, grey flecking, frosting, and peeling. Illustrations of micropitting can be found in ISO 10825.

Micropitting can arrest. However, if micropitting continues to progress, it can result in reduced gear tooth accuracy, increased dynamic loads, and noise. If it does not arrest and continues to propagate, it can develop into macropitting and other modes of gear failure.

5 Basic formulae

5.1 General

The calculation of micropitting load capacity is based on the local specific lubricant film thickness $\lambda_{GF,Y}$ in the contact area and the permissible specific lubricant film thickness λ_{GFP}.[10] It is assumed that micropitting can occur when the minimum specific lubricant film thickness $\lambda_{GF,min}$ is lower than a corresponding critical value λ_{GFP}. Both values $\lambda_{GF,min}$ and λ_{GFP} shall be calculated separately for pinion and wheel in the contact area. It has to be recognized that the determination of the minimum specific lubricant film thickness and the permissible specific lubricant film thickness have to be based on the operating parameters.

The micropitting load capacity can be determined by comparing the minimum specific lubricant film thickness with the corresponding limiting value derived from gears in service or from specific gear testing. This comparison will be expressed by the safety factor S_λ which shall be equal or higher than a minimum safety factor against micropitting $S_{\lambda,min}$.

Micropitting mainly occurs in areas of negative specific sliding. Negative specific sliding is to be found along the path of contact (see Figure 1) between points A and C on the driving gear and between points C and E on the driven gear. Considering the influences of lubricant, surface roughness, geometry of the gears, and operating conditions, the specific lubricant film thickness $\lambda_{GF,Y}$ can be calculated for every point in the field of contact.

5.2 Safety factor against micropitting, S_λ

To account for the micropitting load capacity, the safety factor S_λ according to Formula (1) is defined.

$$S_\lambda = \frac{\lambda_{GF,\,min}}{\lambda_{GFP}} \geq S_{\lambda,min} \tag{1}$$

where

$\lambda_{GF,min} = \min(\lambda_{GF,Y})$ is the minimum specific lubricant film thickness in the contact area;

$\lambda_{GF,Y}$ is the local specific lubricant film thickness (see 5.3);

λ_{GFP} is the permissible specific lubricant film thickness (see 5.4);

$S_{\lambda,min}$ is the minimum required safety factor (see 5.5).

The minimum specific lubricant film thickness is determined from all calculated local values of the specific lubricant film thickness $\lambda_{GF,Y}$ obtained by Formula (2).

5.3 Local specific lubricant film thickness, $\lambda_{\mathrm{GF,Y}}$

For the determination of the safety factor S_{λ}, the local lubricant film thickness h_{Y} according to Dowson/Higginson[5] in the field of contact has to be known and compared with the effective surface roughness.

$$\lambda_{\mathrm{GF,Y}} = \frac{h_{\mathrm{Y}}}{Ra} \tag{2}$$

where

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

$$h_{\mathrm{Y}} = 1600 \cdot \rho_{\mathrm{n,Y}} \cdot G_{\mathrm{M}}^{\;0{,}6} \cdot U_{\mathrm{Y}}^{\;0{,}7} \cdot W_{\mathrm{Y}}^{\;-0{,}13} \cdot S_{\mathrm{GF,Y}}^{\;0{,}22} \tag{4}$$

Ra	is the effective arithmetic mean roughness value;
Ra_1	is the arithmetic mean roughness value of pinion (compare ISO 6336-2);
Ra_2	is the arithmetic mean roughness value of wheel (compare ISO 6336-2);
h_{Y}	is the local lubricant film thickness;
$\rho_{\mathrm{n,Y}}$	is the normal radius of relative curvature at point Y (see Clause 10);
G_{M}	is the material parameter (see Clause 6);
U_{Y}	is the local velocity parameter (see Clause 7);
W_{Y}	is the local load parameter (see Clause 8);
$S_{\mathrm{GF,Y}}$	is the local sliding parameter (see Clause 9).

Formula (4) should be calculated in the case of Method B at the seven local points (Y) defined in 5.3 b) using the values for $\rho_{\mathrm{n,Y}}$, U_{Y}, W_{Y}, and $S_{\mathrm{GF,Y}}$ that exists at each point Y. The minimum of the seven h_{Y} ($\lambda_{\mathrm{GF,Y}}$) values shall be used in Formula (1).

Example calculations are presented in ISO/TR 15144-2.

a) **Method A**

The local specific lubricant film thickness can be determined in the complete contact area by any appropriate gear computing program. In order to determine the local specific lubricant film thickness, the load distribution, the influence of normal and sliding velocity with changes of meshing phase, and the actual service conditions shall be taken into consideration.

b) **Method B**

This method involves the assumption that the determinant local specific lubricant film thickness occurs on the tooth flank in the area of negative sliding. For simplification, the calculation of the local specific lubricant film thickness is limited to certain points on the path of contact. For this purpose, the lower point A and upper point E on the path of contact, the lower point B and upper point D of single pair tooth contact, the midway point AB between A and B, the midway point DE between D and E, as well as the pitch point C, are surveyed. Furthermore, for the calculation, two cases are differentiated: case 1 – no profile modification, case 2 – adequate profile modification according to manufacturers' experience. In case of profile modifications, lower than adequate profile modifications, case 1 has to be used. In case of too high profile modifications it is recommended to use Method A.

5.4 Permissible specific lubricant film thickness, λ_{GFP}

For the determination of the permissible specific lubricant film thickness λ_{GFP}, different procedures are applicable.

a) **Method A**

For Method A, experimental investigations or service experience relating to micropitting on real gears are used.

Running real gears under conditions where micropitting just occurs, the minimum specific lubricant film thickness can be calculated according to 5.3 a). This value is equivalent to the limiting specific lubricant film thickness which is used to calculate the micropitting load capacity.

Such experimental investigations can be performed on gears having the same design as the actual gear pair. In this case, the gear manufacturing, gear accuracy, operating conditions, lubricant, and operating temperature have to be appropriate for the actual gear box.

The cost required for this method is, in general, only justifiable for the development of new products, as well as for gear boxes where failure would have serious consequences.

Otherwise, the permissible specific lubricant film thickness λ_{GFP} can be derived from consideration of dimensions, service conditions, and performance of carefully monitored reference gears operated with the respective lubricant. The more closely the dimensions and service conditions of the actual gears resemble those of the reference gears, the more effective will be the application of such values for the purpose of design ratings or calculation checks.

b) **Method B**

The method adapted is validated by carrying out careful comparative studies of well-documented histories of a number of test gears applicable to the type, quality, and manufacture of gearing under consideration. The permissible specific lubricant film thickness λ_{GFP} is calculated from the critical specific lubricant film thickness λ_{GFT} which is the result of any standardised test method applicable to evaluate the micropitting load capacity of lubricants or materials by means of defined test gears operated under specified test conditions. λ_{GFT} is a function of the temperature, oil viscosity, base oil, and additive chemistry and can be calculated according to Formula (2) in the contact point of the defined test gears where the minimum specific lubricant film thickness is to be found and for the test conditions where the failure limit concerning micropitting in the standardised test procedure has been reached.

The test gears, as well as the test conditions (for example, the test temperature), have to be appropriate for the real gears in consideration.

Any standardised test can be used to determine the data. Where a specific test procedure is not available or required, a number of internationally available standardised test methods for the evaluation of micropitting performance of gears, lubricants, and materials are currently available. Some widely used test procedures are the FVA-FZG-micropitting test,[7] Flender micropitting test,[11] BGA-DU micropitting test,[2] and the micropitting test according to Reference [3]. Annex A provides some generalized test data (for reference only) that have been produced using the test procedure according to FVA-Information Sheet 54/7[7] where a value for λ_{GFP} can be calculated for a generalized reference allowable using Formula (A.1).

5.5 Recommendation for the minimum safety factor against micropitting, $S_{\lambda,\min}$

For a given application, adequate micropitting load capacity is demonstrated by the computed value of S_{λ} and being greater than or equal to the value $S_{\lambda,\min}$, respectively.

Certain minimum values for the safety factor shall be determined. Recommendations concerning these minimum values are made in the following, but values are not proposed.

An appropriate probability of failure and the safety factor shall be carefully chosen to meet the required reliability at a justifiable cost. If the performance of the gears can be accurately appraised through