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Calculation of load capacity of spur and helical gears —

Part 4: Calculation of tooth flank fracture load capacity

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

Partie 4: Calcul de la capacité de charge de la rupture en flanc de dent

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Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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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This document was prepared by Technical Committee ISO/TC 60, *Gears*, Subcommittee SC 2, *Gear capacity calculation*.

A list of all parts in the ISO 6336 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

This corrected version of ISO 6336-4:2019 incorporates the following corrections:

— mistakes in the formulae have been corrected.

Introduction

The ISO 6336 series consists of International Standards, Technical Specifications (TS) and Technical Reports (TR) under the general title *Calculation of load capacity of spur and helical gears* (see Table 1).

— International Standards contain calculation methods that are based on widely accepted practices and have been validated.

— Technical Specifications (TS) contain calculation methods that are still subject to further development.

— Technical Reports (TR) contain data that is informative, such as example calculations.

The procedures specified in ISO 6336-1 to ISO 6336-19 cover fatigue analyses for gear rating. The procedures described in ISO 6336-20 to ISO 6336-29 are predominantly related to the tribological behaviour of the lubricated flank surface contact. ISO 6336-30 to ISO 6336-39 include example calculations. The ISO 6336 series allows the addition of new parts under appropriate numbers to reflect knowledge gained in the future.

Requesting standardized calculations according to the ISO 6336 series without referring to specific parts requires the use of only those parts that are currently designated as International Standards (see Table 1 for listing). When requesting further calculations, the relevant part or parts of the ISO 6336 series need to be specified. Use of a Technical Specification as acceptance criteria for a specific designs need to be agreed in advance between the manufacturer and the purchaser.

Table 1 — Parts of the ISO 6336 series (status as of DATE OF PUBLICATION)

Calculation of load capacity of spur and helical gears	International Standard	Technical Specification	Technical Report
Part 1: Basic principles, introduction and general influence factors	X		
Part 2: Calculation of surface durability (pitting)	X		
Part 3: Calculation of tooth bending strength	X		
Part 4: Calculation of tooth flank fracture load capacity		X	
Part 5: Strength and quality of materials	X		
Part 6: Calculation of service life under variable load	X		
Part 20: Calculation of scuffing load capacity (also applicable to bevel and hypoid gears) — Flash temperature method *(replaces: ISO/TR 13989-1)*		X	
Part 21: Calculation of scuffing load capacity (also applicable to bevel and hypoid gears) — Integral temperature method *(replaces: ISO/TR 13989-2)*		X	
Part 22: Calculation of micropitting load capacity *(replaces: ISO/TR 15144-1)*		X	
Part 30: Calculation examples for the application of ISO 6336 parts 1, 2, 3, 5			X
Part 31: Calculation examples of micropitting load capacity *(replaces: ISO/TR 15144-2)*			X

This document provides principles for the calculation of the tooth flank fracture load capacity of cylindrical involute spur and helical gears with external teeth. The method is based on theoretical and experimental investigations (see References [9], [10], [12] and [15]) on case carburized test gears and gears from different industrial applications.

This document as a part of the ISO 6336 series includes a newly developed method for assessing the risk of tooth flank fracture, which is still subject to further development. It is published in order to gain a broader experience with the obtained results in various scopes of application. The knowledge gained will serve for further development and refinement of this document.

Tooth flank fracture is characterized by a primary fatigue crack in the region of the active contact area, initiated below the surface due to shear stresses caused by the flank contact. Failures due to tooth flank fracture are reported from different industrial gear applications and have also been observed on specially designed test gears for gear running tests. Tooth flank fracture is most often observed on case carburized gears but failures are also known for nitrided and induction hardened gears. Most of the observed tooth flank fractures occurred on the driven partner.

The basis for the calculation of the tooth flank fracture load capacity are sophisticated calculation methods based on the shear stress intensity hypothesis (SIH, see References [13] and [16]) which were transferred to a calculation method in closed form solution. With only a small set of parameters concerning gear geometry, gear material and gear load condition, a calculation of the local material exposure can be performed in order to calculate the tooth flank fracture load capacity.

It should also be understood that some aspects of this type of failure can be a complex interaction of stress fluctuations and material inhomogeneities. As an example, the presence of retained austenite in the carburized case can result in the transformation during service and its associated volumetric change can cause a minute distortion of the teeth and loss of original contact quality thereby changing the localised stress distribution. Another phenomenon is the development of localised “white etching areas” (local work hardening) which ultimately develop into crack initiation and propagation. Clearly, there is considerable research required to isolate these types of effects and the analysis of case histories is paramount to the understanding of the subject.

Calculation of load capacity of spur and helical gears —

Part 4:
Calculation of tooth flank fracture load capacity

1 Scope

This document describes a procedure for the calculation of the tooth flank fracture load capacity of cylindrical spur and helical gears with external teeth.

It is not intended to be used as a rating method in the design and certification process of a gearbox.

The formulae specified are applicable for driving as well as for driven cylindrical gears while the tooth profiles are in accordance with the basic rack specified in ISO 53. They can also be used for teeth conjugate to other racks where the actual transverse contact ratio is less than $\varepsilon_\alpha = 2{,}5$. The procedure was validated for case carburized[15] gears and the formulae of this document are only applicable to case carburized gears with specifications inside the following limits:

— Hertzian stress: 500 N/mm^2 ≤ p_H ≤ 3 000 N/mm^2;

— Normal radius of relative curvature: 5 mm ≤ ρ_red ≤ 150 mm;

— Case hardening depth at 550 HV in finished condition: 0,3 mm ≤ *CHD* ≤ 4,5 mm.

This document is not applicable for the assessment of types of gear tooth damage other than tooth flank fracture.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. 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, *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)*

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

3 Terms, definitions, symbols and abbreviated terms

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.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at http://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.2 Symbols and abbreviated terms

The symbols and abbreviated terms used in this document and their units are given in Table 2. The conversions of the units are included in the given formulae.

Table 2 — Symbols, abbreviated terms and units

Symbol	Description	Unit
A	Tolerance class which shall be according to ISO 1328-1	—
$A_{FF,CP}(y)$	Local material exposure at considered contact point	—
$A_{FF,max}$	Maximum material exposure	—
b	Face width	mm
b^*	Tooth width coordinate for contact point CP	mm
b_H	Half of the Hertzian contact width	mm
$b_{H,CP}$	Half of the Hertzian contact width at contact point CP	mm
C	Auxiliary constant	mm
c_1	Material exposure calibration factor	—
CHD	Case hardening depth at 550 HV	mm
CP	Considered local contact point CP (all parameters with index CP are defined as local values)	—
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_{CP1}	Diameter of pinion at the contact point CP	mm
d_{CP2}	Diameter of wheel at the contact point CP	mm
E_1	Modulus of elasticity of pinion	N/mm^2
E_2	Modulus of elasticity of wheel	N/mm^2
E_r	Reduced modulus of elasticity	N/mm^2
EAP	End of active profile (for driving pinion: contact point E, for driving wheel: contact point A)	—
F_t	(Nominal) Transverse tangential load at reference cylinder per mesh	N
g_α	Length of the path of contact	mm
g_{CP}	Parameter on the path of contact (distance of local contact point CP from point A)	mm
HV	Hardness	HV
HV_{core}	Core hardness	HV
$HV_{surface}$	Surface hardness	HV
K_A	Application factor	—
$K_{H\alpha}$	Transverse load factor	—
$K_{H\beta}$	Face load factor	—
$K_{material}$	Material factor	—
K_v	Dynamic factor	—
K_γ	Mesh load factor	—
$K_{\tau,per}$	Hardness conversion factor	—

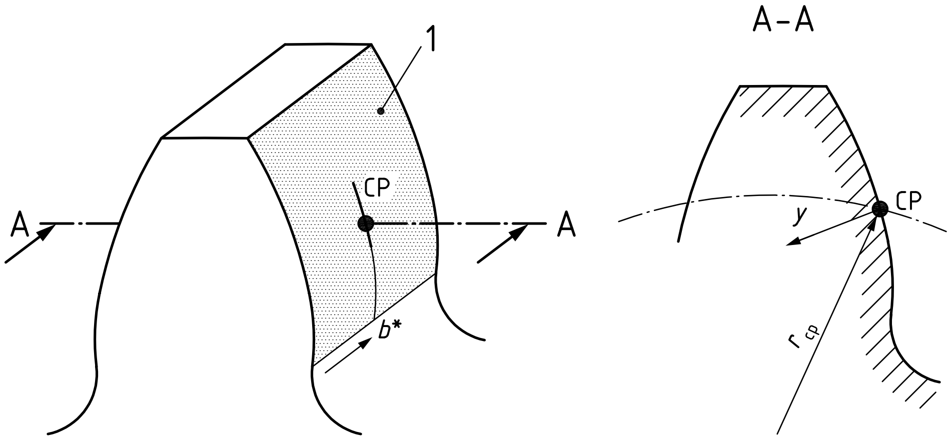
Table 2 *(continued)*

Symbol	Description	Unit
p_{dyn}	Hertzian contact stress including the load factors, K	N/mm^2
$p_{dyn,CP}$	Local Hertzian contact stress at the contact point, CP	N/mm^2
p_{et}	Transverse base pitch	mm
p_H	Nominal Hertzian contact stress	N/mm^2
r_{CP}	Local contact radius	mm
R_m	Tensile strength of the gear material (see ISO 6336-5).	N/mm^2
SAP	Start of active profile (for driving pinion: contact point A, for driving wheel: contact point E)	—
SIH	Shear stress intensity hypothesis	—
$s_{t,B-D}$	Chordal tooth thickness in transverse section at the diameter corresponding to the middle between B and D on the line of action	mm
$X_{but,CP}$	Local buttressing factor	—
X_{CP}	Local load sharing factor	—
y	Material depth (all parameters depending on y or (y) are defined as local values)	mm
y_{Core}	y-coordinate, where $HV(y) = HV_{Core}$	mm
$y_{HV,max}$	y-coordinate of the maximum hardness	mm
Z_E	Elasticity factor	(N/mm^2)^{0,5}
$\Delta\tau_{eff,L,RS,CP}(y)$	Influence of the residual stresses on the local equivalent stress	N/mm^2
α_t	Transverse pressure angle	°
α_{wt}	Working pressure angle	°
β_b	Base helix angle	°
ε_α	Transverse contact ratio	—
ε_β	Overlap ratio	—
$\rho_{t1,CP}$	Local transverse radius of curvature on the pinion	mm
$\rho_{t2,CP}$	Local transverse radius of curvature on the wheel	mm
$\rho_{red,CP}$	Local normal radius of relative curvature	mm
$\rho_{red,t,CP}$	Local transverse radius of relative curvature at the contact point CP	mm
$\sigma_{RS}(y)$	Tangential component of the residual stress	N/mm^2
$\sigma_{RS,max}$	Maximum residual stress	N/mm^2
ν_1	Poisson's ratio of the pinion	—
ν_2	Poisson's ratio of the wheel	—
$\tau_{eff,CP}(y)$	Local equivalent stress	N/mm^2
$\tau_{eff,L,CP}(y)$	Local equivalent stress without consideration of residual stresses	N/mm^2
$\tau_{eff,RS}(y)$	Quasi-stationary residual stress	N/mm^2
$\tau_{per,CP}(y)$	Local material shear strength	N/mm^2

3.3 Definition of local contact point, CP, and material depth, y

The calculation of the tooth flank fracture load capacity is carried out for defined local contact points, CP, in the area of the active tooth flank. Each local contact point, CP, is specified by the tooth width coordinate, b^*, and the tooth height coordinate, r_{CP}, (which is the local contact radius). For a specific contact point, CP, the material depth y is orientated normal to the tooth flank surface in the material and can be defined according to Figure 1. For calculation, a reasonable division of the contact area in order to define single calculation points shall be performed. Influences of tooth flank modifications on the pressure distribution shall be appropriately considered.

NOTE All parameters depending on y respectively (y) are defined as local values in the considered local contact point, CP.



Key

1 area of active tooth flank

Figure 1 — Definition of local contact point, CP, and material depth, y, depending on tooth width, b^*, and contact radius, r_{CP}

4 Definition of tooth flank fracture

Tooth flank fracture is characterized by a primary fatigue crack in the region of the active contact area, initiated below the surface due to shear stresses caused by the flank contact. Failures due to tooth flank fracture are reported from different industrial gear applications and have also been observed on specially designed test gears for gear running tests (images of tooth flank fractures can be found in Reference [9]). Tooth flank fracture is most often observed on case carburized gears but failures are also known for nitrided and induction hardened gears. Tooth flank fracture is sometimes also referred as subsurface-initiated bending fatigue crack, sub-surface fatigue or tooth flank breakage. The main failure characteristics are:

— tooth fracture is due to a crack located in the active flank area, often at approximately half the height of the tooth;

— primary crack initiation is at a considerable depth below the surface of the loaded gear flank, typically at or below the case-core interface;

— the primary crack starter is often but not always associated with a small non-metallic inclusion;

— the primary crack propagates from the initial crack starter in both directions — towards the surface of the loaded flank and into the core towards the opposite tooth root section;

— due to the high hardness in the case, the crack propagation towards the surface is smaller than through the core;

— the angle between primary crack and flank surface is approximate 40° to 50°;

— due to the inner primary crack, secondary and subsequent cracks may occur which originate from the surface;

— the crack propagation rate rapidly increases as soon as the primary crack has reached the surface of the loaded gear flank;

- the final breakage of the tooth is due to forced rupture; typically developing according to local bending stress;
- the fractured surfaces show typical fatigue characteristics with a crack lens around the initiation point and a residual zone of forced rupture;
- in many cases (but not all), no indications of surface related failures such as pitting or micropitting are observed on the gear flanks.

Due to these characteristics the failure type of tooth flank fracture can be clearly differentiated from the classical tooth root fatigue failure that is caused by tooth bending stresses in the tooth root area and also from classical pitting damage that is initiated at or close to the flank surface and characterized by shell-shaped material breakouts from the loaded flank surface. Furthermore, tooth flank fracture may occur at loads below the rated allowable loads for pitting and bending strength as well as on gears, which have completely fulfilled all the requirements regarding gear material, heat treatment and gear quality according to existing standards. Failures due to tooth flank fracture occur typically in excess of 10^7 load cycles pointing out the fatigue character of this failure type.

5 Basic formulae

5.1 General

The calculation method for tooth flank fracture load capacity is based on a local comparison of the total occurring stresses (load induced stresses and residual stresses) and the material strength for each considered point of contact and over the material depth. For the herein presented procedure, the occurring stresses are expressed by the local equivalent stress, $\tau_{\mathrm{eff,CP}}(y)$, and the material strength is described by the local material shear strength, $\tau_{\mathrm{per,CP}}(y)$. The calculation of $\tau_{\mathrm{eff,CP}}(y)$ and $\tau_{\mathrm{per,CP}}(y)$ is performed with help of an approximate calculation approach in closed form. This approach was numerically matched with sophisticated calculation methods based on the SIH (see References [10],[12],[13] and [16]) and was verified by experimental investigations and experiences from industrial application.

The quotient of the local equivalent stress, $\tau_{\mathrm{eff,CP}}(y)$, and the local material shear strength, $\tau_{\mathrm{per,CP}}(y)$, is expressed as a local material exposure, $A_{\mathrm{FF,CP}}(y)$. The local material exposure, $A_{\mathrm{FF,CP}}(y)$, should be calculated for discrete contact points, CP, in the contact area along the tooth width and tooth height and in each considered material depth, y (Method A). If there is no detailed information about the local Hertzian contact stress calculated with a 3D load distribution program, the Hertzian contact stress and the resulting material exposure can also be determined with the formulae according to Method B for some specified points of contact which shall be chosen based upon a reasonable distribution of the contact area. Influences of tooth flank modifications on the pressure distribution shall be appropriately considered.

5.2 Maximum material exposure, $A_{\mathrm{FF,max}}$

$A_{\mathrm{FF,max}}$ is the maximum calculated local material exposure, $A_{\mathrm{FF,CP}}(y)$, for all analysed contact points, CP, over the material depth, y, where y is equal to or greater than half of the Hertzian contact width, $b_{\mathrm{H,CP}}$. The material depth, y, should be chosen to ensure the maximum material exposure, $A_{\mathrm{FF,max}}$, is captured.

$$A_{\mathrm{FF,\,max}} = \max\left[A_{\mathrm{FF,CP}}\left(y\right)\right] \tag{1}$$

with

$$y \geq b_{\mathrm{H,CP}} \tag{2}$$

where

$A_{FF,max}$ is the maximum material exposure;

$A_{FF,CP}(y)$ is the local material exposure in the material depth, y, for the contact point, CP;

$b_{H,CP}$ is half of the Hertzian contact width at the contact point, CP.

$$b_{H,CP} = 4 \cdot \rho_{red,CP} \cdot \frac{p_{dyn,CP}}{E_r} \tag{3}$$

where

$p_{dyn,CP}$ is the local Hertzian contact stress at the contact point CP;

$\rho_{red,CP}$ is the local normal radius of relative curvature at the contact point CP;

E_r is the reduced modulus of elasticity.

It has been observed from experimental investigations on case carburized gears[15] that a maximum material exposure $A_{FF,max} \geq 0,8$ can lead to tooth flank fractures in the case of a constant input torque.

Currently, there is no experience to give an allowable material exposure for practical applications. The specific influences of load factors (application factor, dynamic factor, load distribution factor), and material properties are not known.

5.3 Local material exposure, $A_{FF,CP}(y)$

In good accordance to sophisticated calculation methods based on the SIH, the local material exposure, $A_{FF,CP}(y)$, can be calculated according to Formulae (4) and (5). Based on an extensive comparison between the herein shown calculation method and sophisticated calculation methods, the material exposure calibration factor, c_1, was determined for case carburized steels[15].

As tooth flank fracture is characterized by a primary fatigue crack in the region of the active contact area, initiated below the surface, only material depths deeper than half of the local Hertzian contact width, $b_{H,CP}$,shall be considered herein for evaluating the maximum local material exposure, $A_{FF,max}$. For calculated near-surface (i.e. $y < b_H$) maximum local material exposures it can be assumed that a potential damage would also start near the surface (e.g. pitting). In this case, further influences on the material exposure, for example the influence of surface roughness, lubricant and lubricating condition should be considered (see also ISO 6336-2). These influences are not covered in the herein described approach for the failure mode tooth flank fracture with crack initiation in a considerable depth below the surface.

$$A_{FF,CP}(y) = \frac{\tau_{eff,CP}(y)}{\tau_{per,CP}(y)} + c_1 \tag{4}$$

$$y \geq b_H \tag{5}$$

where

CP is the considered contact point;

y is the local material depth in the contact point, CP;

$A_{FF,CP}(y)$ is the local material exposure in the material depth, y, for the contact point, CP;

$\tau_{eff,CP}(y)$ is the local equivalent stress in the material depth, y, for the contact point, CP;

