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Calculation of load capacity of bevel gears —

Part 2:
Calculation of surface durability (macropitting)

Calcul de la capacité de charge des engrenages coniques —

Partie 2: Calcul de la résistance à la pression superficielle (macro-écaillage)

Reference number
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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 document 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*.

This third edition cancels and replaces the second edition (ISO 10300-2:2014), which has been technically revised.

The main changes are as follows:

— Table 1 has been inserted;

— Table 2 has been inserted;

— the term “pitting” has been replaced by “macropitting”;

— bevel gear factor, Z_K, for the calculation of the nominal value of the contact stress has been removed; instead, a new bevel gear factor, Z_{KP}, has been introduced for the calculation of the permissible contact stress;

— Formula (37) for the calculation of the length of action considering adjacent teeth has been modified;

— subclause 8.3 — work hardening factor, Z_W, has been updated and method A added;

— Figure 2 — load distribution in the contact area has been updated as the symbol for exponent e has been changed to e_{LS};

— Figure 6 — facewidth factor, Z_{FW} has been removed;

— Figure 7 — lubricant factor, Z_L, for mineral oils has been removed;

— Figure 8 — speed factor, Z_V has been removed;

— Figure 9 — roughness factor, Z_R has been removed;

— Figure 10 — work hardening factor, Z_W has been removed;

— former Annex A has been replaced by new Annex A describing a local calculation method for surface durability (macropitting) – Method B1-localised.

A list of all parts in the ISO 10300 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.

Introduction

When ISO 10300:2001 (all parts) became due for its first revision, the opportunity was taken to include hypoid gears, since previously the series only allowed for calculating the load capacity of bevel gears without offset axes. The former structure is retained, i.e. three parts of the ISO 10300 series, together with ISO 6336-5, and it is intended to establish general principles and procedures for rating of bevel gears. Moreover, ISO 10300 (all parts) is designed to facilitate the application of future knowledge and developments, as well as the exchange of information gained from experience.

In view of the decision for ISO 10300 (all parts) to cover hypoid gears also, a separate clause: “Gear flank rating formulae — Method B2” has been included in this document, while the former method B was renamed method B1. It became necessary to present a new, clearer structure of the three parts, which is illustrated in ISO 10300-1:2023, Figure 1.

NOTE ISO 10300 (all parts) gives no preferences in terms of when to use method B1 and when to use method B2.

This document deals with the failure of gear teeth by macropitting, a fatigue phenomenon. Two varieties of macropitting are recognized, initial and destructive macropitting.

In applications employing low hardness steel or through hardened steel, initial macropitting frequently occurs during early use and is not deemed serious. Initial macropitting is characterized by small pits which do not extend over the entire facewidth or profile depth of the affected tooth. The degree of acceptability of initial macropitting varies widely, depending on the gear application. Initial macropitting occurs in localized overstressed areas and tends to redistribute the load by progressively removing high contact spots. Generally, when the load has been redistributed, the macropitting stops.

In applications employing high hardness steel and case carburized steel, the variety of macropitting that occurs is usually destructive. The formulae for macropitting resistance given in this document are intended to assist in the design of bevel gears which stay free from destructive macropitting during their design lives (for additional information, see ISO/TR 22849[5]).

The basic formulae, first developed by Hertz for the contact pressure between two curved surfaces, have been modified to consider the following four items: the load sharing between adjacent teeth, the position of the centre of pressure on the tooth, the shape of the instantaneous area of contact and the load concentration resulting from manufacturing uncertainties. The Hertzian contact pressure serves as the theory for the assessment of surface durability with respect to macropitting. Although all premises for a gear mesh are not satisfied by Hertzian relations, their use can be justified by the fact that, for a gear material, the limits of the Hertzian pressure are determined on the basis of running tests with gears, which include the additional influences in the analysis of the limit values. Therefore, if the reference is within the application range, Hertzian pressure can be used to convert test gear data to gears of various types and sizes.

NOTE Contrary to cylindrical gears, where the contact is usually linear, bevel gears are generally manufactured with profile and lengthwise crowning, i.e. the tooth flanks are curved on all sides and the contact develops an elliptical pressure surface. This is taken into consideration when determining the load factors by the fact that the rectangular zone of action (in the case of spur and helical gears) is replaced by an inscribed parallelogram for method B1 and an inscribed ellipse for method B2 (see ISO 10300-1:2023, Annex A for method B1 and Annex B for method B2). The conditions for bevel gears, different from cylindrical gears in their contact, are thus taken into consideration by the face and transverse load distribution factors.

Calculation of load capacity of bevel gears —

Part 2: Calculation of surface durability (macropitting)

1 Scope

This document specifies the basic formulae for use in the determination of the surface load capacity of straight and helical (skew), Zerol and spiral bevel gears including hypoid gears, and comprises all the influences on surface durability for which quantitative assessments can be made. This document is applicable to oil lubricated bevel gears, as long as sufficient lubricant is present in the mesh at all times.

The formulae in this document are based on virtual cylindrical gears and restricted to bevel gears whose virtual cylindrical gears have transverse contact ratios of $\varepsilon_{v\alpha} < 2$. The results are valid within the range of the applied factors as specified in ISO 10300-1.

The formulae in this document are not directly applicable to the assessment of other types of gear tooth surface damage, such as plastic yielding, scratching, scuffing or any other type not specified.

NOTE This document is not applicable to bevel gears which have an inadequate contact pattern under load.

The user is cautioned that when the formulae are used for large average mean spiral angles $(\beta_{m1} + \beta_{m2})/2 > 45°$, for effective pressure angles $\alpha_e > 30°$ and/or for large facewidths $b > 13\ m_{mn}$, the calculated results of this document should be confirmed by experience.

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 701, *International gear notation — Symbols for geometrical data*

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

ISO 6336-5, *Calculation of load capacity of spur and helical gears — Part 5: Strength and quality of materials*

ISO 10300-1, *Calculation of load capacity of bevel gears — Part 1: Introduction and general influence factors*

ISO 17485, *Bevel gears — ISO system of accuracy*

ISO 23509, *Bevel and hypoid gear geometry*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 1122-1 and ISO 23509 and the following apply.

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

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

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

3.1
macropitting
material fatigue phenomenon of two meshing surfaces under load

3.2
nominal contact stress
σ_{H0}
contact stress calculated on the basis of the Hertzian theory at the critical point of load application for error-free gears loaded by a constant nominal torque

3.3
contact stress
σ_{H}
determinant contact stress at the critical point of load application including the load factors which consider static and dynamic loads and load distribution

3.4
allowable stress number (contact)
$\sigma_{H,lim}$
maximum contact stress of standardized test gears and determined at standardized operating conditions, as specified in ISO 6336-5

3.5
permissible contact stress
σ_{HP}
maximum contact stress of the evaluated gear set including all influence factors

4 Symbols, general subscripts and abbreviated terms

For the purposes of this document, the symbols given in ISO 701, ISO 17485, ISO 23509 and the following shall apply.

Table 1 — Symbols

Symbol	Description or term	Unit
A	Auxiliary factor for calculating the dynamic factor $K_{v\text{-}C}$	—
A^*	Related area for calculating the load sharing factor Z_{LS}	mm
A_m^*	Area above the middle contact line	mm
A_r^*	Area above the root contact line	mm
A_t^*	Area above the tip contact line	mm
b	Facewidth	mm
b_b	Relative base facewidth	—
C_{ZL}, C_{ZR}, C_{ZV}	Constants for determining lubricant film factors	—
d_e	Outer pitch diameter	mm
d_m	Mean pitch diameter	mm
d_v	Reference diameter of virtual cylindrical gear	mm
d_{va}	Tip diameter of virtual cylindrical gear	mm
d_{vb}	Base diameter of virtual cylindrical gear	mm
E	Modulus of elasticity, Young's modulus	N/mm^2
e_{LS}	Exponent for the load distribution along the lines of contact	—
F	Auxiliary variable for mid-zone factor	—
F_{mt}	Nominal tangential force at mid-facewidth of the reference cone	N

Table 1 *(continued)*

Symbol	Description or term	Unit
F_n	Nominal normal force	N
f	Distance from the centre of the zone of action to a contact line	mm
f_{max}	Maximum distance to middle contact line	mm
g_c	Length of contact line (method B2)	mm
g_{va}	Length of path of contact of virtual cylindrical gear in transverse section	mm
g_{van}	Relative length of action in normal section	—
g_η	Relative length of action within the contact ellipse	—
$g_{\eta I}$	Relative length of action at critical point in contact ellipse	—
$g_{\eta I\Sigma}$	Relative length of action considering adjacent teeth	—
HBW	Brinell hardness	—
K_v	Dynamic factor	—
K_A	Application factor	—
$K_{H\alpha}$	Transverse load factor for contact stress	—
$K_{H\beta}$	Face load factor for contact stress	—
k	Positive integer	—
k'	Contact shift factor	—
l_b	Length of contact line (method B1)	mm
l_{bm}	Theoretical length of middle contact line	mm
m_{et}	Outer transverse module	mm
m_{mn}	Mean normal module	mm
N_L	Number of load cycles	—
p	Peak load	N/mm
p_{max}	Maximum peak load	N/mm
p^*	Relative peak load for calculating the load sharing factor (method B1)	—
p_{nb}	Relative mean normal base pitch	—
Ra	Centre line average (CLA) = AA arithmetic average roughness	µm
R_{mpt}	Relative mean back cone distance	—
Rz	Mean peak-to-valley roughness	µm
Rz_H	Equivalent roughness	µm
Rz_{10}	Mean roughness for gear pairs with relative curvature radius ρ_{rel} = 10 mm	µm
r_{va}	Relative mean virtual tip radius	—
r_{vn}	Relative mean virtual pitch radius	—
S_H	Safety factor for contact stress (against macropitting)	—
$S_{H,min}$	Minimum safety factor for contact stress	—
u	Gear ratio of bevel gear	—
V	Ratio of maximum load over the middle contact line and total load	—
v_g	Sliding velocity in the mean point P	m/s
$v_{g,par}$	Sliding velocity parallel to the contact line	m/s
$v_{g,vert}$	Sliding velocity vertical to the contact line	m/s
v_{mt}	Tangential speed at mid-facewidth of the reference cone	m/s
v_w	Circumferential velocity at the pitch line	m/s
v_Σ	Sum of velocities in the mean point P	m/s
$v_{\Sigma h}$	Sum of velocities in profile direction	m/s
$v_{\Sigma l}$	Sum of velocities in lengthwise direction	m/s

Table 1 *(continued)*

Symbol	Description or term	Unit
$v_{\Sigma s}$	Sum of velocities in lengthwise direction	m/s
$v_{\Sigma,vert}$	Sum of velocities vertical to the contact line	m/s
w	Angle of contact line relative to the root cone	°
w_t	Surface velocity	m/s
$w_{t,h}$	Surface velocity in profile direction	m/s
$w_{t,s}$	Surface velocity in lengthwise direction	m/s
$w_{t,vert}$	Surface velocity vertical to the contact line	m/s
X	Intermediate value	—
Z_i	Inertia factor (macropitting)	—
Z_v	Speed factor	—
Z_A	Contact stress adjustment factor (method B2)	—
Z_E	Elasticity factor	$(N/mm^2)^{1/2}$
Z_{FW}	Facewidth factor	—
Z_{Hyp}	Hypoid factor	—
Z_I	Macropitting resistance geometry factor (method B2)	—
Z_{KP}	Bevel gear factor (method B1)	—
Z_L	Lubricant factor	—
Z_{LS}	Load sharing factor (method B1)	—
Z_{M-B}	Mid-zone factor	—
Z_{NT}	Life factor (macropitting)	—
Z_R	Roughness factor for contact stress	—
Z_S	Bevel slip factor	—
Z_W	Work hardening factor	—
Z_X	Size factor	—
z	Number of teeth	—
z_v	Number of teeth of virtual cylindrical gear	—
α_L	Normal pressure angle at point of load application (method B2)	°
α_a	Adjusted pressure angle (method B2)	°
α_{an}	Normal pressure angle at tooth tip	°
$\alpha_{eD,C}$	Effective pressure angle for drive side/coast side	°
α_{lim}	Limit pressure angle	°
$\alpha_{nD,C}$	Generated pressure angle for drive side/coast side	°
α_{vet}	Transverse pressure angle of virtual cylindrical gears	°
β_B	Inclination angle of contact line	°
β_{bm}	Mean base spiral angle	°
β_m	Mean spiral angle	°
ε_{NI}	Load sharing ratio for macropitting (method B2)	—
ζ_R	Pinion offset angle in root plane	°
ζ_{vert}	Slip vertical to the contact line	°
λ	Adjustment angle for contact angle of hypoid gears (method B2)	°
λ_r	Adjustment angle for virtual spiral angle of hypoid gears (method B2)	°
ρ	Density of gear material	kg/mm^3
ρ_{rel}	Local equivalent radius of curvature vertical to contact line	mm
ρ_t	Relative radius of profile curvature between pinion and wheel (method B2)	—

Table 1 *(continued)*

Symbol	Description or term	Unit
$\rho_{\Delta \text{red}}$	Relative radius of curvature change	—
$\rho_{\Delta 1,2}$	Relative radius of curvature difference between point of load application and mean point	—
Σ	Shaft angle	°
σ_{H}	Contact stress	N/mm^2
$\sigma_{\text{H,lim}}$	Allowable stress number for contact stress	N/mm^2
σ_{HP}	Permissible contact stress	N/mm^2
ν	Poisson's ratio	—
ν_{40}, ν_{50}	Nominal kinematic viscosity of the oil at 40 °C and 50 °C respectively	mm^2/s
ω_{wt}	Angle between surface velocity in lengthwise and profile direction	°
ω_{Σ}	Inclination angle of the sum of velocities vector results	°

Table 2 — General subscripts

Subscripts	Description
0	Tool
1	Pinion
2	Wheel
A, B, B1, B2, C	Value according to method A, B, B1, B2 or C
D	Drive flank
C	Coast flank
T	Relative to standardized test gear dimensions
(1), (2)	Trials of interpolation

Table 3 — Abbreviated terms

Abbreviated term	Material	Type
St	Normalized low carbon steels/cast steels	Wrought normalized low carbon steels
St (cast.)		Cast steels
GTS (perl.)	Cast iron materials	Black malleable cast iron (perlitic structure)
GGG (perl., bai., ferr.)		Nodular cast iron (perlitic, bainitic, ferritic structure)
GG		Grey cast iron
V	Through hardened wrought steels	Carbon steels, alloy steels
V (cast)	Through hardened cast steels	Carbon steels, alloy steels
Eh	Case-hardened wrought steels	
IF	Flame or induction hardened wrought or cast steels	
NT (nitr.)	Nitrided wrought steels/nitriding steels/ through hardening steels, nitrided	Nitriding steels
NV (nitr.)		Through hardening steels
NV (nitrocar.)	Wrought steels, nitrocarburized	Through hardening steels

5 Macropitting damage — General aspects

5.1 Acceptable versus unacceptable macropitting

When limits of the surface durability of the meshing flanks are exceeded, particles break out of the flank, thus leaving pits. This damage is called pitting, also known as macropitting. The extent, to which such pits may be tolerated, in terms of their size and number, varies within wide limits which depend largely on the field of application. In some fields, extensive macropitting is acceptable; in others, no macropitting is acceptable. The descriptions in 5.2 and 5.3 are relevant to average working conditions and give guidelines to distinguish between initial and destructive, and acceptable and unacceptable macropitting varieties.

A linear or progressive increase in the total area of pits (linear or progressive macropitting) is generally considered to be unacceptable. However, it is possible that the effective tooth bearing area is enlarged by initial macropitting, and the rate of pit generation subsequently decreases (degressive macropitting), or even ceases (arrested macropitting), and then may be considered tolerable. Nevertheless, where there is dispute over the acceptability of macropitting the next subclause shall be determinant.

5.2 Assessment requirements

Macropitting involving the formation of pits which increase linearly or progressively with time under unchanged service conditions shall be unacceptable. Damage assessment shall include the entire active area of all the tooth flanks. The number and size of newly developed pits in unhardened tooth flanks shall be taken into consideration. Pits are frequently formed on just one, or only a few, of the surface hardened gear tooth flanks. In such circumstances, assessment shall be centred on the flanks actually pitted.

Teeth suspected of being especially at risk should be marked for critical examination if a quantitative evaluation is required.

In special cases, it is possible that a first, rough assessment can be based on considerations of the entire quantity of wear debris. But in critical cases, the condition of the flanks should be examined at least three times. The first time, however, the examination should take place only after at least 10^6 cycles of load. Depending on the results of previous examinations, further ones should be carried out after a period of service.

When deterioration caused by macropitting is such that it puts human life in danger, or poses a risk of other grave consequences, the macropitting shall not be tolerated. Due to stress concentration effects, a pit of 1 mm in diameter near the fillet of a through hardened or case-hardened gear tooth can become the origin of a crack which can lead to tooth breakage; for this reason, such a pit shall be considered unacceptable (for example, in aerospace transmissions).

Similar considerations should be taken into account in respect of turbine gears. In general, during the long life (10^{10} to 10^{11} cycles) demanded of these gears, neither macropitting nor unduly severe wear should be considered acceptable as such damage can lead to unacceptable vibrations and excessive dynamic loads. Appropriately generous safety factors should be included in the calculation: only a low probability of failure shall be tolerated.

In contrast, macropitting on the operating flanks may be tolerated for some slow speed industrial gears with large teeth (e.g. module 25) made from low hardness steel, which can safely transmit the rated power for 10 years to 20 years. Individual pits can be up to 20 mm in diameter and 0,8 mm deep. The apparently “destructive macropitting”, which occurs during the first two or three years of service, normally slows down. In such cases, the tooth flanks become smoothed and work hardened to the extent of increasing the surface Brinell hardness number by 50 % or more. For such conditions, relatively low safety factors (in some, less than 1) may be chosen, with a correspondingly higher probability of tooth surface damage. However, a high safety factor against tooth breakage shall be chosen.

5.3 General rating procedure

There are two main methods for rating the surface durability of bevel and hypoid gears: method B1 and method B2. They are provided in Clause 6 and Clause 7, while Clause 8 contains those influence factors which are equal for both. Although methods B1 and B2 use the same basis of calculation, the calculation procedure is unique to each method.

With both methods, the capability of a gear tooth to resist macropitting shall be determined by the comparison of the following stress values:

— contact stress, σ_H, based on the geometry of the tooth, the accuracy of its manufacture, the rigidity of the gear blanks, bearings and housing, and the operating torque, expressed by the contact stress Formulae (1) and (20) (see 6.1 and 7.1);

— permissible contact stress, σ_{HP}, based on the endurance limit for contact stress, $\sigma_{H,lim}$, and the effect of the operating conditions under which the gears operate, expressed by the permissible contact stress Formulae (4) and (22) (see 6.2 and 7.2).

The ratio of the permissible contact stress and the calculated contact stress is the safety factor S_H. The value of the minimum safety factor for contact stress, $S_{H,min}$, should be 1,0. For further recommendations on the choice of this safety factor and other minimum values, see ISO 10300-1.

The gear designer and customer should agree on the value of the minimum safety factor.

Information on a local calculation method based on method B1 can be found in Annex A.

6 Gear flank rating formulae — Method B1

6.1 Contact stress formula

The calculation of macropitting resistance is based on the contact (Hertzian) stress, in which the load is distributed along the lines of contact (see ISO 10300-1:2023, Annex A). Calculations shall be carried out for pinion and wheel together; however, in case of different pressure angles of drive and coast side (hypoid gears, asymmetric bevel gears) separately for drive and coast side flank.

$$\sigma_{H-B1} = \sigma_{H0-B1} \cdot \sqrt{K_A \cdot K_v \cdot K_{H\beta} \cdot K_{H\alpha}} \le \sigma_{HP-B1} \tag{1}$$

with load factors K_A, K_v, $K_{H\beta}$, $K_{H\alpha}$ as specified in ISO 10300-1.

The nominal value of the contact stress is given by Formula (2):

$$\sigma_{H0-B1} = \sqrt{\frac{F_n}{l_{bm} \cdot \rho_{rel}}} Z_{M-B} \cdot Z_{LS} \cdot Z_E \tag{2}$$

where F_n is the nominal normal force of the virtual cylindrical gear at mean point P according to Formula (3):

$$F_n = \frac{F_{mt1}}{\cos\alpha_n \cdot \cos\alpha_{m1}} \tag{3}$$

where

$\alpha_n = \alpha_{nD}$	is the generated pressure angle for drive side in accordance with ISO 23509;
$\alpha_n = \alpha_{nC}$	is the generated pressure angle for coast side in accordance with ISO 23509;
l_{bm}	is the length of contact line in the middle of the zone of action as specified in ISO 10300-1:2023, A.2.7;