BSI Standards Publication

Calculation of load capacity of spur and helical gears

Part 21: Calculation of scuffing load capacity (also applicable to bevel and hypoid gears) — Integral temperature method

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National foreword

This Published Document is the UK implementation of ISO/TS 6336-21:2017. It supersedes BS ISO/TR 13989-2:2000, which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee MCE/5/-/6, Calculation of gear performance.

A list of organizations represented on this committee can be obtained on request to its secretary.

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Published by BSI Standards Limited 2017

ISBN 978 0 580 98181 4

ICS 21.200

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This Published Document was published under the authority of the Standards Policy and Strategy Committee on 31 December 2017.

Amendments/corrigenda issued since publication

Date	Text affected

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TECHNICAL SPECIFICATION

ISO/TS 6336-21

First edition
2017-11-16

Calculation of load capacity of spur and helical gears —

Part 21: Calculation of scuffing load capacity (also applicable to bevel and hypoid gears) — Integral temperature method

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

Partie 21: Calcul de la capacité de charge au grippage (applicable également aux engrenages conique et hypoïde) - Méthode de la température intégrale

Reference number
ISO/TS 6336-21:2017(E)

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Ch. de Blandonnet 8 • CP 401
CH-1214 Vernier, Geneva, Switzerland
Tel. +41 22 749 01 11
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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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For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

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

This first edition of ISO/TS 6336-21 cancels and replaces ISO/TR 13989-2.

A list of all parts in the ISO 6336 series can be found on the ISO website. See also the Introduction for an overview.

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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.

— TS contain calculation methods that are still subject to further development.

— 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 ISO 6336 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 ISO 6336 need to be specified. Use of a Technical Specification as acceptance criteria for a specific design needs to be agreed in advance between manufacturer and purchaser.

Table 1 — Overview of ISO 6336

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 6336-1, ISO 6336-2, ISO 6336-3 and ISO 6336-5			X
Part 31: Calculation examples of micropitting load capacity (Replaces: ISO/TR 15144-2)			X
At the time of publication of this document, some of the parts listed here were under development. Consult the ISO website.			

This document describes the surface damage "warm scuffing" for cylindrical (spur and helical), bevel and hypoid gears for generally used gear materials and different heat treatments. "Warm scuffing" is characterized by typical scuffing and scoring marks, which can lead to increasing power loss, dynamic load, noise and wear. For "cold scuffing", generally associated with low temperature and low speed, under approximately 4 m/s, and through-hardened, heavily loaded gears, the formulae are not suitable.

There is a particularly severe form of gear tooth surface damage in which seizure or welding together of areas of tooth surfaces occurs due to absence or breakdown of a lubricant film between the contacting tooth flanks of mating gears caused by high temperature and high pressure. This form of damage is

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termed "scuffing" and most relevant when surface velocities are high. Scuffing may also occur for relatively low sliding velocities when tooth surface pressures are high enough, either generally or, because of uneven surface geometry and loading, in discrete areas.

Risk of scuffing damage varies with the properties of gear materials, the lubricant used, the surface roughness of tooth flanks, the sliding velocities and the load. Excessive aeration or the presence of contaminants in the lubricant such as metal particles in suspension, also increases the risk of scuffing damage. Consequences of the scuffing of high speed gears include a tendency to high levels of dynamic loading due to increase of vibration, which usually leads to further damage by scuffing, pitting or tooth breakage.

High surface temperatures due to high surface pressures and sliding velocities can initiate the breakdown of lubricant films. On the basis of this hypothesis, two approaches to relate temperature to lubricant film breakdown are presented:

— the flash temperature method (presented in ISO/TS 6336-20), based on contact temperatures which vary along the path of contact;

— the integral temperature method (presented in this document), based on the weighted average of the contact temperatures along the path of contact.

The integral temperature method is based on the assumption that scuffing is likely to occur when the mean value of the contact temperature (integral temperature) is equal to or exceeds a corresponding critical value. The risk of scuffing of an actual gear unit can be predicted by comparing the integral temperature with the critical value, derived from a gear test for scuffing resistance of lubricants. The calculation method takes account of all significant influencing parameters, i.e. the lubricant (mineral oil with and without EP-additives, synthetic oils), the surface roughness, the sliding velocities, the load, etc.

In order to ensure that all types of scuffing and comparable forms of surface damage due to the complex relationships between hydrodynamical, thermodynamical and chemical phenomena are dealt with, further methods of assessment may be necessary. The development of such methods is the objective of ongoing research.

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Calculation of load capacity of spur and helical gears —

Part 21: Calculation of scuffing load capacity (also applicable to bevel and hypoid gears) — Integral temperature method

1 Scope

This document specifies the integral temperature method for calculating the scuffing load capacity of cylindrical, bevel and hypoid gears.

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

ISO 1122-2, *Vocabulary of gear terms — Part 2: Definitions related to worm gear 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 10300-1, *Calculation of load capacity of bevel gears — Part 1: Introduction and general influence factors*

3 Terms, definitions, symbols and units

3.1 Terms and definitions

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

ISO and IEC maintain terminological 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/

3.2 Symbols and units

The symbols used in this document are given in Table 2.

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Table 2 — Symbols and units

Symbol	Description	Unit
a	centre distance	mm
a_v	virtual centre distance of virtual cylindrical gear	mm
b	face width, smaller value of pinion or wheel	mm
b_{eB}	effective facewidth for scuffing	mm
c_v	specific heat capacity per unit volume	N/(mm^2·K)
c'	single stiffness	N/(mm·µm)
c_γ	mesh stiffness	N/(mm·µm)
d	reference circle diameter	mm
d_{Na}	effective tip diameter	mm
d_a	tip diameter	mm
d_b	base diameter	mm
d_m	diameter at mid-facewidth	mm
d_s	reference circle of virtual crossed axes helical gear	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
$g_{an1,2}$	recess path of contact of pinion, wheel	mm
$g_{fn1,2}$	approach path of contact of pinion, wheel	mm
g^*	sliding factor	—
h_{am}	addendum at mid-facewidth of hypoid gear	mm
m	module	mm
m_{mn}	normal module of hypoid gear at mid-facewidth	mm
m_{sn}	normal module of virtual crossed axes helical gear	mm
n_p	number of meshing gears	—
p_{en}	normal base pitch	mm
u	gear ratio	—
u_v	gear ratio of virtual cylindrical gear	—
v	reference line velocity	m/s
$v_{tl,2}$	tangential velocity of pinion, wheel of hypoid gear	m/s
$v_{g\gamma l}$	maximum sliding velocity at tip of pinion	m/s
v_{gs}	sliding velocity at pitch point	m/s
$v_{g1,2}$	sliding velocity	m/s
$v_{g\alpha 1}$	sliding velocity	m/s

Subscripts:

1 pinion

2 wheel

a tip diameter of the virtual gear

b base circle of the virtual gear

m mid-facewidth of bevel or hypoid gears

n normal section

s virtual crossed axes helical gear

t tangential direction

T test gear

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Symbol	Description	Unit
$v_{g\beta 1}$	sliding velocity	m/s
v_{mt}	tangential speed at reference cone at mid-facewidth of bevel gear	m/s
$v_{\Sigma C}$	sums of tangential speeds at pitch point	m/s
$v_{\Sigma s}$	tangential speed	m/s
$v_{\Sigma h}$	tangential speed	m/s
w_{Bt}	specific tooth load, scuffing	N/mm
z	number of teeth	—
z_v	number of teeth of virtual cylindrical gear	—
B_M	thermal contact coefficient	$N/(mm \cdot s^{1/2} \cdot K)$
C_1, C_2, C_{2H}	weighting factors	—
C_a	nominal tip relief	µm
C_{eff}	effective tip relief	µm
E	module of elasticity (Young's modulus)	N/mm^2
F_{mt}	nominal tangential load at reference cone at mid-facewidth	N
F_n	normal tooth load	N
F_t	nominal tangential load at reference circle	N
K_A	application factor	—
K_v	dynamic factor	—
$K_{B\alpha}$	$= K_{H\alpha}$ transverse load factor (scuffing)	—
$K_{B\beta}$	$= K_{H\beta}$ face load factor (scuffing)	—
$K_{B\gamma}$	helical load factor (scuffing)	—
$K_{B\beta be}$	bearing factor	—
$K_{H\alpha}$	transverse load factor	—
$K_{H\beta}$	face load factor	—
$K_{H\beta be}$	bearing factor	—
L	contact parameter	—
R_a	arithmetic mean roughness	µm
S_{intS}	scuffing safety factor	—
S_{Smin}	minimum required scuffing safety factor	—
T_1	torque of the pinion	Nm
T_{1T}	scuffing torque of test pinion	Nm
X_{BE}	geometry factor at pinion tooth tip	—
X_E	run-in factor	—
X_{Ca}	tip relief factor	—

Subscripts:

1 pinion

2 wheel

a tip diameter of the virtual gear

b base circle of the virtual gear

m mid-facewidth of bevel or hypoid gears

n normal section

s virtual crossed axes helical gear

t tangential direction

T test gear

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Symbol	Description	Unit
X_G	geometry factor of hypoid gears	—
X_L	lubricant factor	—
X_M	thermal flash factor	—
X_Q	approach factor	—
X_R	roughness factor	—
X_S	lubrication factor	—
X_W	welding factor of executed gear	—
X_{WT}	welding factor of test gear	—
X_{WrelT}	relative welding factor	—
X_{mp}	contact factor	—
$X_{\alpha\beta}$	pressure angle factor	—
X_ε	contact ratio factor	—
α	pressure angle	°
α_{mn}	normal pressure angle at mid-facewidth of hypoid gear	°
α_n	normal pressure angle	°
α_{sn}	normal pressure angle of crossed axes helical gear	°
α_{st}	transverse pressure angle of crossed axes helical gear	°
α_t	transverse pressure angle	°
α_t'	transverse working pressure angle	°
α_{vt}	transverse pressure angle of virtual cylindrical gear	°
α_y	arbitrary angle	°
β	helix angle	°
β_b	helix angle at base circle	°
β_m	helix angle at reference cone at mid-facewidth of hypoid gear	°
β_s	helix angle of virtual crossed axes helical gear	°
γ	auxiliary angle	°
δ	reference cone angle	°
ε_a	recess contact ratio	—
ε_f	approach contact ratio	—
ε_n	contact ratio in normal section of virtual crossed axes helical gear	—
ε_1	addendum contact ratio of the pinion	—
ε_2	addendum contact ratio of the wheel	—
ε_α	contact ratio	—
$\varepsilon_{v\alpha}$	transverse contact ratio of virtual cylindrical gear	—

Subscripts:

1 pinion

2 wheel

a tip diameter of the virtual gear

b base circle of the virtual gear

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n normal section

s virtual crossed axes helical gear

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T test gear

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Symbol	Description	Unit
ε_{v1}	tip contact ratio of virtual cylindrical pinion	—
ε_{v2}	tip contact ratio of virtual cylindrical wheel	—
ξ	Hertzian auxiliary coefficient	—
μ_{mC}	mean coefficient of friction	—
η_{oil}	dynamic viscosity at oil temperature	mPa · s
λ_M	heat conductivity	N/(s · K)
ν	Poisson's ratio	—
ν_{40}	kinematic viscosity of the oil at 40 °C	mm^2/s; cSt
$\rho_{E1,2}$	radius of curvature at tip of the pinion, wheel	mm
ρ_{Cn}	relative radius of curvature at pitch point in normal section	mm
$\rho_{n1,2}$	radius of curvature at pitch point in normal section	mm
ρ_{redC}	relative radius of curvature at pitch point	mm
η	Hertzian auxiliary coefficient	—
ϑ	Hertzian auxiliary angle	°
ϑ_{flaE}	flash temperature at pinion tooth tip when load sharing is neglected	K
ϑ_{flaint}	mean flash temperature	K
$\vartheta_{flainth}$	mean flash temperature of hypoid gear	K
ϑ_{int}	integral temperature	K
ϑ_{intP}	permissible integral temperature	K
ϑ_{intS}	scuffing integral temperature (allowable integral temperature)	K
$\vartheta_{flaintT}$	mean flash temperature of the test gear	K
ϑ_{oil}	oil sump or spray temperature	°C
$\vartheta_{M\text{-}C}$	bulk temperature	°C
ϑ_{MT}	test bulk temperature	°C
φ	axle angle of virtual crossed axes helical gear	°
Σ	crossing angle of virtual crossed axes helical gear	°
φ_E	run-in grade	—
Γ	parameter on the line of action	—

Subscripts:

1 pinion

2 wheel

a tip diameter of the virtual gear

b base circle of the virtual gear

m mid-facewidth of bevel or hypoid gears

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4 Field of application

4.1 General

The calculation methods are based on results of the rig testing of gears run at pitch line velocities less than 80 m/s. The formulae can be used for gears which run at higher speeds, but with increasing uncertainty as speed increases. The uncertainty concerns the estimation of bulk temperature, coefficient of friction, allowable temperatures, etc. as speeds exceed the range with experimental background.

4.2 Scuffing damage

When once initiated, scuffing damage can lead to gross degradation of tooth flank surfaces, with increase of power loss, dynamic loading, noise and wear. It can also lead to tooth breakage if the severity of the operating conditions is not reduced. In the event of scuffing due to an instantaneous overload, followed immediately by a reduction of load, e.g. by load redistribution, the tooth flanks may self-heal by smoothing themselves to some extent. Even so, the residual damage will continue to be a cause of increased power loss, dynamic loading and noise.

In most cases, the resistance of gears to scuffing can be improved by using a lubricant with enhanced extreme pressure (E.P.) properties. It is important, however, to be aware that some disadvantages attend the use of E.P. oils, e.g corrosion of copper, embrittlement of elastomers, lack of world-wide availability, etc. These disadvantages are to be taken into consideration if optimum lubricant choice is to be made, which means as few additive as possible, as much as necessary.

Due to continuous variation of different parameters, the complexity of the chemical properties and the thermo-hydro-elastic processes in the instantaneous contact area, some scatter in the calculated assessments of probability of scuffing risk, is to be expected.

In contrast to the relatively long time of development of fatigue damage, one single momentary overload can initiate scuffing damage of such severity that affected gears may no longer be used. This should be carefully considered when choosing an adequate safety factor for gears, especially for gears required to operate at high circumferential velocities.

4.3 Integral temperature criterion

This approach to the evaluation of the probability of scuffing, is based on the assumption that scuffing is likely to occur when the mean value of the contact temperatures along the path of contact is equal to or exceeds a corresponding "critical value". In the method presented herein, the sum of the bulk temperature and the weighted mean of the integrated values of flash temperatures along the path of contact is the "integral temperature". The bulk temperature is estimated as described under 6.1.6 and the mean value of the flash temperature is approximated by substituting mean values of the coefficient of friction, the dynamic loading, etc., along the path of contact. A weighting factor is introduced, accounting for possible different influences of a real bulk temperature value and a mathematically integrated mean flash temperature value on the scuffing phenomenon.

The probability of scuffing is assessed by comparing the integral temperature with a corresponding critical value derived from the gear testing of lubricants for scuffing resistance (e.g. different FZG test procedures, the IAE and the Ryder gear tests) or from gears which have scuffed in service.

5 Influence factors

5.1 Mean coefficient of friction, μ_{mC}

The actual coefficient of friction between the tooth flanks is an instantaneous and local value which depends on several properties of the oil, surface roughness, lay of the surface irregularities such as those left by machining, properties of the tooth flank materials, tangential velocities, forces at the

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surfaces and the dimensions. Assessment of the instantaneous coefficient of friction is difficult since there is no method currently available for its measurement.

The mean value for the coefficient of friction, μ_{mC}, along the path of contact was derived from measurements[4] and approximated by Formula (1). Although the local coefficient of friction is near to zero in the pitch point C, the mean value can be approximated with the parameters at the pitch point and the oil viscosity, η_{oil}, at oil temperature, ϑ_{oil}, when introduced into Formula (1).

$$\mu_{mC} = 0{,}045 \cdot \left(\frac{w_{Bt} \cdot K_{B\gamma}}{v_{\Sigma C} \cdot \rho_{redC}} \right)^{0{,}2} \cdot \eta_{oil}^{-0{,}05} \cdot X_R \cdot X_L \tag{1}$$

NOTE Formula (1) is derived from testing of gears with centre distance $a \approx 100$ mm.

The coefficient of friction of the integral temperature method takes account of the size of the gear in a different way as the coefficient of friction of the flash temperature method. Formula (1) for calculating the coefficient of friction should not be applied outside the field of the part where it is presented, e.g. coefficient of friction for thermal rating.

$$\mu_{mc} = 0{,}048 \cdot \left(\frac{F_{bt} / b}{v_{\Sigma C} \cdot \rho_{redC}} \right)^{0{,}2} \cdot \eta_{oil}^{-0{,}05} \cdot R_a^{0{,}25} \cdot X_L \tag{2}$$

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where

X_L is $0{,}75 \cdot \left(\frac{6}{v_{\Sigma C}}\right)^{0{,}2}$ 1 for polyglycols;

X_L is 1,0 for mineral oils;

X_L is 0,8 for polyalfaolefins;

X_L is 1,5 for traction fluids;

X_L is 1,3 for phosphate esters.

Formula (2) represents results of tests within a range of a = 91,5 mm to 200 mm. The application of this formula makes it necessary to adjust Figures 9, 10 and 11 for the scuffing temperature, ϑ_{intS}, accordingly.

The formula for the calculation of μ_{mC} was derived from experiments in the following range of operating conditions. Extrapolation may lead to deviations between the calculated and the real coefficient of friction.

$1\ \text{m/s} \leq v \leq 50\ \text{m/s}$

At reference line velocities, v, lower than 1 m/s, higher coefficients of friction are expected. At reference line velocities, v, higher than 50 m/s, the limiting value of $v_{\Sigma C}$ at v = 50 m/s has to be used in Formula (1).

$w_{Bt} \geq 150\ \text{N/mm}$

For lower values of the specific normal tooth load, w_{Bt}, the limiting value, w_{Bt} = 150 N/mm, has to be used in Formula (1).

$$v_{\Sigma C} = 2 \cdot v \cdot \tan_{\alpha_{t'}} \cdot \cos_{\alpha_t} \tag{3}$$

$$\rho_{redC} = \frac{u}{(1+u)^2} \cdot a \cdot \frac{\sin \alpha_{t'}}{\cos \beta_b} \tag{4}$$

$$w_{Bt} = K_A \cdot K_v \cdot K_{B\beta} \cdot K_{B\alpha} \cdot \frac{F_t}{b} \tag{5}$$

$K_{B\gamma}$ is the helical load factor. Scuffing takes account of increasing friction for increasing total contact ratio (see Figure 1).

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