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Calculation of load capacity of spur and helical gears -- Part 5: Strength and quality of materials

Calcul de la capacité de charge des engrenages cylindriques à dentures droite et hélicoïdale -- Partie 5: Résistance et qualité des matériaux

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Calculation of load capacity of spur and helical gears —

Part 5: Strength and quality of materials

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

Partie 5: Résistance et qualité des matériaux

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ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.org
Web www.iso.org

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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.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 6336-5 was prepared by Technical Committee ISO/TC 60, *Gears*, Subcommittee SC 2, *Gear capacity calculation*.

This second edition cancels and replaces the first edition (ISO 6336-5:1996), which has been technically revised.

ISO 6336 consists of the following parts, under the general title *Calculation of load capacity of spur and helical gears*:

— *Part 1: Basic principles, introduction and general influence factors*

— *Part 2: Calculation of surface durability (pitting)*

— *Part 3: Calculation of tooth bending strength*

— *Part 5: Strength and quality of materials*

Part 6, *Calculation of service life under variable load*, is under preparation.

Introduction

This part of ISO 6336, together with ISO 6336-1, ISO 6336-2 and ISO 6336-3, provides the principles for a coherent system of procedures for the calculation of the load capacity of cylindrical involute gears with external or internal teeth. ISO 6336 is designed to facilitate the application of future knowledge and developments, as well as the exchange of information gained from experience.

Allowable stress numbers, as covered by this part of ISO 6336, may vary widely. Such variation is attributable to defects and variations of chemical composition (charge), structure, the type and extent of hot working (e.g. bar stock, forging, reduction ratio), heat treatment, residual stress levels, etc.

Tables summarize the most important influencing variables and the requirements for the different materials and quality grades. The effects of these influences on surface durability and tooth bending strength are illustrated by graphs.

This part of ISO 6336 covers the most widely used ferrous gear materials and related heat treatment processes. Recommendations on the choice of specific materials, heat treatment processes or manufacturing processes are not included. Furthermore, no comments are made concerning the suitability or otherwise of any materials for specific manufacturing or heat treatment processes.

Calculation of load capacity of spur and helical gears —

Part 5: Strength and quality of materials

1 Scope

This part of ISO 6336 describes contact and tooth-root stresses, and gives numerical values for both limit stress numbers. It specifies requirements for material quality and heat treatment and comments on their influences on both limit stress numbers.

Values in accordance with this part of ISO 6336 are suitable for use with the calculation procedures provided in ISO 6336-2 and ISO 6336-3 and in the application standards for industrial, high speed and marine gears. They are applicable to the calculation procedures given in ISO 10300 for rating the load capacity of bevel gears. This part of ISO 6336 is applicable to all gearing, basic rack profiles, profile dimensions, design, etc., covered by those standards. The results are in good agreement with other methods for the range indicated in the scope of ISO 6336-1.

2 Normative references

The following referenced documents are indispensable for the application 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: 1998, *Cylindrical gears for general and heavy engineering — Standard basic rack tooth profile*

ISO 642:1999, *Steel — Hardenability test by end quenching (Jominy test)*

ISO 643:—[1)], *Steel — Micrographic determination of the ferritic or austenitic grain size*

ISO 683-1:1987, *Heat-treatable steels, alloy steels and free-cutting steels — Part 1: Direct hardening unalloyed and low alloyed wrought steel in form of different black products*

ISO 683-9:1988, *Heat-treatable steels, alloy steels and free-cutting steels — Part 9: Wrought free-cutting steels*

ISO 683-10:1987, *Heat-treatable steels, alloy steels and free-cutting steels — Part 10: Wrought nitriding steels*

ISO 683-11:1987, *Heat-treatable steels, alloy steels and free-cutting steels — Part 11: Wrought case-hardening steels*

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

1) To be published. (Revision of ISO 643:1983)

ISO 1328-1:1995, *Cylindrical gears — ISO system of accuracy — Part 1: Definitions and allowable values of deviations relevant to corresponding flanks of gear teeth*

ISO 2639:2002, *Steel — Determination and verification of the effective depth of carburized and hardened cases*

ISO 3754:1976, *Steel — Determination of effective depth of hardening after flame or induction hardening*

ISO 4948/2:1981, *Steels — Classification — Part 2: Classification of unalloyed and alloy steels according to main quality classes and main property or application characteristics*

ISO 4967:1998, *Steel — Determination of content of non-metallic inclusions — Micrographic method using standard diagrams*

ISO 6336-1:—[2)], *Calculation of load capacity of spur and helical gears — Part 1: Basic principles, introduction and general influence factors*

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

ISO 6336-3: —[2)], *Calculation of load capacity of spur and helical gears — Part 3: Calculation of tooth bending strength*

ISO 9443:1991, *Heat-treatable and alloy steels — Surface quality classes for hot-rolled round bars and wire rods — Technical delivery conditions*

ISO 10474:1991, *Steel and steel products — Inspection documents*

ISO 14104:1995, *Gears — Surface temper etch inspection after grinding*

ASTM[3)] A388-01, *Standard Practice for Ultrasonic Examination of Heavy Steel Forgings*

ASTM E428-00, *Standard Practice for Fabrication and Control of Steel Reference Blocks Used in Ultrasonic Inspection*

ASTM A609-91, *Standard Practice for Castings, Carbon, Low Alloy and Martensitic Stainless Steel, Ultrasonic Examination Thereof*

ASTM E1444-01, *Standard Practice for Magnetic Particle Examination*

3 Terms, definitions and symbols

For the purposes of this document, the terms and definitions given in ISO 1122-1 and the symbols and units given in ISO 6336-1 apply.

4 Methods for the determination of allowable stress numbers

4.1 General

Allowable stress numbers should be determined for each material and material condition, preferably by means of gear running tests. Test conditions and component dimensions should equate, as nearly as is practicable, to the operating conditions and dimensions of the gears to be rated.

2) Under preparation. (Revisions of ISO 6336-1:1996, ISO 6336-2:1996 and ISO 6336-3:1996, respectively)

3) American Society for Testing and Materials

When evaluating test results or data derived from field service, it is always necessary to ascertain whether or not specific influences on permissible stresses are already included with the evaluated data, e.g. in the case of surface durability, the effects of lubricants, surface roughness and gear geometry; in the case of tooth bending strength, the fillet radius, surface roughness and gear geometry. Where appropriate, 1,0 should be substituted for the relevant influence factor when calculating the permissible stresses.

4.2 Method A

The allowable stress numbers for contact and bending are derived from endurance tests of gears having dimensions closely similar to those of the gears to be rated, under test conditions which are closely similar to the intended operating conditions.

4.3 Method B

The allowable stress numbers for contact and bending were derived from endurance tests of reference test gears under reference test conditions. Tooth-root allowable stress numbers were also derived from pulsator tests. Practical experience should be taken into account. The standard allowable stress numbers specified in 5.2 and 5.3 are based on such tests and experience.

Three different classes, ME, MQ and ML, are given for the allowable stress numbers. The appropriate choice of class will depend, as described in Clause 6, on the type of production and quality control exercised.

4.4 Method B_k

Allowable stress numbers for bending are derived from the results of testing notched test pieces. Preferably, the ratio of the test piece notch radius to thickness should be similar to that of the fillet radius to the tooth-root chord in the critical section and the surface condition should be similar to that of the tooth root. When evaluating test data, it should be understood that test pieces are usually subjected to pure, alternating bending stress, whereas in the case of a gear tooth the fillets of the teeth are subjected to combined bending, shear and compressive stresses. Data on the various materials can be obtained from in-house testing, experience or from the literature.

4.5 Method B_p

Allowable stress numbers for bending are derived from the results of testing un-notched test pieces. See 4.4 for comments on evaluation of test results. In order to take into account the effect of notch sensitivity, it is necessary that actual notch form and notch factors be included in calculations; thus their results will be influenced by the extreme unreliability of these factors. Data on the various materials can be obtained from known test facilities or from the literature (see Bibliography).

5 Standard allowable stress numbers — Method B

5.1 Application

The allowable stress numbers shown in Figures 1 to 16 are based on the assumption that material composition, heat treatment and inspection methods are appropriately chosen for the size of the gear.

If test values for specific materials are available they can be used in replacement of the values in Figures 1 to 16.

The data furnished in this part of ISO 6336 are well substantiated by tests and practical experience.

The values are chosen for 1 % probability of damage. Statistical analysis enables adjustment of these values in order to correspond to other probabilities of damage.

When other probabilities of damage (reliability) are desired, the values of $\sigma_{\mathrm{H\,lim}}$, $\sigma_{\mathrm{F\,lim}}$, and σ_{FE} are adjusted by an appropriate "reliability factor". When this adjustment is made, a subscript shall to be added to indicate the relevant percentage (e.g. $\sigma_{\mathrm{H\,lim10}}$ for 10 % probability of damage).

The allowable stress numbers indicated in Figures 9 and 10 were derived for effective case depths of about $0{,}15m_{\mathrm{n}}$ to $0{,}2m_{\mathrm{n}}$ on finish-machined gears.

The extent to which the level of surface hardness influences the strength of contour-hardened, nitrided, carbonitrided and nitro-carburized gears, cannot be reliably specified. Other surface related factors of the material and heat treatment have a much more pronounced influence.

In some cases the full hardness range is not covered. The ranges covered are indicated by the length of the lines in Figures 1 to 16.

For surface-hardened steels (Figures 9 to 16), the HV scale was chosen as the reference axis. The HRC scale is included for comparison. To define the relationship between Vickers and Rockwell hardness numbers conversion tables are included in Annex B.

5.2 Allowable stress number (contact), $\sigma_{\mathrm{H\,lim}}$

The allowable stress number, $\sigma_{\mathrm{H\,lim}}$, is derived from a contact pressure that may be sustained for a specified number of cycles without the occurrence of progressive pitting. For some materials, 5×10^7 stress cycles are considered to be the beginning of the long-life strength range (see life factor in ISO 6336-2).

Values of $\sigma_{\mathrm{H\,lim}}$ indicated in Figures 1, 3, 5, 7, 9, 11, 13 and 15 are appropriate for the reference operating conditions and dimensions of the reference test gears, as follows[4]:

— Centre distance $a = 100$ mm

— Helix angle $\beta = 0$ ($Z_\beta = 1$)

— Module $m = 3$ mm to 5 mm ($Z_{\mathrm{x}} = 1$)

— Mean peak-to-valley roughness of the tooth flanks $Rz = 3$ µm ($Z_{\mathrm{R}} = 1$)

— Tangential velocity $v = 10$ m/s ($Z_{\mathrm{v}} = 1$)

— Lubricant viscosity $\nu_{50} = 100$ mm^2/s ($Z_{\mathrm{L}} = 1$)

— Mating gears of the same material ($Z_{\mathrm{W}} = 1$)

— Gearing accuracy grades 4 to 6 according to ISO 1328-1

— Facewidth $b = 10$ mm to 20 mm

— Load influence factors $K_{\mathrm{A}} = K_{\mathrm{v}} = K_{\mathrm{H}\beta} = K_{\mathrm{H}\alpha} = 1$

Test gears were deemed to have failed by pitting when the following conditions were met: when 2 % of the total working flank area of through hardened gears, or when 0,5 % of the total working flank area of surface hardened gears, or 4 % of the working flank area of a single tooth, is damaged by pitting. The percentages refer to test evaluations; they are not intended as limits for product gears.

4) Data obtained under different conditions of testing were adjusted to be consistent with reference conditions. It is important to note $\sigma_{\mathrm{H\,lim}}$ is not the contact pressure under continuous load, but rather the upper limit of the contact pressure derived in accordance with ISO 6336-2, which can be sustained without progressive pitting damage, for a specified number of load cycles.

5.3 Bending stress number values for $\sigma_{F\,lim}$ and σ_{FE}

5.3.1 Nominal stress numbers (bending), $\sigma_{F\,lim}$

The nominal stress number (bending), $\sigma_{F\,lim}$, was determined by testing reference test gears (see ISO 6336-3). It is the bending stress limit value relevant to the influences of the material, the heat treatment and the surface roughness of the test gear root fillets.

5.3.2 Allowable stress number (bending), σ_{FE}

The allowable stress number for bending, σ_{FE} (for definition of σ_{FE}, see ISO 6336-3), is the basic bending strength of the un-notched test piece, under the assumption that the material condition (including heat treatment) is fully elastic:

$$\sigma_{FE} = \sigma_{F\,lim} Y_{ST} \qquad (1)$$

For the reference test gear, the stress correction factor Y_{ST} = 2,0. For most materials, 3×10^6 stress cycles are considered to be the beginning of the long-life strength range (see life factor in ISO 6336-3).

Values of $\sigma_{F\,lim}$ and σ_{FE} indicated in Figures 2, 4, 6, 8, 10, 12, 14 and 16 are appropriate for the reference operating conditions and dimensions of the reference test gears, as shown below (see 5.2, Footnote 3):

— Helix angle: $\beta = 0$ ($Y_\beta = 1$)

— Module: m = 3 mm to 5 mm ($Y_X = 1$)

— Stress correction factor: Y_{ST} = 2,0

— Notch parameter: q_{ST} = 2,5 ($Y_{\delta\,rel\,T} = 1$)

— Mean peak-to-valley roughness of the tooth fillets: Rz = 10 µm ($Y_{R\,rel\,T} = 1$)

— Gearing accuracy grades: 4 to 7 according to ISO 1328-1

— Basic rack: according to ISO 53

— Facewidth: b = 10 mm to 50 mm

— Load factors: $K_A = K_v = K_{F\beta} = K_{F\alpha} = 1$

5.3.3 Reversed bending

The allowable stress numbers indicated in Figures 2, 4, 6, 8, 10, 12, 14 and 16 are appropriate for repeated, unidirectional, tooth loading. When reversals of full load occur, a reduced value of σ_{FE} is required. In the most severe case (e.g. an idler gear where full load reversal occurs each load cycle), the values $\sigma_{F\,lim}$ and σ_{FE} should be reduced to 0,7 times the unidirectional value. If the number of load reversals is less frequent than this, a different factor, depending on the number of reversals expected during the gear lifetime, can be chosen. For guidance on this, see ISO 6336-3: —[2)], Annex B.

5.4 Graphs for $\sigma_{H\,lim}$ and $\sigma_{F\,lim}$ and σ_{FE}

Allowable stress numbers for hardness values which exceed the minimum and maximum hardness values in Figures 1 to 16 are subject to agreement between manufacturer and purchaser on the basis of previous experience.

5.5 Calculation of $\sigma_{\text{H lim}}$ and $\sigma_{\text{F lim}}$

The allowable stress numbers, $\sigma_{\text{H lim}}$, and the nominal stress numbers, $\sigma_{\text{F lim}}$, can be calculated by the following equation:

$$\left.\begin{matrix}\sigma_{\text{Hlim}}\\ \sigma_{\text{Flim}}\end{matrix}\right\} = \text{A}\cdot x + \text{B} \tag{2}$$

where

x is the surface hardness HBW or HV;

A, B are constants (See Table 1).

The hardness ranges are restricted by the minimum and maximum hardness values given in Table 1.

Table 1 — Calculation of $\sigma_{\text{H lim}}$ and $\sigma_{\text{F lim}}$

No.	Material	Stress	Type	Abbre-viation	Fig.	Quality	A	B	Hard-ness	Min. hardness	Max. hardness
1	Normalized low carbon steels/cast steels [a]	contact	wrought normalized	St	1 a)	ML/MQ	1,000	190	HBW	110	210
2			low carbon steels			ME	1,520	250		110	210
3			cast steels	St	1 b)	ML/MQ	0,986	131	HBW	140	210
4				(cast)		ME	1,143	237		140	210
5		bending	wrought normalized	St	2 a)	ML/MQ	0,455	69	HBW	110	210
6			low carbon steels			ME	0,386	147		110	210
7			cast steels	St	2 b)	ML/MQ	0,313	62	HBW	140	210
8				(cast)		ME	0,254	137		140	210
9	Cast iron materials	contact	black malleable	GTS	3 a)	ML/MQ	1,371	143	HBW	135	250
10			cast iron	(perl.)		ME	1,333	267		175	250
11			nodular cast iron	GGG	3 b)	ML/MQ	1,434	211	HBW	175	300
12						ME	1,500	250		200	300
13			grey cast iron	GG	3 c)	ML/MQ	1,033	132	HBW	150	240
14						ME	1,465	122		175	275
15		bending	black malleable	GTS	4 a)	ML/MQ	0,345	77	HBW	135	250
16			cast iron	(perl.)		ME	0,403	128		175	250
17			nodular cast iron	GGG	4 b)	ML/MQ	0,350	119	HBW	175	300
18						ME	0,380	134		200	300
19			grey cast iron	GG	4 c)	ML/MQ	0,256	8	HBW	150	240
20						ME	0,200	53		175	275
21	Through hardened wrought steels [b]	contact	carbon steels	V	5	ML	0,963	283	HV	135	210
22						MQ	0,925	360		135	210
23						ME	0,838	432		135	210
24			alloy steels	V	5	ML	1,313	188	HV	200	360
25						MQ	1,313	373		200	360
26						ME	2,213	260		200	390
27		bending	carbon steels	V	6	ML	0,250	108	HV	115	215
28						MQ	0,240	163		115	215
29						ME	0,283	202		115	215
30			alloy steels	V	6	ML	0,423	104	HV	200	360
31						MQ	0,425	187		200	360
32						ME	0,358	231		200	390

Table 1 (*continued*)

No.	Material	Stress	Type	Abbreviation	Fig.	Quality	A	B	Hardness	Min. hardness	Max. hardness
33	Through hardened cast steels	contact	carbon steels	V	7	ML/MQ	0,831	300	HV	130	215
34				(cast)		ME	0,951	345		130	215
35			alloy steels	V	7	ML/MQ	1,276	298	HV	200	360
36				(cast)		ME	1,350	356		200	360
37		bending	carbon steels	V	8	ML/MQ	0,224	117	HV	130	215
38				(cast)		ME	0,286	167		130	215
39			alloy steels	V	8	ML/MQ	0,364	161	HV	200	360
40				(cast)		ME	0,356	186		200	360
41	Case hardened wrought steels [c]	contact		Eh	9	ML	0,000	1 300	HV	600	800
42						MQ	0,000	1 500		660	800
43						ME	0,000	1 650		660	800
44		bending	core hardness:	Eh	10	ML	0,000	312	HV	600	800
45			$\geqslant$ 25 HRC, lower			MQ	0,000	425		660	800
46			$\geqslant$ 25 HRC, upper				0,000	461		660	800
47			$\geqslant$ 30 HRC				0,000	500		660	800
48						ME	0,000	525		660	800
49	Flame or induction hardened wrought and cast steels	contact		IF	11	ML	0,740	602	HV	485	615
50						MQ	0,541	882		500	615
51						ME	0,505	1 013		500	615
52		bending		IF	12	ML	0,305	76	HV	485	615
53						MQ	0,138	290		500	570
54							0,000	369		570	615
55						ME	0,271	237		500	615
56	Nitrided wrought steels/nitriding steels [d] /through hardening steels [b] nitrided	contact	nitriding steels (a)	NT	13 a)	ML	0,000	1 125	HV	650	900
57				(nitr.)		MQ	0,000	1 250		650	900
58						ME	0,000	1 450		650	900
59			through hardening steels (b)	NV	13 b)	ML	0,000	788	HV	450	650
60				(nitr.)		MQ	0,000	998		450	650
61						ME	0,000	1 217		450	650
62		bending	nitriding steels (a)	NT	14 a)	ML	0,000	270	HV	650	900
63				(nitr.)		MQ	0,000	420		650	900
64						ME	0,000	468		650	900
65			through hardening steels (b)	NV	14 b)	ML	0,000	258	HV	450	650
66				(nitr.)		MQ	0,000	363		450	650
67						ME	0,000	432		450	650
68	wrought steels nitro-carburized [e]	contact	through hardening steels	NV	15	ML	0,000	650	HV	300	650
69				(nitro-		MQ/ME	1,167	425		300	450
70				car.)			0,000	950		450	650
71		bending	through hardening steels	NV	16	ML	0,000	224	HV	300	650
72				(nitro-		MQ/ME	0,653	94		300	450
73				car.)			0,000	388		450	650

[a] In accordance with ISO 4948-2.
[b] In accordance with ISO 683-1.
[c] In accordance with ISO 683-11.
[d] In accordance with ISO 683-10.
[e] In accordance with ISO 683-1, ISO 683-10 or ISO 683-11.

