TECHNICAL REPORT

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Design recommendations for bevel gears

Recommandations pour le dimensionnement d'engrenages coniques

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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.

In exceptional circumstances, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

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/TR 22849 was prepared by Technical Committee ISO/TC 60, *Gears*, Subcommittee SC 2, *Gear capacity calculation*.

Design recommendations for bevel gears

1 Scope

This Technical Report provides information for the application of bevel and hypoid gears using the geometry in ISO 23509, the capacity as determined by ISO 10300 (all parts) and the tolerances in ISO 17485.

This Technical Report provides additional information on the application, manufacturing, strength and efficiency of bevel gears for consideration in the design stage of a new bevel gear set.

The term “bevel gear” is used to mean straight, spiral, zerol bevel and hypoid gear designs. Where this Technical Report pertains to one or more, but not all, the specific forms are identified.

The manufacturing process of forming the desired tooth form is not intended to imply any specific process, but rather to be general in nature and applicable to all methods of manufacture.

This Technical Report is intended for use by an experienced gear designer capable of selecting reasonable values for the required data based on his/her knowledge and background. It is not intended for use by the engineering public at large.

2 Symbols, descriptions and units

The symbols and descriptions used in this Technical Report are, wherever possible, consistent with other International Standards on bevel gears. As a result of certain limitations, some symbols and descriptions are different than in similar literature pertaining to spur and helical gearing.

Symbol	Description	Unit
A_g	Arrangement constant	—
a_v	Centre distance of virtual cylindrical gears	mm
α_n	Generated pressure angle according to ISO 23509	°
α_{vat1}, α_{vat2}	Pressure angle at tip of virtual cylindrical gear	°
α_{vt}	Pressure angle in transverse plane of virtual cylindrical gear	°
b_{eff}	Face width in contact with mating element	mm
β_e	Outer spiral angle according to ISO 23509	—
β_{m1}, β_{m2}	Mean spiral angle	°
β_v	Spiral angle of virtual cylindrical gear	°
C_1	A constant	—
D	Outside diameter of the considered rotating element	mm
d_{ae1}, d_{ae2}	Outside diameter	mm
d_{v1}, d_{v2}	Reference diameter of virtual cylindrical gear	mm
d_{va1}, d_{va2}	Tip diameter of virtual cylindrical gear	mm
$\Delta\alpha_{t1}$, $\Delta\alpha_{t2}$	Change in pressure angle from pitch point to outside	°
δ_{a1}, δ_{a2}	Face angle	°
δ_1, δ_2	Pitch angle	°
ΣP_{GW}	Sum of power losses regarding churning	kW
f_g	Gear dip factor	—
φ	Friction angle	°
h_{am1}, h_{am2}	Mean addendum	mm
η_{ffc}	Sum of element churning efficiency (see 6.1.6)	—
η_{ffl}	Lengthwise sliding efficiency (see 6.1.5)	—
η_{ffp}	Profile sliding efficiency (see 6.1.4)	—
j_{et}	Outer transverse backlash	mm
j_{en}	Outer normal backlash	mm
K	Load intensity for calculating the coefficient of friction	N/mm^2
L	Length of the element of the considered rotating element	mm
m_t	Transverse tooth module of the gear considered	mm
μ_m	Coefficient of friction (see 6.1.6)	—
n	Rotational shaft speed	r/min
υ, υ_K	Kinematic oil viscosity at operating temperature, kinematic viscosity at 40 °C	mm^2/s (cSt)
v_{et}	Pitch line velocity at outside diameter	m/s
P	Design power	kW
P_{GWi}	Power loss for each individual element	kW
R_{m1}, R_{m2}	Mean cone distance	mm
R_f	Roughness factor	—
T_{o2}	Output torque, wheel, per unit force	mm
T_{i1}, T_{i2}	Input torque per unit force, pinion and wheel	mm
t_{B1}, t_{B2}	Pinion back angle distance	mm
t_{E1}, t_{E2}	Pinion crown to back	mm
t_{F1}, t_{F2}	Pinion face angle distance	mm
T_1	Pinion torque	Nm
z_1, z_2	Number of pinion, wheel teeth	—

3 Application

3.1 Geometry

For the purposes of this Technical Report, the geometry of bevel and hypoid gear pairs is assumed to be calculated according to ISO 23509. These calculations need at least a set of initial data. If these data are not completely given or known from similar applications, a rough estimate of the gear dimensions can be determined by means of the power to be transmitted (see Annex B of ISO 23509:2006).

In any case, a complete geometry calculation has to be successfully executed before any other of the following considerations makes sense.

3.2 Rating

3.2.1 General

To make a rating of a pair of bevel gears one should have a mathematically correct set of geometry (see 3.1). This enables the designer to proceed to more detailed calculations which complete the design insofar as the transmitted torque is concerned. Additional rating criteria for bending strength and pitting resistance should also be considered. The method for calculating the bending strength and pitting resistance of bevel gears except hypoid gears is stated in ISO 10300 (all parts).

3.2.2 Bending strength

Bending strength as a criterion of bevel and hypoid gear capacity can be defined as the ability of the gear set to withstand repeated or continued operation under nominal load without fracture of the teeth in their roots by fatigue in bending. It is a function of the bending (tensile) stresses in a cantilever beam and is proportional to the applied load. It also involves the fatigue strength of the gear materials and the shape of the teeth. Therefore, either the pinion or the wheel can be the limiting member of the pair.

3.2.3 Pitting resistance

Pitting resistance as a criterion of bevel and hypoid gear capacity can be defined as the ability of the gear set to withstand repeated or continued operation under nominal load without suffering destructive pitting of the tooth surfaces. The experienced gear designer recognizes that moderate, non-destructive pitting of the tooth surfaces can occur during the early stages of operation, especially on non-hardened or through-hardened gears. In these cases, the pitting ceases to progress after the asperities have been removed by the initial operation. This process, called initial pitting, should not affect the gear life.

Destructive pitting, although attributable in principle to the same phenomena, progresses widely enough to destroy the geometry of the flank surfaces and ultimately leads to failure. The distinction between initial and destructive pitting is defined more thoroughly in ISO 10825.

Pitting is a function of several factors; the most significant is Hertzian contact (compressive) stresses between the two mating tooth surfaces and is proportional to the square root of the applied tooth load. The ability of bevel and hypoid gear teeth to withstand repeated surface contact under load without destructive pitting involves the resistance of the gear material to fatigue under contact stresses. The smaller gear is usually the limiting member of the pair because the teeth receive more stress cycles per unit time. In some cases, the smaller gear is made harder than its mate, to increase its surface durability so that the limiting capacity can exist in either member.

3.2.4 Other forms of bevel gear tooth deterioration

The rating standards are not applicable to other types of gear tooth deterioration such as micropitting, case crushing, wear, plastic yielding and welding.

Information on scuffing can be found in ISO/TR 13989-1.

3.3 Materials

The quality of materials and methods of heat treatment required are governed by the application. Care should be taken to choose the proper material for each application to transmit the load and obtain the life desired. Heat treatment is usually needed to develop the necessary hardness, strength and wear resistance.

For information about materials and heat treatment, see ISO 6336-5.

3.4 Gear tolerances

Bevel gears are manufactured to suit many engineering applications. In order to satisfy these needs properly, it is necessary to analyse the conditions under which these gears should operate. Reasonable tolerances should then be established to ensure that the gears perform satisfactorily in the application.

Tolerance values for unassembled bevel gears, hypoid gears and gear pairs are provided in ISO 17485. Additionally, information about bevel gear measurement methods is given in ISO/TR 10064-6.

3.5 Gear noise

3.5.1 General

The gear noise can be produced by the vibration of the gear unit caused by the transmission error of the gear pair. The flank form deviations of the teeth, a misalignment between the gears, and the elastic deformation of the teeth under load affect the transmission error. Table 1 shows typical values of transmission errors for different gear applications.

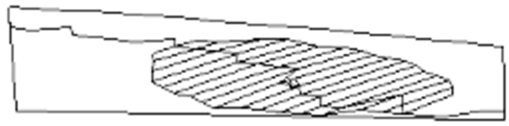
Table 1 — Typical values of transmission error

Application	Recommendation value µrad
Passenger car	<30
Truck	20 to 50
Industrial	40 to 100
Aircraft	40 to 200 (80 average)

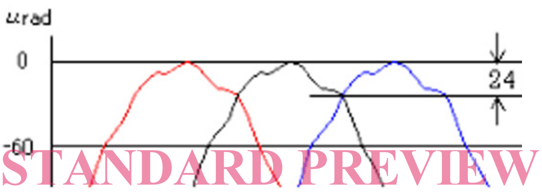
3.5.2 Tooth flank form corrections

The tooth flank form of bevel gears is corrected in order to prevent edge contact of tooth bearing during operation. Figure 1 a) shows the tooth flank form deviation of a spiral bevel gear after lapping. The amount of deviation between adjoining contour lines is 2 μm. It turns out that a crowning of remarkable size occurs in face width direction. On the other hand, the amount of deviation in the profile direction is small. Figure 1 b) shows the pertaining tooth bearing and Figure 1 c) the waveform of the transmission error. The peak-to-peak value of the transmission error is 24 μrad.

a) Tooth flank deviation



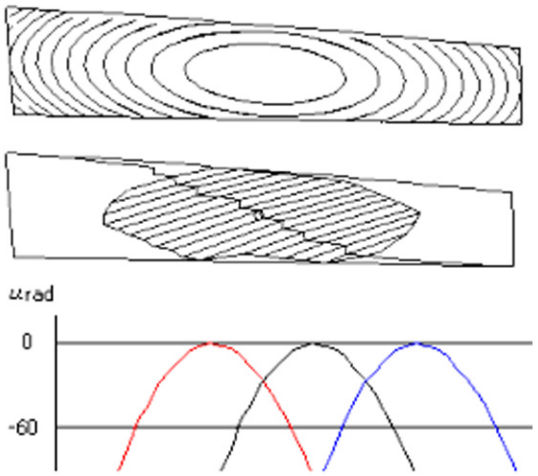
b) Tooth bearing



c) Transmission error

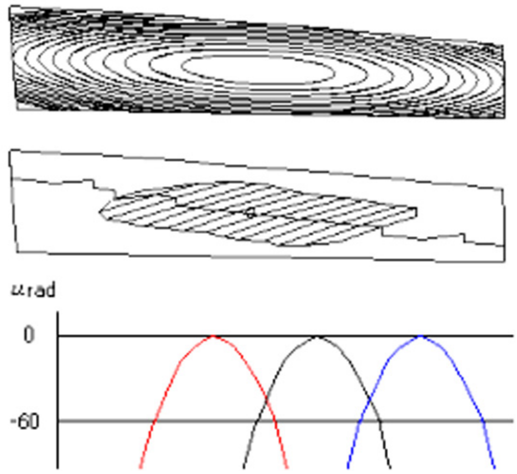
Figure 1 — Example of a gear pair finished by lapping process

Figure 2 shows the effect of profile crowning and flank twist where the amount of lengthwise crowning is fixed at 20 μm. In the case of 5 μm profile crowning in Figure 2 a), the width of tooth bearing is wide, and the transmission error is 27 μm. On the other hand, in the case of 20 μm profile crowning in Figure 2 b), the width of tooth bearing is narrow, and the transmission error increases to 43 μm. This means that excessive profile crowning should be avoided. However, in the case of Figure 2 c) with a flank twist correction of 80 μm, the transmission error decreases to 24 μrad. This shows the effectiveness of flank twist modifications if the profile crowning is enlarged.



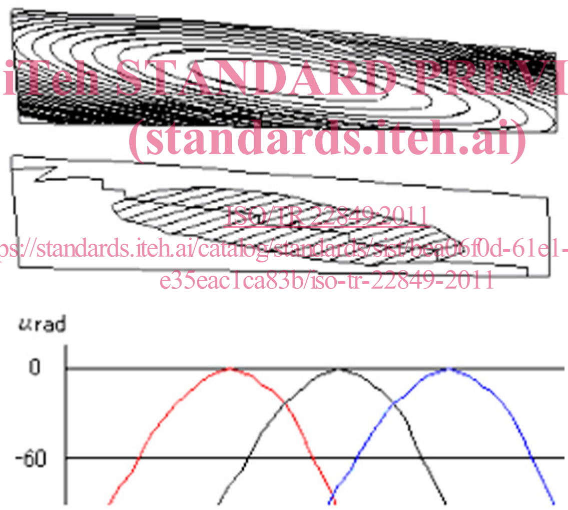
NOTE The transmission error is 27 μrad.

a) Profile crowning of 5 μm



NOTE The transmission error is 43 μrad.

b) Profile crowning of 20 μm



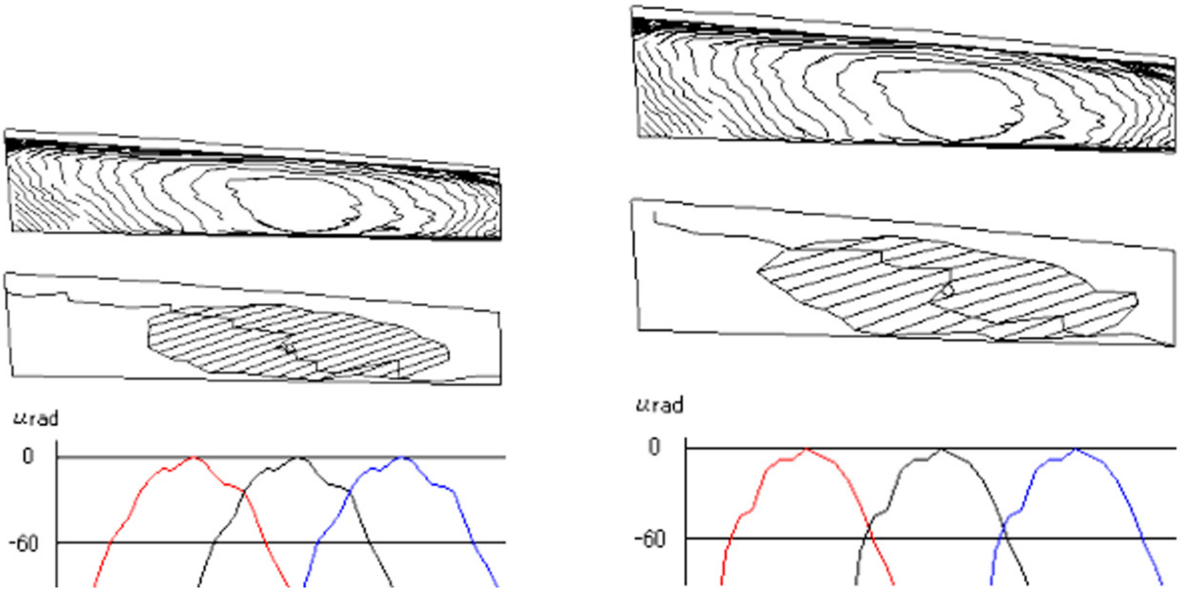
NOTE The transmission error is 24 μrad.

c) Profile crowning at 20 μm and flank twist of 80 μm

Figure 2 — Effect of profile crowning and flank twist on transmission error — Lengthwise crowning of 20 μm

Since tooth flanks are subject to elastic deformations under load, this needs to be considered for flank form corrections. However, as the noise of a gear set in many cases becomes a problem under light load, the measure indicated above is rather effective.

3.5.3 Design contact ratio



NOTE The transmission error is 24 µrad.

NOTE The transmission error is 52 µrad.

a) Number of teeth of 10/43 and contact ratio of 3:02

b) Number of teeth of 7/30 and contact ratio of 2:23

Figure 3 — The effect of design contact ratio on transmission error

The design contact ratio is the angle of transmission of one pair of teeth divided by the angular pitch. It is favourable, therefore, to enlarge the design contact ratio of a gear set in order to reduce gear noise. To get a higher design contact ratio, it is effective to increase the number of teeth, to enlarge the working tooth depth and to increase the spiral angle. However, if the number of teeth is increased, the mean normal module becomes smaller and reduces the load carrying capacity. Moreover, there is a risk that undercut can occur in the pinion root or the topland can become too small if the tooth depth is enlarged too much. Caution is required in those points.

Figure 3 shows the effect of design contact ratio on the transmission error. In the case of smaller tooth numbers of 7/30, the contact ratio which is less than that of 10/43, the size of the tooth bearing increases, but the transmission error also increases from 24 µrad to 52 µrad, although the tooth flank deviations are the same.

The actual contact ratio can change under load by deformation of the flanks and deflections of teeth and shafts.

3.5.4 Other noise consideration

Where a large misalignment is in the mountings of a gear pair or the misalignment produced by deflection under load is considerable, the tooth flanks can have edge contact and the transmission error can increase. Therefore, caution is advised to make the mountings of the gears accurate and the rigidity of the gearbox high.

4 Manufacturing consideration

4.1 Outline of production methods and their features — Face milling and face hobbing

In principle, there are two different methods used for manufacturing spiral bevel gears and hypoid gears: single indexing, which is also called face milling (FM) and continuous indexing, which is also called face hobbing (FH).

For the FH method, the rotation of the tool and of the workpiece are coupled in a fixed ratio so that one blade group of the cutter head enters one tooth gap and the next blade group enters the next gap, etc. This method is called continuous indexing, where all gaps are cut at the same time and which produces an epicycloid in the lengthwise direction. Generally, the tooth depth is constant along the face width so that root angle and face angle are equal. The tooth geometry results in a tapered topland and a tapered slot width. With a reasonably sized cutter radius, the tooth gap at the toe is slightly smaller than at the heel. If the cutter radius is too small, the inner tooth end becomes thicker than the outer. Therefore, too small cutter radii should be avoided.

In the FM method, the cutter blades are set in a circle on the cutter head. This method is used for cutting and for grinding. The tooth gaps are manufactured by single indexing which means that one gap is finish cut (or ground), then the gear blank is rotated by one pitch and the next gap is cut. Consequently, this method produces a circular arc in tooth lengthwise direction and in its standard geometry the tooth depth is tapered as well as topland and slot width. However, if root angle and face angle are specifically changed by a tilted root line depending on the cutter radius, the tapered tooth gets constant slot width and nearly constant topland, while maintaining proper space width taper (see 5.3.2.1 of ISO 23509:2006). The advantage of this measure is that FM bevel gears can also be completely cut in one single clamping.

Although there is an obvious difference between face hobbed gears and face milled gears, it does not lead to a general rule that one or the other method gives better results. The only fact is that for hardened spiral bevel gears no grinding process exists with continuous indexing, but instead precision hard cutting. Moreover, for bevel gears with diameters of more than 1 000 mm, there is no other way than continuous hard cutting because such big grinding machines are not available.

Regarding operating properties and load carrying capacity, no difference between FH and FM bevel gears can be found, if all crucial parameters are kept the same. These findings are also promoted by modern tooth contact analyses and FM calculation programs by which bevel gear designs can be checked and optimized. These programs also allow the study of detailed tooth flank modifications prior to manufacturing.

Historically, the choice of the manufacturing method was determined by the cutting machine available from a particular distributor. Nearly all new machines are 6-axes CNC machines, which can realize both face milling as well as face hobbing, and most of the current submethods.

Any heat treatment distortions are independent of the FH or FM method. With small distortions, lapping is the usually applied finishing process which also works equally with FH and FM bevel gears. However, in the case of larger distortions, a grinding or cutting process is required. Then, it is obvious to use grinding for FM gears and hard cutting for FH gears as their respective geometries are identical. Face hobbed gears can also be ground, however by single indexing, and both flanks should be ground separately for a correct engagement.

Unfortunately, hardening distortions hinder a geometrically stable lapping process. If these distortions are known exactly in advance, the flank form can be modified in the cutting process to compensate for the distortion so that the lapping process can be used more effectively. Contrary to grinding and hard cutting, lapping is a process without high geometric consistency but with the advantage of less noise emission by reducing relative tooth profile error between pinion and wheel, if heat treatment distortion is limited. Lapping does not eliminate any deviation in pitch and runout. Generally, the lapping process cannot be used to apply any designed flank or profile modification. This is possible with grinding and precision hard cutting only.

The cutting method and finishing method that should be used depends on the intended use of the respective gears, the equipment available and a lot of other aspects.

4.2 Blank design and tolerances

4.2.1 General aspects

The quality of any finished gear is dependent on the design and accuracy of the gear blank. A number of important factors which affect cost, as well as performance, should be considered.

Bores, hubs, and other locating surfaces should be in proper proportion to the gear diameter and module. Small bores, thin webs, and any condition that results in excessive overhang and deflection, should be avoided.

4.2.2 Clamping surface

Nearly all bore-type bevel gears are held by means of a clamp plate at the front face of the hub when the teeth are being cut; therefore, the blank should incorporate a suitable surface for this purpose, as shown in Figure 4.

Key

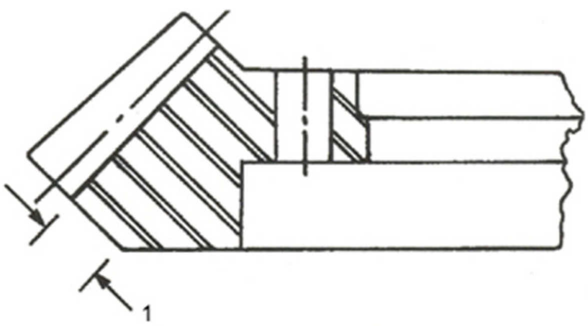
1 no surface provided for clamping, not recommended

2 clamping surface, as recommended

Figure 4 — Recommended clamping surface of the blank

4.2.3 Tooth backing

Sufficient thickness of metal should be provided under the roots of gear teeth to give proper support for the teeth. It is suggested that the minimum amount of material under the teeth not be less than the whole depth of the tooth. Highly stressed gears can require additional backing. This material depth should be maintained under the small ends of the teeth as well as under the middle (see Figure 5). In addition, on webless-type wheels the minimum stock between the bottom of the tap drill hole and the gear root line should be one third the tooth depth.



Key

1 tooth backing, as recommended

Figure 5 — Tooth backing

