New Dimensions in Bevel Gear Production

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1 Introduction

For meanwhile more than 80 years right angle gear boxes have successfully proven their reliability for the use in marine drives. One of the prime applications was built by the Company Voith in Germany, the Voith-Schneider® Propeller. The worldwide first thruster was invented by another German company. After the Second World War Josef Becker, the founder of Schottel Company, was focussing his activities on commercial shipping. Based on the principle of the already known outboard motors he combined two rear axle drives from trucks, blocked the differential gears and the first Z-Drive was completed (Figure 1). The term Z-Drive is derived from the shape of the drive train. The horizontal shaft of an engine driving a vertical shaft which again drives the horizontal propeller shaft, is connected by an upper respectively a lower right angle gear box. The main characteristic of a Z-Drive is the capability to rotate the lower part 360° around the vertical shaft. This combines an excellent manoeuvrability of the ship with space saving integration as well as easy installation and dismantling. As a reference it was first installed on the motor yacht “Magdalena” driven by an engine with $P = 150$ hp input power [WITT11], [BRAB01]. Nowadays the general principle as well as the main characteristics and advantages are very much the same (Figure 1). Today’s most powerful installations are running for instance in Finnish icebreakers with an input power of $P = 7500$ kW.

In the following, this paper focuses on the bevel gear drives in thruster units as one of its key components. Chapter 2 covers the gear design. Starting at the very beginning of the design phase based on the input data and boundary conditions, the design of the macro geometry is explained, followed by the rating process according to established standards. A further optimization of micro geometry, also called flank form modifications, only makes sense if detailed knowledge of the relative position of the mating gears under load is available. Therefore, a new software tool to calculate static deflections is presented.

How to produce real workpieces exactly according to design is the main topic in chapter 3. A new generation of gear cutting machines for production of even larger bevel gears combined with a new tooling system and an improved process is introduced, followed by an outlook.
2 Design of Bevel Gears

State-of-the-art bevel gear sets applied to marine drives and dynamic positioning applications are high quality machine elements which have to fulfill a wide variety of requirements. One of the most important features is of course a maximum of reliability in power transmission. High power density for lightweight design is also relevant in combination with high efficiency as well as low noise emission. In order to meet those specifications the gear design phase is most important.

2.1 Design of Macro Geometry and Rating

Prior to the first draft in gear design some basic input data is required, such as the gear ratio \( u \), the shaft angle \( \Sigma \) and the input power \( P \) or torque \( T \) in combination with the rotational speed \( n \) if already defined (Figure 2). Due to a lower degree of efficiency caused by the additional sliding movement in face width direction hypoid gears are normally not applied to units used for dynamic positioning purposes. The application factor \( K_A \) is one of the most important input data. It defines the amount of outer overloads to the gear set compared to the nominal load. Hence, it has significant influence on the required size of the gear set.

![Input Data and Design Considerations](source: Rolls-Royce)

**Input Data:**
- \( u \) gear ratio
- \( \Sigma \) shaft angle
- \( T \) torque
- \( n \) rotational speed
- \( K_A \) application factor

**Design Considerations:**
- definition of gearing system
- input of basic data
- computer aided design by proposals for missing gear parameters
- review and optimization of the actual design based on characteristic values
- load induced stress levels within the teeth

\[
\sigma_F = \frac{F_{mv}}{b \cdot m_{mn}} \cdot Y_{Fa} \cdot Y_{Sa} \cdot Y_f \cdot Y_K \cdot Y_{LS} \cdot K_A \cdot K_v \cdot K_{F\beta} \cdot K_{F\alpha}
\]

**Figure 2:** Input Data and Design Considerations

The complex method of geometry calculation for bevel gears is covered by [ISO23509]. In order to be able to handle this huge number of formulas in everyday business the design engineer needs appropriate software tools such as KIMoS (Klingelnberg Integrated Manufacturing of Spiral bevel gears). This program package has a modular structure and one of its main modules is the user interface for dimensioning.

As a first step the gearing system needs to be selected. The most common one for cutting large bevel gears with an outer pitch diameter of the ring gear of about \( d_2 > 1100 \text{ mm} \) is the Klingelnberg Cyclo-Pallloid system. It is a continuous cutting process, also known as face hobbing, which is characterized by a constant tooth depth along the face width and a lengthwise tooth curvature of an epicycloid.
After the gearing system is selected, the basic input data has to be entered next as far as known already. If only ratio and load data is known, the software is capable to provide a draft design. The correlation of parameters which define the basic geometry of a bevel gear set is described by the equation

\[ d_{e2} - b \cdot \sin \delta_2 = u \cdot z_1 \cdot \frac{m_{mn}}{\cos \beta_m} \]

where \( d_{e2} \) is the outer pitch diameter, \( b \) is the face width and \( \delta_2 \) is the pitch cone angle of the ring gear. On the right side of the formula \( u \) is the gear ratio, followed by the number of teeth of the pinion \( z_1 \), the mean normal module \( m_{mn} \) and the mean spiral angle \( \beta_m \). A first design check is normally based on the characteristic values such as profile contact ratio \( \varepsilon_{\alpha} \) and overlap ratio \( \varepsilon_{\beta} \), the ratio between face width \( b \) and mean normal module \( m_{mn} \) and others. If one or more of those values are out of a given range it is up to the experienced gear designer to modify the basic input data.

Applying the designated load to the gear set induces certain stress levels inside the workpieces. In order to be capable to reliably transmit the load the selected material has to endure the occurring stresses. The chart in Figure 3 illustrates typical values of material strength for different gear materials. 18CrNiMo7-6 (key no. 1.6587) is the most common material used for large bevel gears. This type of case hardening steel is characterized by both, high values of achievable case hardening depth (CHD) as well as high hardness of core material.

\[ \sigma_F \leq \frac{\sigma_{FP}}{S_F} \]
\[ \sigma_H \leq \frac{\sigma_{HP}}{S_H} \]

to avoid tooth breakage

to avoid pitting

**Figure 3:** Material Strength and Rating

Work standards, national and international rating standards, such as [KN3030], [DIN3991], [ISO10300] or [AGMA2003], are the gear designer’s set of tools. With these can be proved whether the combination of geometry, loads and selected material is suitable for the designated application. On the same basis different gear designs can easily be compared. The rating process consists of the calculation of safety factors against typical gear failures. All standards cover at least the failure modes of tooth breakage and pitting. However, tooth interior fatigue fracture (TIFF) is still an open issue. Safety factors are the ratio between permissible and occurring stresses. Both are determined by load data respectively material strength in combination with a variety of influence factors. The principle of using influence factors is a
general characteristic of all rating standards. These allow fast and easy determination of the safety factors. On the other hand, these always involve certain abstractions and simplifications. When comparing the calculated safety factors with minimum requirements it is easy for the experienced gear designer to decide whether the gear design fits for the application, if gear size may be reduced or if it needs to be increased. Most strength values of gear materials have been evaluated on cylindrical gears. Therefore, virtual cylindrical gears are determined with equivalent meshing conditions as the bevel gears to be designed. The geometry parameters at the design point P in the mean transverse section of the bevel gears are used to calculate the virtual cylindrical gears.

To find an appropriate design, which is capable of reliable power transmission and which on the other hand requires a minimum of installation space, is an iterative process. The success depends primarily on the experience of the gear engineer. At the very end of this process all information is gathered in a data set which completely defines the gear design (Figure 4).

- Basic parameters of the toothing
- Blank dimensions
- EaseOff (crowning data)
- Contact pattern without load
- Transmission error
- Machine settings
- Tooling information

Figure 4: Results of Macro Design

Beside the basic parameters of the bevel gear set, such as number of teeth \( z \), diameter of the ring gear \( d_{2} \) etc., all blank dimensions of the toothed part of the gears are given in the two sketches of Figure 4. Based hereon, the gear bodies of pinion and ring gear can be designed in detail.

Furthermore, a contact pattern under test load is calculated. For standard design it is located in the center of the flank and covers approximately 50% of the face width \( b \). This is achieved by a certain amount of lengthwise and profile crowning. Without crowning, the contact pattern would cover the whole flank, also known as conjugate flanks. However, a minimum of displacement between pinion and ring gear (see chapter 2.2) would cause hard contact at the edge of the tooth flanks. For standard design the quantity of crowning is typically defined by factors related to the mean normal module \( m_{bn} \).

The so-called EaseOff is used for description of tooth contact between pinion and ring gear without load. After spreading a grid along the tooth flanks the distance from contact between the mating flanks can be determined for each point of the grid. A fitting surface of distances from contact is defined for the current position in mesh by the combination of all points of the grid. The envelope of all those momentary surfaces is defined as the EaseOff, which is typically displayed as a surface of deviations towards a flat
plane. It is obvious that there is a correlation between the contact pattern under test load and the EaseOff. Based on a certain layer thickness for the marking compound, for instance $t = 5 \mu m$, the contour of the contact pattern is defined by the intersection of the EaseOff surface with a plane which is parallel to the base plane at a distance of $t = 5 \mu m$.

Another result of tooth contact analysis is the transmission error. Meshing of conjugate flanks is kinematically exact with constant nominal gear ratio. In practice crowning is applied to all tooth flanks. This leads to a variation of gear ratio corresponding to the momentary position in mesh, even if the gear set is produced in highest quality.

Last but not least the gear software also calculates the complete machine settings and defines the tooling data. Thus, at the end of the design process the macro geometry of a standard gear design is available, which under normal circumstances is satisfactory for the designated application, including all information that is necessary to produce the bevel gear set.

2.2 Design of Micro Geometry

When talking about the micro geometry design of bevel gears, this means modification of the flank topography. It is done in order to improve the contact pattern as to get appropriate load distribution along the flank, to influence the noise emission or both. Prior to this kind of optimization some other basic aspects need to be discussed.

Depending on the application the conditions during real operation of a bevel gear set are more or less different compared to laboratory conditions as for instance on a tester. There are tolerances in manufacturing and assembly of all parts. Weakness of the surrounding components (Figure 5) in combination with the applied loads leads to deflections within the system. Further effects are caused by thermal expansion and bearing clearances. As a consequence there will be a spatial displacement between the mating members.

**Figure 5: Bevel Gear Set and Surrounding Components**
The standard gear design discussed in chapter 2 represents a compromise of adequate gear size in combination with a standard EaseOff which is capable to compensate typical small amounts of displacements due to characteristic insensitivity against deflections. An optimization of flank form always comes along with a decrease in sensitivity with respect to displacements. Hence, a detailed knowledge of what happens in the gear box during real operation is an indispensable precondition before starting optimization of micro geometry.

Typical rating standards as mentioned earlier are based on simplifications and some rough assumptions on shape and size of contact pattern and load distribution. Any kind of flank form modification is normally not covered by those standards. Therefore, it is necessary to apply superior methods, such as BECAL [LINK01], which is another module also included in the KIMoS software package. Based on a simulation of the cutting process for pinion and ring gear the complex geometry of the tooth flanks is known exactly. This information is used for further tooth contact analysis. While the teeth are flexible the gear bodies are characterized by infinite stiffness in the calculation model (Figure 6). Multiple contacts of flank pairs at one time in mesh can be taken into account as well as tooth stiffness variation depending on the position of tooth force application in profile direction. Beside the profile of tooth root stresses, distribution of contact pressure across the tooth flank can be calculated on the basis of Hertzian approach. The loaded tooth contact analysis of bevel gears using BECAL is state of the art for quite some years now.

Figure 6: System Boundaries of Software Tools

In the past it was always difficult to get detailed information on deflections caused by the surrounding components of the gear set. Generally, a complex and time consuming finite element analysis was required. With the recent introduction of an interface to and from RomaxDesigner, a new method to determine the relative spatial position of the mating members is available [MUEL11]. RomaxDesigner is a widespread software tool which focuses on static analysis of the overall system of flexible components such as gear bodies, shafts, bearings, housings etc. whereas the stiffness of teeth is infinite. Due to clearly defined system boundaries both, the gear calculation tool and the static analysis tool are complementary to each other in an optimal way. The efficient algorithms of both packages enable the gear engineer to analyze and optimize the overall system within a reasonable time frame.
The ideal relative position of a pinion and ring gear, which belong to a bevel gear set without offset, is characterized in that their axes intersect in one point and that in the same point their pitch cone apexes touch each other. As already mentioned and shown in Figure 7 displacements occur during gear operation caused by deflections of gear bodies and surrounding components. For instance the mounting distance (MD) of the pinion may vary which means that it is shifted along its axis by the amount of H. The mounting distance of the ring gear (J) may be affected, too. Also the shaft angle between the axes (Σ) can be influenced. If both axes are no longer part of the same plane, this kind of deviation is called vertical offset (V). All displacements between pinion and ring gear can be reduced to the parameters V, H, J and Σ which allow a sufficient determination of the relative position between both members.

Figure 7: Relative Position of Pinion and Ring Gear

Displacements between pinion and ring gear affect size and position of contact pattern as well as backlash. When optimizing flank forms or micro geometry, the main goal is to achieve an appropriate contact pattern which is centered on the flank and covers most of it at the duty point in order to utilize the available flank in the best way. Most often there are several duty points at different loads and different speeds, which mean that the optimization has to be a compromise satisfactory for all of those conditions. Gear optimization is a process of iteration (Figure 8). It all starts for instance with the standard EaseOff as a calculation result described in chapter 2. Based hereon, a loaded tooth contact analysis needs to be performed using the relevant part of the gear calculation software. The results of this analysis are tooth forces and data of torsion stiffness, each as a function of rotation angle φ. These parameters are then transferred to the static analysis tool. A model of the overall structure of the thruster must be available within this software. After application of outer loads in combination with the input data out of KIMoS the static analysis can be started. It ends up with the calculation of deflections and the determination of characteristic parameters of misalignment V, H, J and Σ which will be returned to the gear calculation software.

The EaseOff contains the most important information for the gear engineer during optimization. There are five characteristic parameters describing the EaseOff which are the crowning in lengthwise (LB) and profile (HB) direction and angle deviations again in lengthwise (dβ) and profile (dα) direction. The last
parameter is the longitudinal twist (dv). This description of the whole EaseOff by five parameters is done for practical reasons because these parameters are directly correlating with shape and position of the contact pattern.

Flank form modifications are based on defined changes in machine settings and tooling profiles whereby the macro geometry of the bevel gear set is normally not affected. With the support of the gear calculation software the gear engineer does not need to concentrate on machine settings or tool data. Once he has defined the degrees of freedom of machines and tooling system designated to be used for production of the gear set by selecting the related parameters in the background, he can focus on the above mentioned parameters describing the EaseOff along with the further process of optimization.

As the displacements between pinion and ring gear are now known it is up to the experienced gear designer to optimize the micro geometry by applying appropriate flank form modifications on the computer. The developed EaseOff can be checked on the basis of the characteristic values of the loaded tooth contact analysis prior to the next step of iteration which includes the static analysis tool.

Thus, a closed loop process of gear design is available as a helpful package to assist the gear designer. At the very end of the process an optimized macro and micro geometry is defined which assures satisfactory tooth contact even when having displacements during operation for appropriate load capacity and reliable power transmission of the bevel gear set.

Some significant advantages with respect to the design process of new products need to be pointed out when making use of the closed loop of gear design for thrusters. Figure 9 shows a comparison between the standard and the advanced product development process. In the past best practice to establish new products was as follows: First a standard gear design with standard EaseOff is defined and produced. After assembly of the thruster the second step is a full load test in order to check size and position of the loaded contact pattern. If the contact pattern is acceptable the unit can be released for the designated operation. If not, an optimization based on the results of the full load test is required which ends up either with improved and modified gear assembly, recutting of the existing bevel gear set as far as possible or even with the production of a new one. As long as the full load test following up again shows a contact...
pattern which is not satisfactory another iteration process is required. Thus, this method is both, very time and cost consuming.

The advanced process, the closed loop in gear design presented above, is based on a simulation of the overall thruster system. Displacements of pinion and ring gear, which occur during operation and affect size and position of the contact pattern, can be determined by simulation. With the results of this simulation the flank forms can be optimized prior to manufacturing of the bevel gear set. This assures to find a satisfactory contact pattern during full load test with a high degree of reliability and the unit can be released for operation without any further intervention. Hence, costs and time frame between first draft and first operation of new products can be reduced significantly.

**Figure 9:** Product Development Processes in Comparison

### 3 Production of Bevel Gears

All characteristics of a bevel gear set are defined during the process of gear design as described in the previous chapter. Now the task is to manufacture those gears precisely according to the design in order to guarantee reliable power transmission during operation. Recent developments and improvements in production of large bevel gears for thrusters and other applications are presented in the following.

#### 3.1 New Generation of Gear Cutting Machines

Gear cutting is definitely one of the key operations along the process chain for manufacturing of bevel gears. During this operation the main functional surfaces of the gear members are machined. Those are the gear flanks where power transmission happens when in mesh.

Special machine tools are used for cutting of large bevel gears. At the end of the 1970s the AMK1600 machine series was introduced. This mechanical type of cutting machine was capable to soft and hard cut spiral bevel gears up to a nominal outer pitch diameter of the ring gear of \( d_{2} = 1600 \) mm. It was relatively easy to design standard gears and to calculate the corresponding machine settings. Based on a hardcopy the operator was able to setup the machine as well as the tools for the cutting process. Thus, this type of cutting machine proved its ability to produce high quality gears for quite a long time.
Along with the tendencies to increase power transmission the market was demanding for even larger bevel gears. Soon the limits of the existing machines were reached. On the other hand there were vast improvements in the process of cutting smaller bevel gears for the automotive and truck industry. A gap in the technology occurred which was constantly becoming larger.

As a consequence a new generation of gear cutting machines was designed and first installed at the end of 2008. The C300 (Figure 10) is capable to produce bevel gears up to an outer pitch diameter of \( d_e = 3000 \) mm. Contrary to its preceding model, the C300 machine is based on a CNC concept with each axis being individually controlled. This offers even more degrees of freedom to apply flank form modifications which could not be realized on mechanical gear cutting machines.

![New Gear Cutting Machine C300](image)

- Double spindle for cutting pinions in one clamping
- Dry processing for soft cutting
- Max. diameter \( d_e = 3000 \) mm
- Max. mean normal module \( m_{mn} = 50 \) mm

Figure 10: New Gear Cutting Machine C300

The new generation of gear cutting machines offers state-of-the-art setup process. Time consuming transfer of settings from a hardcopy into the machine by the operator with the involving risk of failures is not required any more. After loading the designated data set all machine settings are available for automatic positioning of the axes when pushing a button. Intervention of the operator is reduced to a minimum of checks. There is a rotatable device in front of the machine which allows preliminary setup of the next workpiece parallel to primary processing time. Another fixed device is used for taking down the machined workpiece. Both units allow minimized part change times.

As mentioned earlier, the most common gearing system for large bevel gears is the Klingelnberg Cyclo-Palloid system using one-piece cutter heads. This method is implemented in the C300 operating software. It requires two tooling setups to cut the pinion. Therefore, the new machine is equipped with two spindles in order to be able to cut the pinion in one clamping.

Parallel with the new generation of gear cutting machines a new tooling system has been introduced (Figure 11) whereas the gearing system according to Cyclo-Palloid method still remains. When manufacturing large bevel gears, the number of pieces of each production lot is typically very small. Thus, contrary to mass production with specialized toolings designed only for current geometry, universal tooling equipment is required. Based on a modular system the new tooling system is capable to cover the wide variety of different gearing geometries of large bevel gears.
All blades are clustered by the nominal blade module, each profiled to be used for different gear geometries within a certain range of mean normal module $m_n$ of the workpieces. Due to cutting without middle blades, the number of starts of the cutter head has been increased to $z_0 = 7$, coming from $z_0 = 3$ which was typical for toolings used on the former generation of gear cutting machines.

![Tooling System](image)

- Modular system
- Cutter heads with radii $r = 350, 450, 550$ and $650$ mm
- No. of starts of all cutter heads $z_0 = 7$
- Universal blades clustered by nominal module $14 \leq m_n \leq 46$ mm
- Coated carbide inserts for soft cutting

Figure 11: Tooling System

The limits of the common former sizes of cutter head radii which were $r = 350$ and $r = 450$ mm have already been reached in the past. In order to be able to cut larger bevel gears than approximately $d_e = 2000$ mm outer pitch diameter the new tooling system includes additional cutter heads with radii of $r = 550$ mm and $r = 650$ mm. All cutter heads can be used both, for soft cutting as well as for hard cutting. They are also not constrained to a certain spiral direction of the workpiece.

Another improvement is the adaption of the dry cutting process which is already best practice for high batch production of small bevel gears for quite some time now. It offers high speed soft cutting with process parameters being increased significantly due to the use of coated carbide blades. For cost efficiency carbide inserts are used instead of making the whole blade out of expensive carbide material. Inserts are disposables, each offering four cutting edges. As there is no more need to use lubrication oil, dry cutting of bevel gears comes along with positive effects on environmental impact.

Crowning in lengthwise direction of teeth is created by using different tooling radii for cutting the mating flanks of pinion and ring gear. The new tooling system offers setup of radii which is continuously variable. For the Cyclo-Palloid system using one-piece cutter heads the lengthwise crowning is completely applied to the flanks of the pinion. Thus, two tooling setups are required for the pinion as mentioned earlier.

The profile crowning of the flanks is created by the profile of the blades used for hard cutting. There is a certain hollow in the profile of the CBN blades. Its amount is related to the nominal blade module. CBN blades can be re-used after resharpening for several times.

The combination of all the improvements in machines, toolings and processes ends up with an optimized lead time and an increase of production capacity characterizing a new state-of-the-art in cutting large bevel gears [HOUB10].
3.2 Heat Treatment

Heat treatment by case hardening is another important step along the process chain which determines the quality of bevel gears. All gears for dynamic positioning applications are case hardened. During mechanical processing of gear bodies and tothing adequate machinability is in focus. This is reached by homogeneous microstructure of the material characterized by relatively low strength. However, these are by no means sufficient for the designated application. In order to meet the operational demands a surface layer of high hardness in combination with a ductile core material is needed. By thermochemical treatment this gradual material profile can be reached by selective manipulation of chemical composition along depth. As to be seen in Figure 12 for instance the bending stresses in the tooth root of the active flank are affected by residual compressive stresses due to heat treatment. As a result the total stresses are reduced.

First the content of carbide within the surface layer of the workpiece needs to be increased to achieve hardenability. Therefore, the workpiece is exposed to a gas atmosphere within a furnace. After recooling for refining it is once again heated up to hardening temperature, followed by the quenching process in order to achieve a martensitic microstructure. Afterwards an annealing process is carried out to reduce brittleness and the risk of crack initiation.

![Figure 12: Heat Treatment](image)

Beside positive effects on the material properties there are also some undesirable implications which come along with the heat treatment. Hardness distortions occur which are due to the change in volume caused by microstructural transformation. Furthermore, gear shape, residual stresses, material inhomogeneities and other parameters affect deformations. Thus, recorded process control as well as the way of how the workpieces of a hardening batch are applied to a supporting rack are important factors for an appropriate heat treatment [KLIN08].

Hardness distortions at bevel gears mostly cause deviations in axial and radial runout. In Figure 12 a measurement report for a ring gear of diameter $d_2 = 1400$ mm can be found. It shows the variation in tooth root position in axial direction of the workpiece after heat treatment but prior to the hard cutting process. This variation ends up with unbalanced values of remaining case hardening depth of the flanks.
3.3 Closed Loop Production

Parallel with the installation of the new generation of gear cutting machines, the manufacturing process of large bevel gears was analyzed in detail and improved significantly. In this context the adaption of the closed loop production as another established principle in bevel gear production for automotive and truck industry was an important aspect. One of the basic elements of this principle is a central database which contains all data sets provided for production (Figure 13). All machines and devices required for manufacturing and quality control are connected to this database. The data sets are filed to the database directly by the gear engineer using network connection.

Each data set contains all information required for production. For instance the CS300 device for tooling setup imports the tooling data for semi-automatic setup. The operator only needs to mount the required blades into the cutter head prior to starting the setup process. As mentioned earlier the machine settings are imported to the gear cutting machine for positioning of the axes. No more summary sheets are required as hardcopy. Nominal data is imported by the gear measuring center. It can be used for measurements of pitch variation as well as for topography measurements.

- networking:
  - no more manual input of summaries and corrective settings
- appropriate flank form modifications already defined during gear design

![Database Connection Diagram](image)

**Figure 13: Closed Loop Production**

A fundamental improvement within the process chain is the introduction of general gear measurement after heat treatment but prior to hard cutting. The hardness distortions as described in the previous chapter are recorded. Aim is to minimize the reduction of allowance on the flanks to achieve a maximum remaining case hardening depth. So, the gear data is adjusted whereas the characteristics defined during gear design remain almost similar.

The high degree of accuracy of the gear cutting machine results in a flank form which is precisely corresponding to the nominal geometry. It is also possible to measure the workpiece after premachining and perform a comparison between actual and nominal data if highest precision is required. Based on the deviations detected, the necessary corrective settings can be calculated by a special software tool and filed to the data set. This file is then imported to the gear cutting machine for the final cut eliminating deviations.
3.4 Quality Record

Large bevel gears for dynamic positioning applications have to meet high demands especially with respect to reliability. Thus, quality requirements are very ambitious. In order to fulfill those requirements and provide proof, gear members have to pass through a variety of tests and inspections all along the process chain (Figure 14). The results of those tests and inspections as well as other important process data need to be recorded.

Extensive inspections are already scheduled for the forging blanks, which need to be proved by material certificates. Beside the number of cast and results of metallurgical tests with respect to grain size, cleanliness and chemical composition of the source material, for instance, results of ultrasonic testing and crack detection are recorded. Additionally, forging rate and hardenability as well as mechanical properties such as impact energy or tensile strength can be sourced.

For proof of heat treatment further testing and documentation is required. In addition to process control of the furnace and analysis of microstructure, particularly hardness profile, surface hardness and mechanical properties found on test specimen need to be pointed out.

![Figure 14: Quality Record](image)

Important test dimensions of machining operations are kept within dimension records. Tooling setup for soft and hard cutting is filed into reports. On the gear measuring center measurements of pitch deviation and topography are carried out. The results can be found within the measurement reports. In addition contact pattern, mounting distances and backlash for each bevel gear set are checked on a gear tester. Documentation of contact pattern is based on photographs.

Generally the overall manufacturing process of a bevel gear set is supervised by classification societies. It is important that origin and development of each workpiece can be traced back at any stage along the process chain. Thus, each gear is labeled by a stamp marking which has to remain permanently.
4 Summary & Outlook

As a precondition for optimization of the micro geometry by applying flank form modifications, boundary conditions of the application and displacements of pinion and ring gear due to the static behaviour of surrounding components need to be known very exactly. By the combination of the gear calculation software KIMoS and the static analysis tool RomaxDesigner, a powerful package to perform a simulation of the overall system is available.

The principle of closed-loop production assures bevel gear manufacturing to be precise according to design. Load capacity of gear components is decisively influenced by the process of heat treatment. Extensive testing and inspections combined with continuous records of the results all along the process chain are important aspects with respect to quality and reliability of gears.

In addition to static analysis as described in this paper also the dynamic behaviour of the overall thruster system is of important interest (Figure 15). Natural frequencies and eigenmodes can be determined by the use of finite element method. Due to complexity of the overall system and the lack of knowledge, for instance on damping effects caused by the surrounding water flowing around, it is impossible to make a prediction on the occurring eigenmodes as well as on their magnitudes. Hence, measurements such as condition monitoring are required in order to allow interpretation of simulation results.

![Static Analysis of Drive System](image1)

![Dynamic Analysis of Drive System](image2)

Displacements of the bevel gear set due to the load, as far as known, can be compensated by flank form modifications.

**Figure 15: Simulation of the Overall Drive System**

Due to the installation of the new generation of gear cutting machines C300 it is now possible to cut gears up to an outer pitch diameter of the ring gear of \(d_{e2} = 3000\) mm. The chart in Figure 16 shows the significant increase in capacity of power transmission. Based on an existing gear set with power capacity of \(P = 7000\) kW the gear design has been upscaled. It can easily be seen that already a gear set with ring gear diameter of \(d_{e2} = 2855\) mm is capable to transmit power of more than \(P > 20000\) kW even if an application factor of \(K_A = 2.0\) is considered.
Figure 16: Load Capacity of Large Bevel Gears

Basic parameters: \( u = 1.72, \beta_m = 26^\circ, K_A = 2.0 \)
5 References


[ISO23509] ISO 23509 (September 2006): Bevel and hypoid gear geometry


[KN3030] Klingelnberg Standards KN3030 Issue No. 1.2: Rating of Spiral Bevel Gears according to Klingelnberg Cyclo-Palloid System

