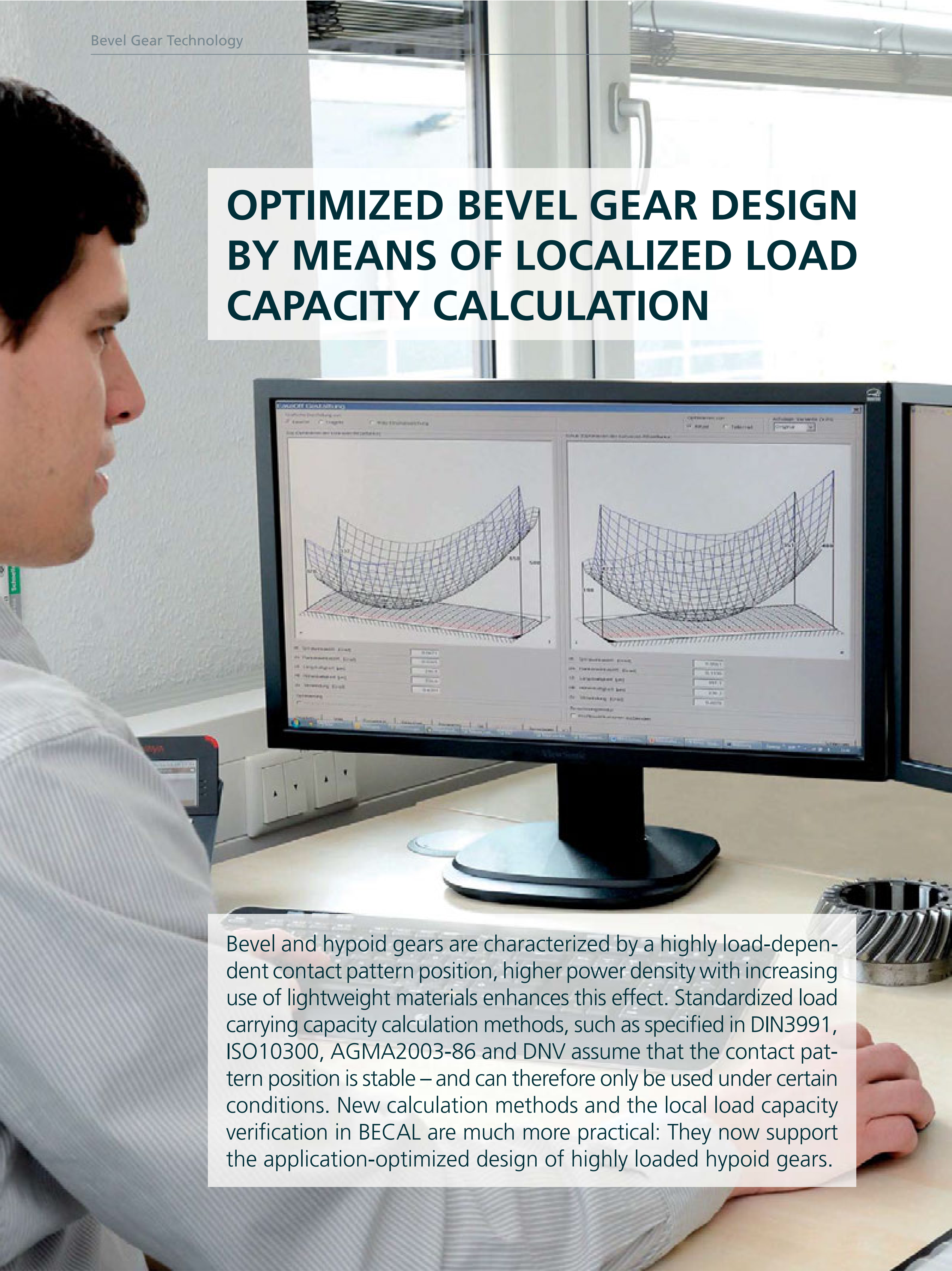
OPTIMIZED BEVEL GEAR DESIGN BY MEANS OF LOCALIZED LOAD CAPACITY CALCULATION



Bevel and hypoid gears are characterized by a highly load-dependent contact pattern position, higher power density with increasing use of lightweight materials enhances this effect. Standardized load carrying capacity calculation methods, such as specified in DIN3991, ISO10300, AGMA2003-86 and DNV assume that the contact pattern position is stable – and can therefore only be used under certain conditions. New calculation methods and the local load capacity verification in BECAL are much more practical: They now support the application-optimized design of highly loaded hypoid gears.

Simulating the complex interrelationships that occur in bevel and hypoid gearing and predicting the properties of a gear as accurately as possible (particularly with regard to load capacity and noise) calls for a local approach that can evaluate the influences of the pinion and gear macro- and micro-geometry and their load-specific relative positions.

Local loadcapacity verification in BECAL

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This kind of local approach has been pursued and developed for many years with the BECAL program package from the Institute for Machine Elements and Machine Design (IMM) at the Technical University of Dresden.

Precise knowledge of gear geometry is always a prerequisite for local calculation of loads and stresses. These can be calculated with KIMoS (Klingelnberg Integrated Manufacturing of Spiral Bevel Gears) and specified point by point. By transferring this multitude of flank and root points of the gearing to a tensor product surface, the tooth contact can be simulated. Both the specific relative position of the pinion and ring gear and known tooth profile deviation can be taken into account here. It is also possible to incorporate measured data from 3D coordinate measuring machines in the simulation of the actual tooth geometry.

Based on the load-free tooth contact simulation, numerical load distribution calculation takes place, which has been developed and optimized specifically for the non-linear contact conditions at the bevel gear. This makes it possible to carry out an extremely fast yet extremely precise calculation of the load distribution over the tooth flank, which is then followed by a local determination of the pressure and root-stress distribution. It is also possible to determine local sliding velocities and the directions thereof, which represent another important input variable for subsequent load capacity verifications. Safety factors can thus be calculated for pitting, micropitting, scoring or tooth root breckage.

To evaluate noise behaviour, BECAL makes use of the transmission error under load, which is also calculated based on the relative position of the pinion and ring gear. It is the key parameter for the parametric excitation oscillations and noise.

HIGHLIGHTS IN BRIEF

Safety factors for pitting, micropitting, scoring, or tooth root breckage are calculated according to BECAL as follows:

- Prerequisite: precise knowledge of the gear geometry (via BECAL or KIMoS).
- Flank and root points are transferred to a tensor product surface in order to simulate the tooth contact.
- Optional: integration of actual measured data from 3D coordinate measurement machines.
- Numeric load distribution calculation based on load-free tooth contact simulation.
- Pressure and root-stress distribution, determined locally on this basis.
- Determination of local sliding velocities and their direction.

The local approach used in BECAL makes it possible to predict a gear's properties extremely accurately.

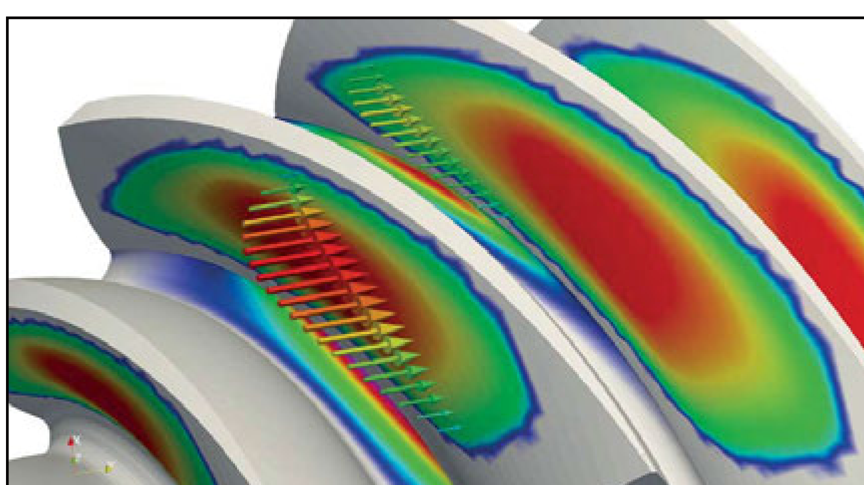


Fig. 1: Loads and stresses on a bevel gear

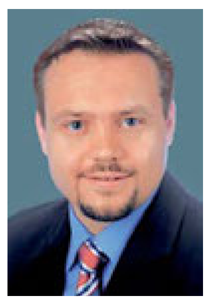
Compact

About BECAL

Experimental investigations on bevel gears, conducted by the FVA (German Power Transmission Research Association), formed the basis for the local load capacity verification for pitting damage and tooth root fracture in the BECAL simulation.

The local approach used in BECAL makes it possible to also use linear damage accumulation from load spectrum calculations on discrete points on the tooth flank or tooth root. In this way, facilitated by the short calculation times, the bevel gearing design can be adapted to the prevailing load spectrum.

Load capacity calculation for pitting and root breckage damage



by Dr.-Ing. Christian Wirth, ZG – Zahnräder und Getriebe GmbH

Knowledge of the strength is the foundation of a load capacity verification (safety calculation). This is based on experimental tests and requires coordination with the stress calculation beforehand. Investigations such as this on bevel gears were conducted in a series of research projects by the FVA (German Power Transmission Research Association), supported by the German Federation of Industrial Research Associations (AiF); they form the basis for load capacity verification of damage from pitting and tooth root breckage in the BECAL simulation and led to the revised version of the ISO 10300 Method B1 standardized calculation method.

As part of the experimental investigations of a project completed in 2008, which focused on the pitting resistance and tooth strength in conjunction with the axis offset, pinion load capacities were determined in Wöhler fatigue tests for ten different gear variants (total of 200 gear sets). The root stresses and contact stresses of the pinion basically reduce as the axis offset increases, with the same number of teeth, the same ring gear diameter, the same total helix angle ($\beta_{m1}+\beta_{m2}$), and comparable contact ratios. This is a result of factors such as the pinion diameter, which increases together with the axis offset.

The experiments showed that the tooth root stress in the vicinity of the 30° tangent (as known from cylindrical gears) is largely decisive for evaluating the tooth root load. However, determination of the pitting resistance requires not only an evaluation of the pressure, but also an evaluation of

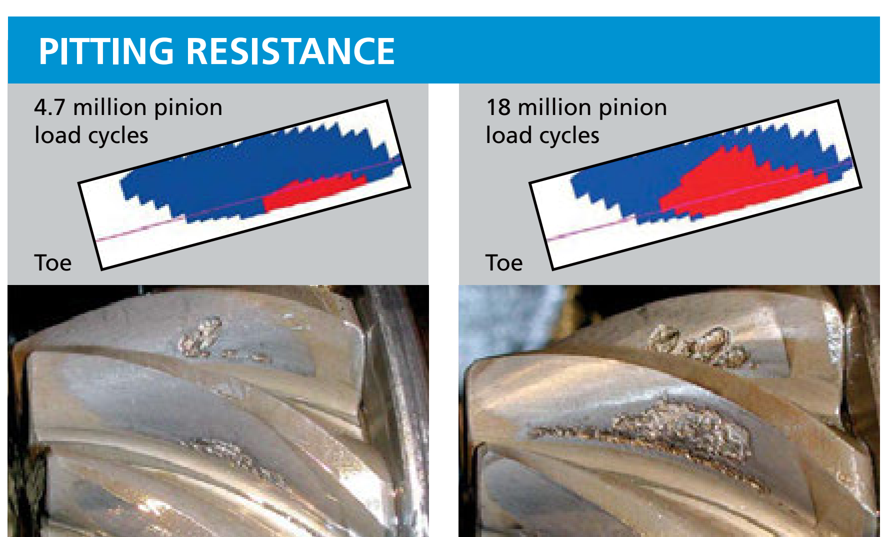


Fig. 2: Side-by-side comparison of calculation and testing

the sliding ratios, as shown by the tests. Although pinion load capacity increases were measured at moderate axis offsets, the permissible flank compressions decreased by more than 20% at the highest axis offset tested (25% axis offset, relative to the outside ring gear diameter). A major influence is exerted here by the tooth mass temperatures, which are influenced by the sliding velocities on the flank on the one hand, and on the other hand by the tangential flank velocities and the resulting lubrication conditions (flash temperature, friction coefficient, etc.) in the tooth contact.

From the theoretical experiments and the test results, locally identifiable factors that make a local load capacity verification possible were determined for the higher-order calculation method. The influence of the microgeometry of the gearing with regard to load capacity can be analyzed arithmetically in this way. The load capacity potential of the gearing can be optimized by modifying the contact pattern.

The results of the research project are available as a calculation method in BECAL. The simple, standardized calculation method was derived from the higher-order method and calibrated with it. It was incorporated in the revision of ISO 10300 "Calculation of load capacity of bevel gears", which was published in April 2014. In contrast to the first edition in 2001, offset bevel gears can now be evaluated with respect to root strength and pitting resistance.

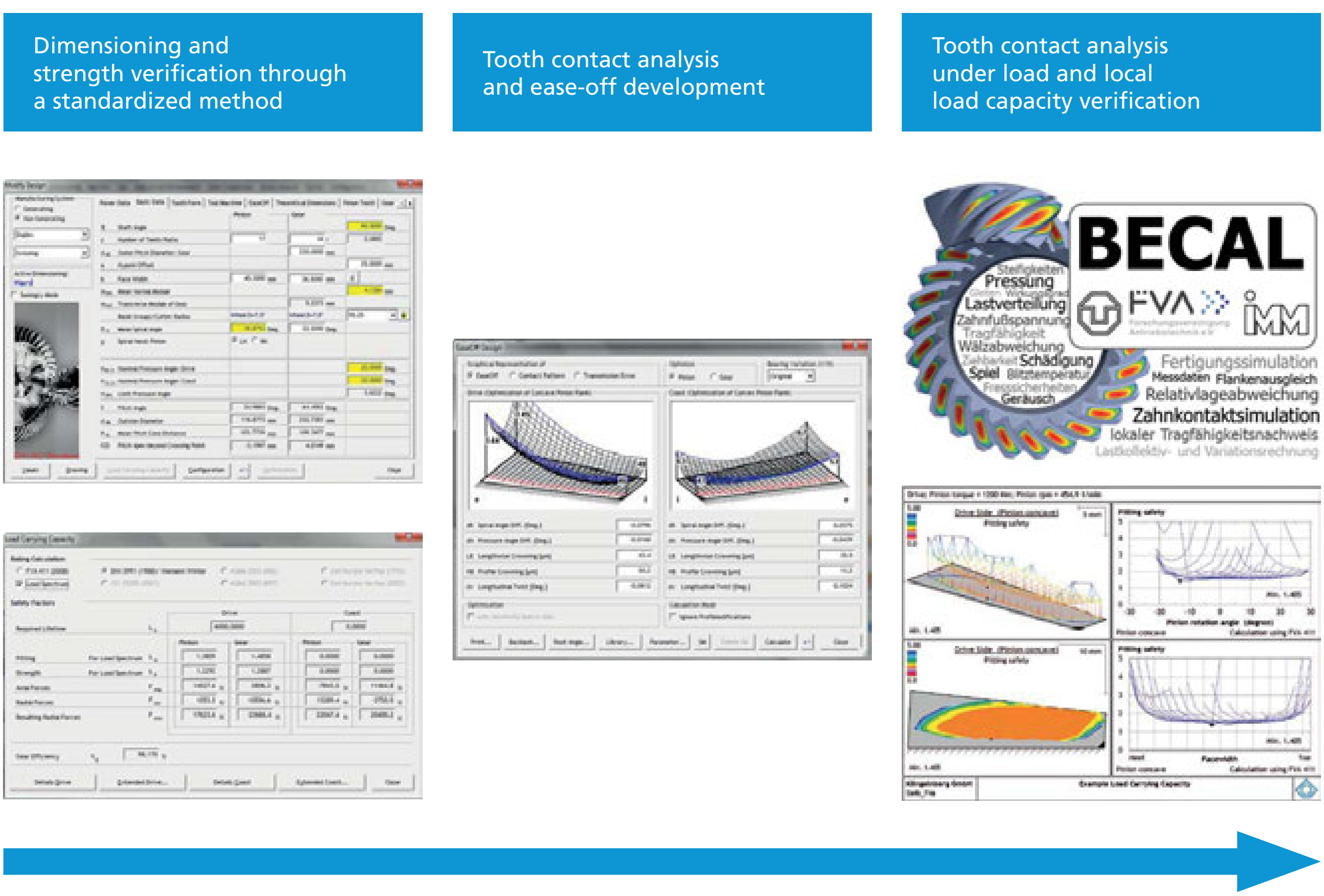


Fig. 3: Gear design sequence

Compatibility: The KN_Plus (standardized load capacity verification) and BECAL (local load capacity verification) programs can be incorporated in KIMoS; a load spectrum editor can also be integrated.

Application in KIMoS

The KN_Plus (standardized load capacity verification) and BECAL (local load capacity verification) programs can be optionally integrated in KIMoS. This allows the user to carry out the entire design and subsequent calculation of the bevel gear or hypoid gearing in a single program package. This largely entails performing the following steps:

- Dimensioning calculation for defining the macrogeometry
- Load capacity verification through the standardized calculation method in KN_Plus
- Production simulation as a basis for subsequent EaseOff development for defining the microgeometry
- Local load capacity verification in BECAL

The definition of the macrogeometry during the dimensioning calculation depends on the selected gear cutting process and tool, as well as the specifications from the gearbox design department. With the subsequent load capacity verification by means of standardized calculation method, the user quickly obtains a reliable assessment of the load capacity to be expected for the gear – and can directly modify macrogeometrical parameters as needed.

In the next step, the tooth profile of the intermating tooth pairs can be determined with a production simulation. The tooth flanks described by coordinate grids are then used for a contact analysis, from which the EaseOff is determined as the most important result – and the contact pattern, rotational error, backlash, etc., are then derived from this. By modifying the parameters describing the EaseOff, it is optimized until the contact pattern position, transmission error, and deflection requirements are met.

In order to test the V/H capability, the changes in the relative position between the intermating flanks must be specified.

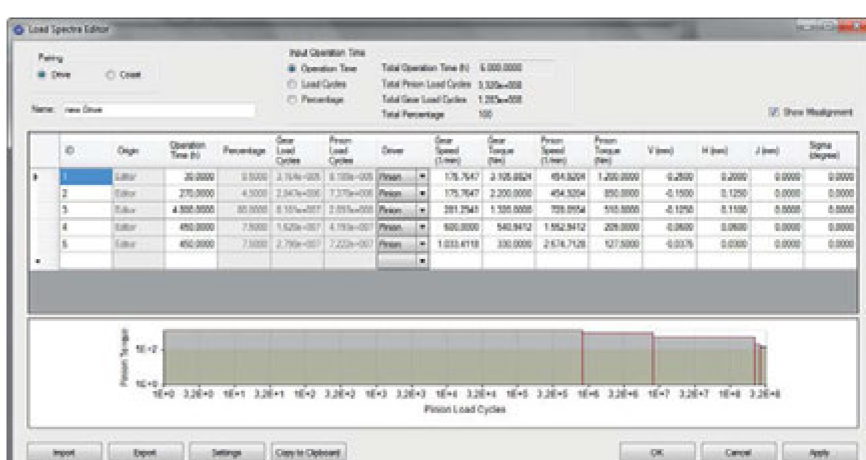


Fig. 4: Load spectrum editor

KIMoS has an integrated load spectrum editor with which load increments, including the associated displacements, can be entered manually or imported. The ROMAX Designer provides a convenient option for calculating the relative displacements of the intermating flanks. In this program, entire gear trains can be modeled relatively quickly and can undergo static analysis. The results can be imported into KIMoS in the form of complete load spectra with the associated displacements.

If the microgeometry, loads, and associated displacements are now defined, the prerequisites for tooth contact analysis under load have been met, including a meaningful local load capacity verification. All of the necessary data is transferred to the BECAL program, and calculation takes place within a short time. Based on the results, the user is in a position to decide whether the gear design corresponds to the required criteria for load capacity, safety with respect to tooth damage, and quiet running behavior. If further optimizations are needed, they are implemented in the EaseOff development, and validation is then performed via the tooth contact analysis under load in BECAL. ◆

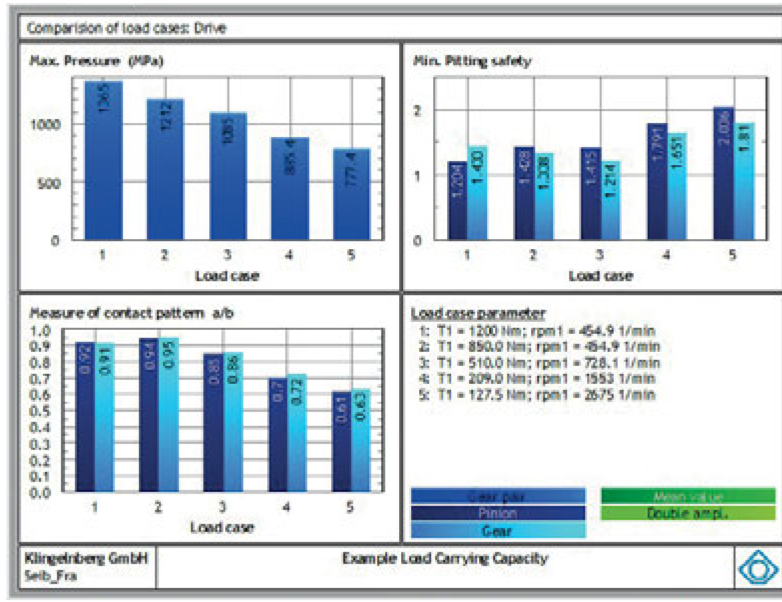


Fig. 5a: Overview of all load increments (gear train in this example)

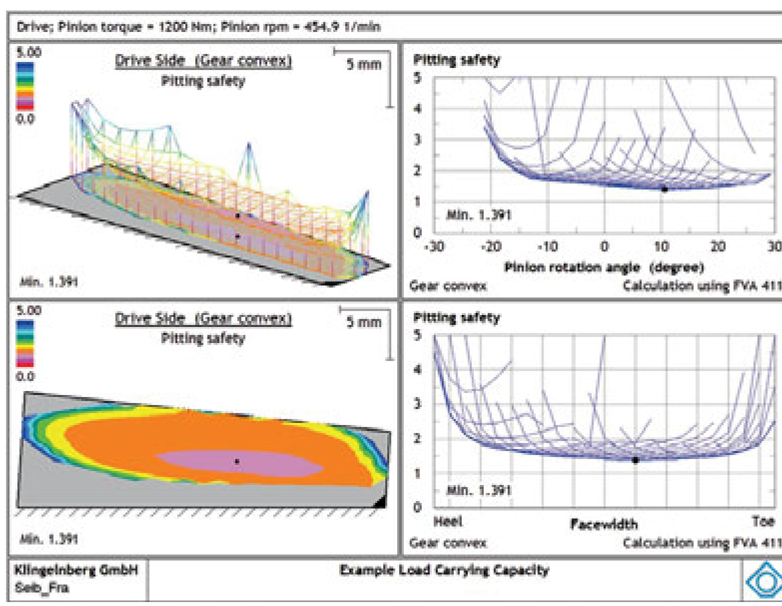
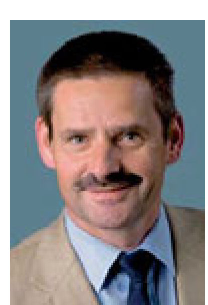


Fig. 5b: Detailed results for safety against pitting



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