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# Future-oriented Developments in Azimuth Thruster Technologies: HTG Bevel Gears, the New Performance Class in Azimuth Thruster Gears

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## SYNOPSIS

Propulsion systems like the Schottel Rudderpropeller are high-end products with state-of-the-art technology contained in every mechanical element. They incorporate the latest materials, a power train design with high-performance bevel gears and bearings, and are designed using simulation methods for structural and hydrodynamic calculations (such as the finite element method, computational fluid dynamics and multibody simulation), as well as further efficiency approaches through operation point optimisation.

In particular, the power train has been continuously improved to reach higher power densities than ever before. Materials used for bearings and gear sets come with the highest fatigue limits and are the best quality available. As the bevel gear is the size-determining element within the upper and lower gearboxes of an azimuth thruster, there is a significant trickle effect on to many downstream features of the overall system. The smaller the bevel gear, the smaller the housing around it, and for the underwater part of the thruster this means improved hydrodynamic properties, leading to a better propeller-to-housing ratio and therefore better efficiency.

Every manufacturer of propulsion systems has its own know-how, and with increased technical opportunities the challenge to make the best products using the given resources has grown over the past decades. As part of its research programme, Schottel has developed a unique and major improvement of a key element within the azimuth thruster: a new type of bevel gear which comes with a unique gearing geometry never used before, and which has a significantly increased load capacity.

## INTRODUCTION

After a development process lasting more than 10 years, Schottel has fundamentally improved the expertise and the processes involved in the development and manufacturing of high-performance bevel gearboxes. This high-torque gear (HTG) technology is already being used in several new products and has proven itself over years of operation in heavy use. Development began in 2005, a period when the shipbuilding market was moving into a sustainable growth phase.

Bevel gear sets *(Figure 1 and 2, overleaf)* are individually developed in accordance with the structural and geometrical constraints of the thruster, a situation which applies for all makers. The manufacture of such specialised gears was in the past only undertaken by a handful of gear set makers worldwide.

In order to develop its own new production process, Schottel teamed up with Bierens of the Netherlands, a medium-sized company with extensive general experience in gear design and manufacturing. Bierens was on the way to producing large bevel gear sets in a diameter range of 1,000-2,000mm using more or less standard 5-axis milling machines. Some essential modifications of these standard machines and the milling strategy parameters generated by self-developed software enabled the company to produce to the quality and within the tolerances that Schottel required.

*Figure 1: Bevel gear set from the underwater gearbox of a large azimuth thruster* *(Image: Schottel)*

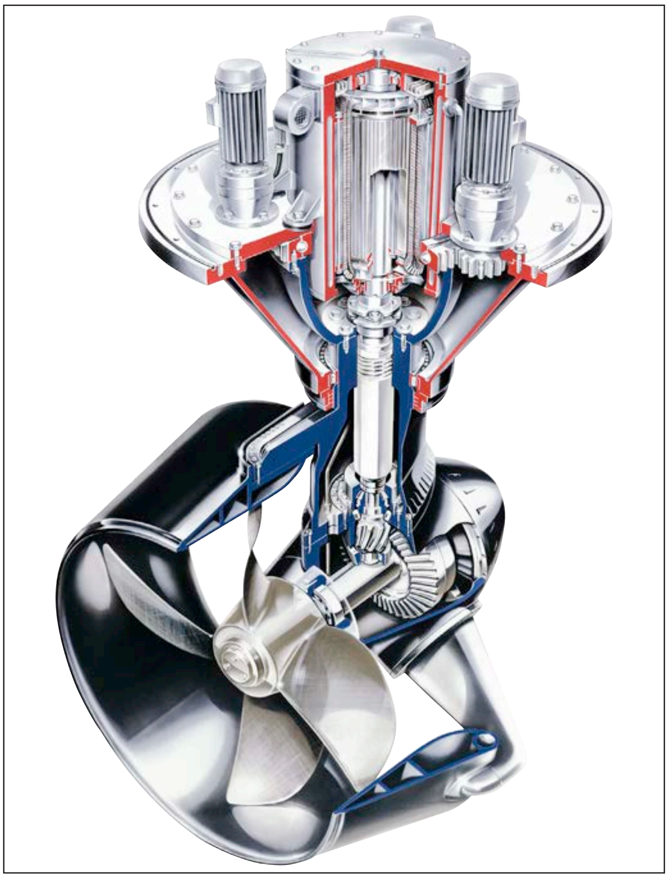

*Figure 2: Rudderpropeller with bevel gear sets* *(Image: Schottel)*

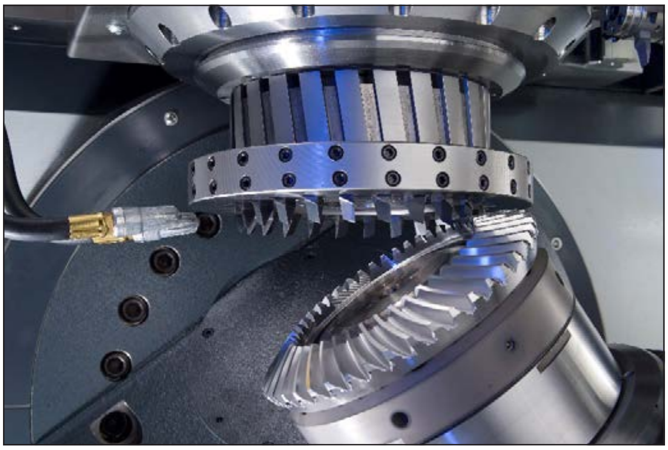

*Figure 3: Conventional machining with cutter head* *(Image: Klingelnberg)*

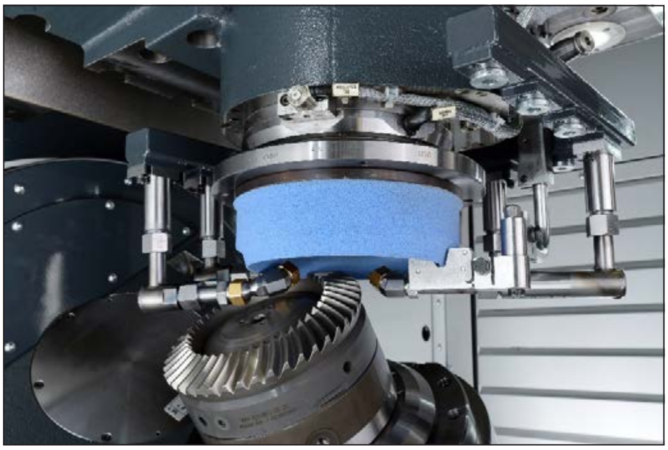

*Figure 4: Conventional machining using a bevel gear grinding machine* *(Image: Klingelnberg)*

*Figure 5: Alternative machining using the 5-axis milling process* *(Image: Bierens)*

To further develop this new production method for use in Schottel thrusters, extensive expertise regarding accuracy optimisation, usage of tools and the cutting strategy for very large bevel gears had to be gained. While established manufacturers of such gear sets were bound to large and expensive machines and tooling equipment, this new flexible production method was able to catch up and offer improvements *(Figures 3, 4 and 5).*

After test machining *(see Figures 6 and 7)*, extensive measurement, and experimental as well as numerical tooth contact simulation, the alternative machining solution was developed and brought to market-readiness. Co-operation between Schottel, Bierens and the Technical University of Dresden (TU Dresden) made it possible to achieve a fully compatible 'copy' of conventionally produced large thruster gear sets. This breakthrough was achieved after two years of intensive development, and was consolidated through several subsequent research projects, such as:

- metrological quality assurance/gear calculation with actual data;
- surface measurement technology;
- comparison of production accuracy data of conventional versus 5-axis machined gear sets;
- software developments for tooth contact analysis;
- testing technology / large bevel gear test benches.

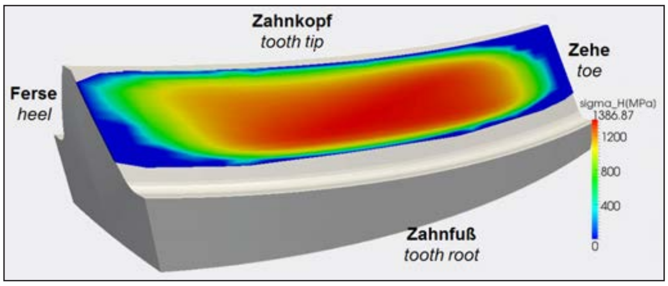

*Figure 6: Tooth contact analysis using GearDesigner software* *(Image: Schottel, TU Dresden)*

With these measures, the new process was scaled and tested to meet quality standards for bevel gear

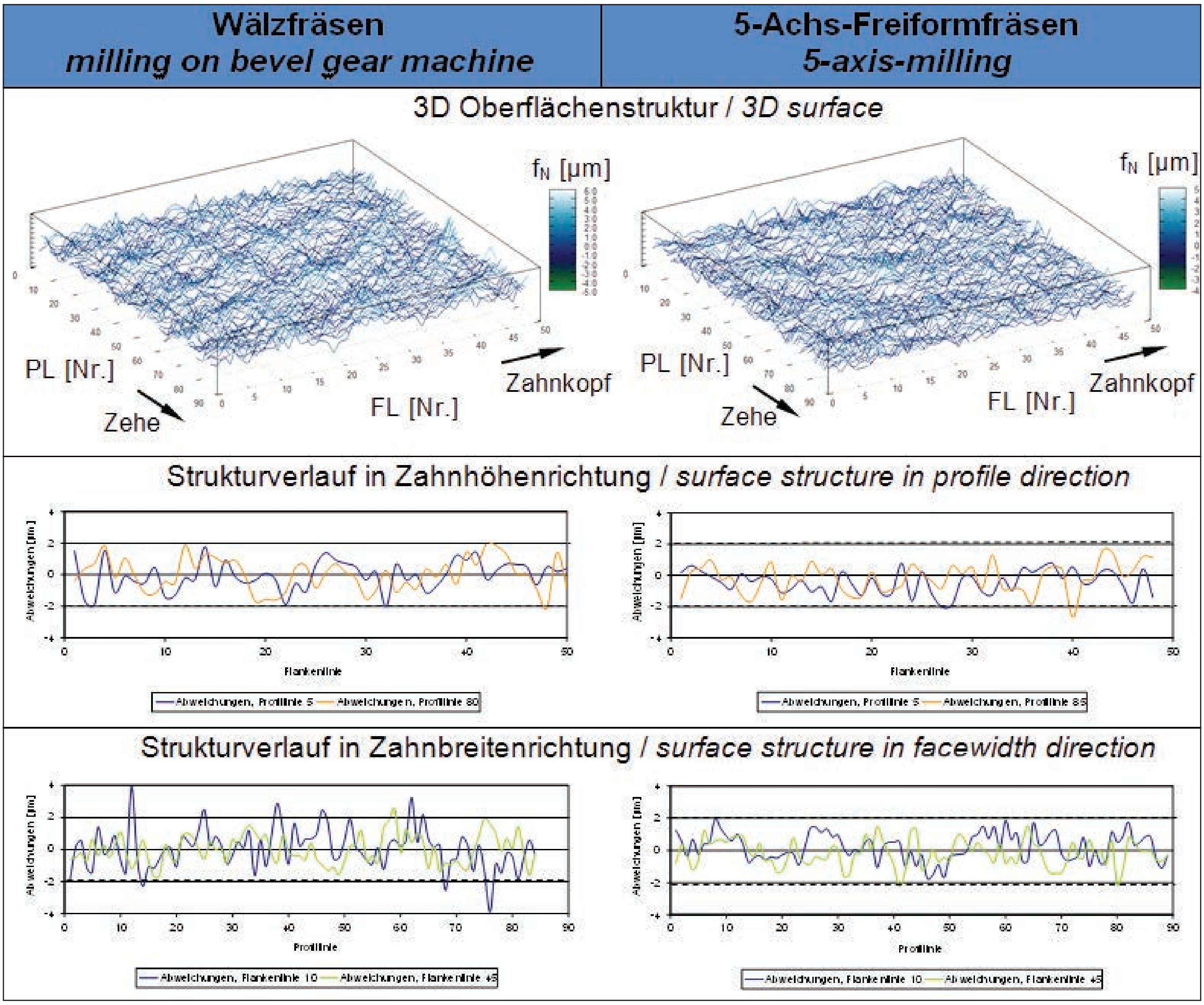

*Figure 7: Comparison of the surface structure of conventional versus 5-axis-machined tooth flanks (Image taken from Potts[1], Wolfien[2])*

sets in main propulsion azimuth thrusters. Almost every single step in the design and production process was examined and improved. As a result, conventionally machined bevel gear sets (still used in a huge number of product variants) can now be machined with either the conventional or the 5-axis method, and many of the findings of the 5-axis machining project have been transferred to the conventional machining process *(Figure 8, overleaf)*.

In addition to these properties, the controversial issue of enveloping cut failure was carefully examined and optimised.[3] While conventional ‘continuously dividing’ processes usually deliver a high number of enveloping cuts (the cutter head method) or virtually no enveloping cut failure (grinding process), the finger cutter in the 5-axis process works along the flank height ‘row-by-row’, thereby generating as many facets with determinable height (failure), as rows are chosen by the machining strategy *(Figure 9)*.

Because the milling cutter has a significantly lower chip performance than the structurally larger cutter head, the processing time for 5-axis milling is generally significantly longer than that for specialised gear cutting machines. By contrast, the much lower machine-hour rate of the universal 5-axis machine reduces manufacturing costs, both in terms of the cost of the machine and the cost of tools.

Through extensive theoretical calculations with simulated surfaces and test runs on a tension tester in accordance with DIN 51354, optimal feasible facet elevations were identified, which in turn enabled calculation of the required number of enveloping cuts for each gear, taking into account the respective flank curvatures. Considering bevel gear sets with higher transmission ratios (in Rudderpropeller gearboxes, these are typically i=2.5...4), the more extensively curved pinion flank requires several times more cuts than the much straighter gear wheel flank. Ultimately this point, raised by the critics of the new method, could be refuted through careful analysis, calculation and testing, and is today automatically considered in the company’s design software for the 5-axis machining strategy.

This experience enabled an optimised processing time, and thus increased the profitability of the process. Unacceptably large enveloping cut failures manifest themselves, for example, in increased grey staining

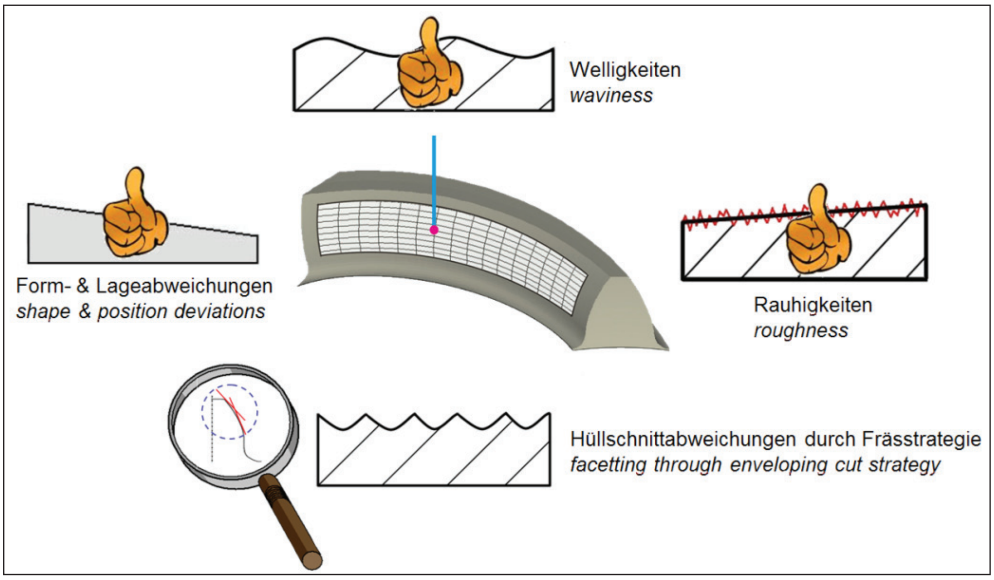

*Figure 8: Verified flank characteristics*
*(Image: Schottel)*

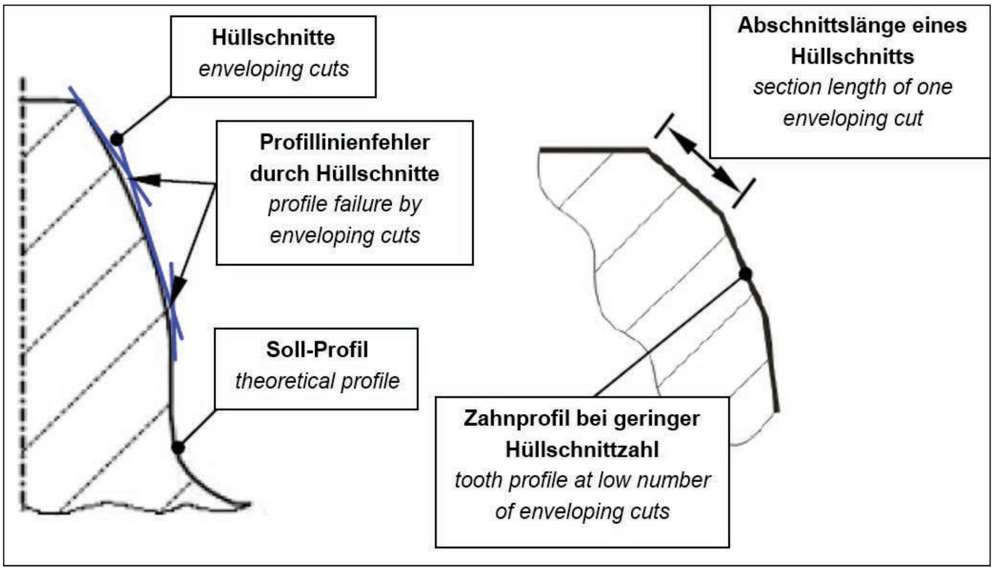

*Figure 9: Enveloping cut failure ('faceting') by tangential operation of the finger cutter (Image: Schottel)*

damage risks (micro-pitting of the tooth flank). Through extensive studies, the permissible envelope cut deviation required to achieve standard required micro-pitting safety could be found theoretically by calculation and subsequently proven in respective tests *(Figure 10)*.

## DEVELOPMENT OF THE HTG TECHNOLOGY

Development of HTG technology continued at an increased pace from 2007 onwards. A comprehensive funding project, 'High-torque Gear for Rudderpropellers', was sponsored from 2008 to 2011 by the Investment and Economic Development Bank of Rhineland-Palatinate (ISB), and was executed by Schottel's development team together with other partners. During the course of this project, and also during subsequent further co-operation with TU Dresden, optimised 5-axis bevel gears with conventional macro and micro geometry, new tooth geometries and studied topographies were developed and ultimately tested on a 3,500kW offshore thruster.

A major objective of this project was to increase the operational reliability of large Rudderpropeller gearboxes, which are increasingly being used with exceptionally high annual operating hours and extended service intervals. Tests with large gears, whose production and testing is associated with enormous effort, were carried out at an early stage in the project. The results of this research were so promising that further co-operation projects were initiated with the participation of development engineers at Schottel's

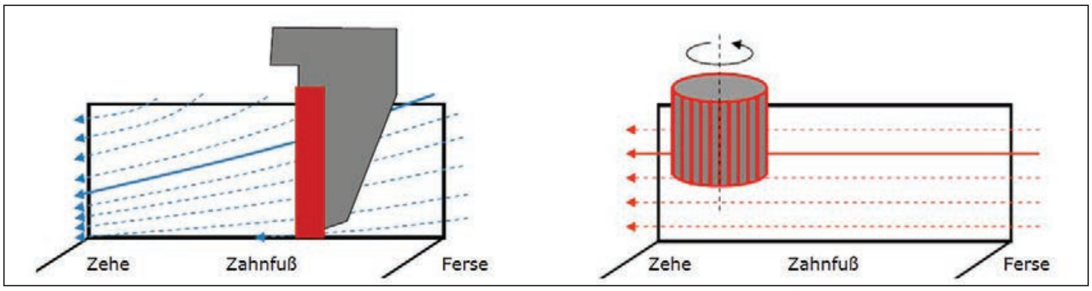

*Figure 10: Enveloping cuts in 5-axis milling/ enveloping cuts on a conventional machine*
*(Image: Klingelnberg)*

bases in Spay and Wismar and the Institute for Machine Elements and Machine Design at TU Dresden under the direction of Prof Dr Berthold Schlecht *(Figure 11)*.

Based on the excellent performance of standard bevel gears achieved in the meantime, with a very high manufacturing quality (typically of DIN3965 Q4), several new gearing characteristics were conceived and studied in the period up to 2011. These new features were specially tailored to the requirements of power transmission in the Rudderpropeller *(Figure 12)*.

Further features of the thruster gear sets of the future were developed, taking advantage of the virtually unlimited design possibilities of the 5-axis milling process, which aimed for significant performance improvements and increased safety gains. A total of seven independent beneficial gearing characteristics were defined and analysed. The main objectives were: the optimisation of production quality, increasing the load capacity, and the targeted increase of individual safety values for the teeth against the failure modes of foot fracture, pitting, sub-surface fatigue, scuffing and micro-pitting (grey staining) *(Figure 13)*. Some of these features are explained further below.

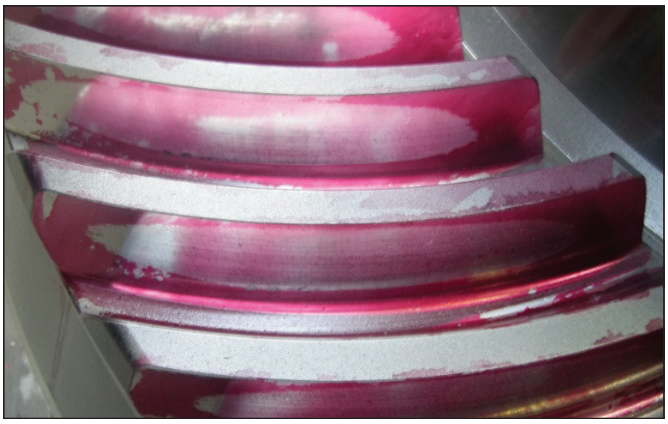

*Figure 12: Loaded contact pattern of a 3,500kW thruster gear. The relatively low contact width is specially designed for this application* (Image: Schottel, ISB Fördervorhaben Hochdrehmoment-Ruderpropeller, 2011)

*Figure 13: Typical types of gear damage of a bevel gear set* (Image: Schottel)

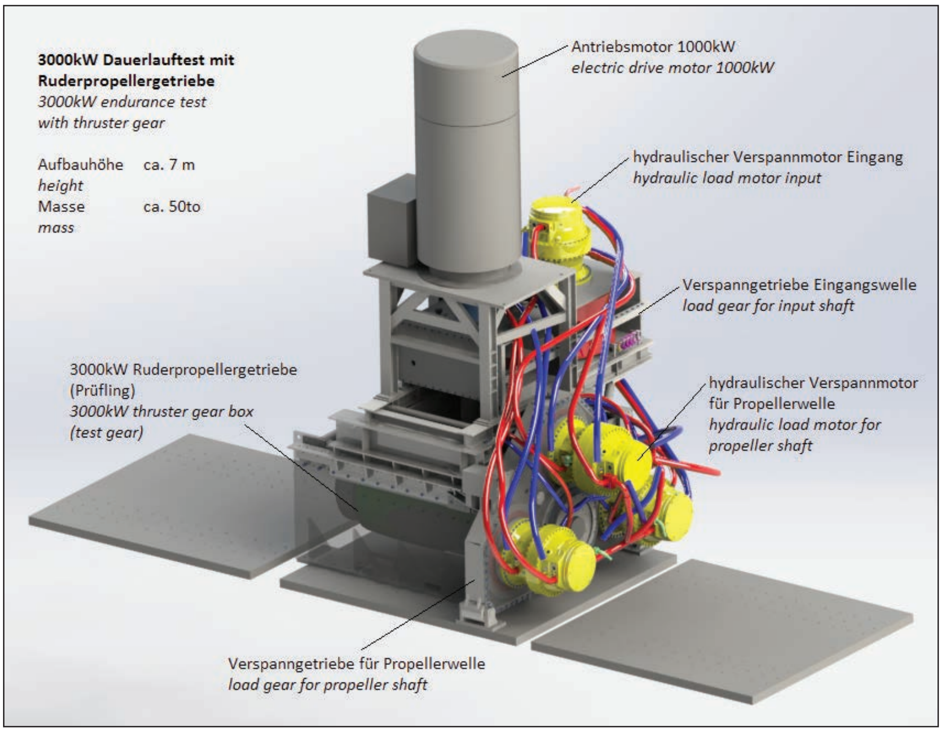

*Figure 11 (above and right): Test setup of a 3,500kW full-power test bench*
*(Image: Schottel)*

## FEATURE: ASYMMETRICAL PRESSURE ANGLE

In conventional bevel gear production on special machines with cutter head or grinding cup tools, standardised symmetrical pressure angles are usually applied, and the load flank and coast flank normally have the same pressure angle. The pressure angle indicates the steepness of the flank of the bevel gear *(Figure 14)*.

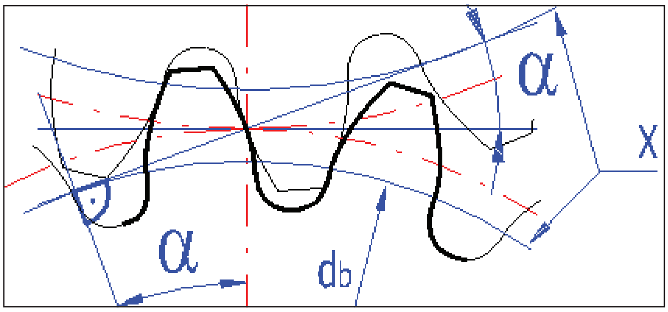

*Figure 14: Pressure angle α (Image: Mitcalc)*

A certain standardisation (typically α = 20 degrees) is required to limit the number of different tools, and hence guarantee economical production processes. By varying angle α towards larger pressure angles, the active flank area is increased. This positive effect of a gain in flank surface is lessened by the negative effect of an increased normal tooth force resulting from the unchanged transmitted torque.

With the kinematic freedom of 5-axis milling, any pressure angle of the load flank, and even varying pressure angles over the tooth width, can be machined. Thus the ‘asymmetrical tooth flank’ feature increases the load capacity of the gear set without increasing the external dimensions of the gears. Another positive effect is the reduction in the global surface sliding speed at the beginning and end of the tooth engagement. The increased pressure angle changes the tooth engagement from ‘sliding’ toward ‘rolling’, and this has a positive effect (for instance, on scuffing safety). The effect of reduced surface sliding speeds is so significant (approximately 20 per cent reduced sliding speeds) that the tooth height can also be increased without risk of excessive friction load. This additional improvement then results in even more torque capacity, and safety can be further increased *(see Figures 15, 16 and 17)*.

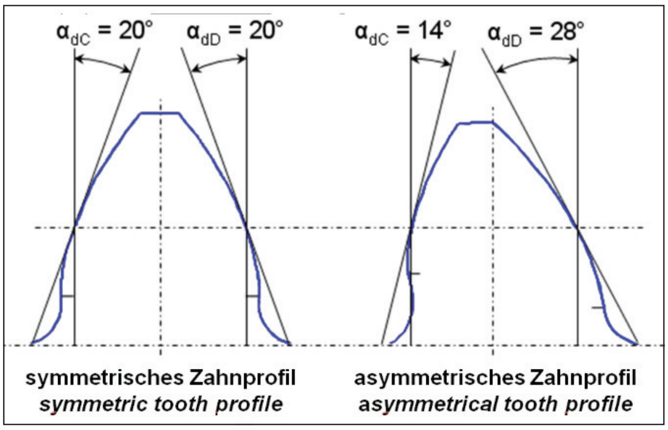

*Figure 15: Comparison of symmetrical and asymmetrical tooth profiles (Image: Schottel, Potts/Schaefer[3])*

The performance increase achieved in practical applications of asymmetrical thruster bevel gears amounted to approximately 15 per cent, still with the same safety factors. The distinct asymmetrical tooth shape results from the combination of an increased pressure angle of the load flank and a reduced pressure angle of the coast flank. The latter is necessary because at constant diameters of meshing gears, a flatter load flank cannot be achieved without an equally steeper coast flank, otherwise the teeth would not fit around the pitch circle circumference.

However, in the Rudderpropeller application this restriction is of no importance: as a 360-degree controllable drive unit, the Rudderpropeller can steer its thrust in any direction without reversing the propeller’s turning direction, so the thruster always uses the thrust-optimised direction of rotation of the propeller, and now also the load-optimised direction of rotation of the bevel gear.

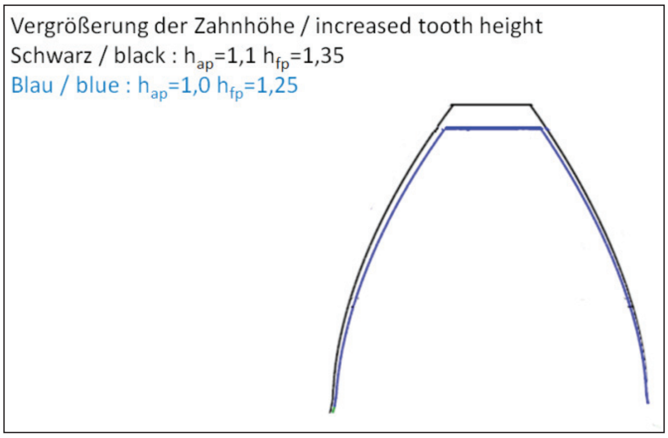

*Figure 16: Increased tooth height (Image: Schottel)*

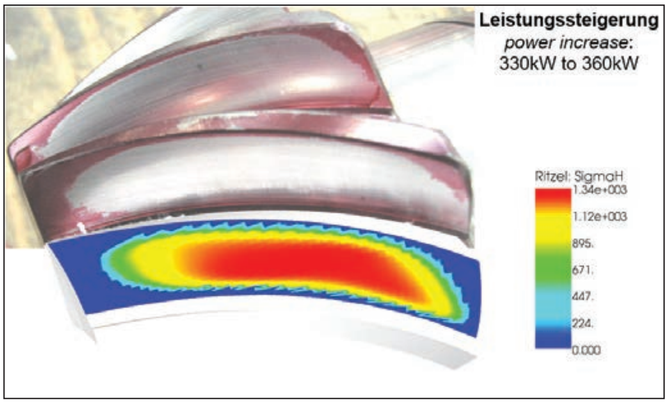

*Figure 17: Comparison of real and simulated contact patterns of asymmetrical HTG toothing (Image: Schottel, Potts/Schaefer[3])*

Provided that using the HTG technique is converted into a reduction in diameter of the gears, a slimmer gearbox nacelle can also be realised, offering further hydrodynamic advantages.

## FEATURE: FREE FLANK MODIFICATION (LOGARITHMIC CROWNING)

The asymmetry discussed above is a macro-geometric feature of the teeth. A much more complex approach was to design and implement a further idea: ‘free flank topography modification', with the aim of optimising pressure distribution on the tooth surface with reduced maxima.[3,4]

It should be noted that the gear bodies, in particular in the thruster application, in no way remain fixed on their axes of rotation. The underwater gear transmission of an azimuthing propulsor is a supporting component and has to bear the huge ship propulsion and steering forces. Consequently, it is subject to considerable deformations and displacements of its elastic steel structure, which have an adverse effect on tooth contact.

By using multibody simulation, we were able to forecast bevel gear displacements, considering not only the bevel gear forces at a static operation point, but also the influence of external forces on the structure, the structure's modal behaviour and the torsional behaviour of the power train *(Figure 18)*.

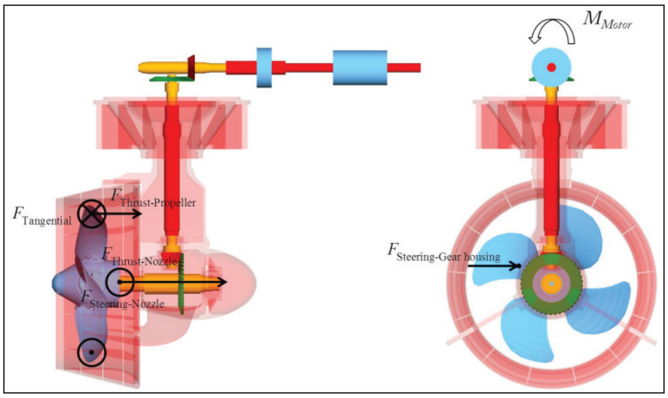

*Figure 18: Multibody simulation of the Rudderpropeller SRP 3030 CP* *(Image: Schottel/TU Dresden)*

Calculation possibilities were created in software that captured the tooth contact analysis of tooth flanks, mathematically defined with micron precision, taking into account the deformation of the shaft-bearing system and the housing. Using parametric studies, typical operating conditions were analysed, and appropriate flank topographies were developed and described mathematically.

The resulting 3D point cloud, a grid defined with micron precision describing the real tooth flanks, is the output of the software and also the direct CNC manufacturing specification for the 5-axis milling machine. The milling machine uses the tooth topography to precisely cut into the 700HV hard tooth surface *(see Figures 19 and 20)*.

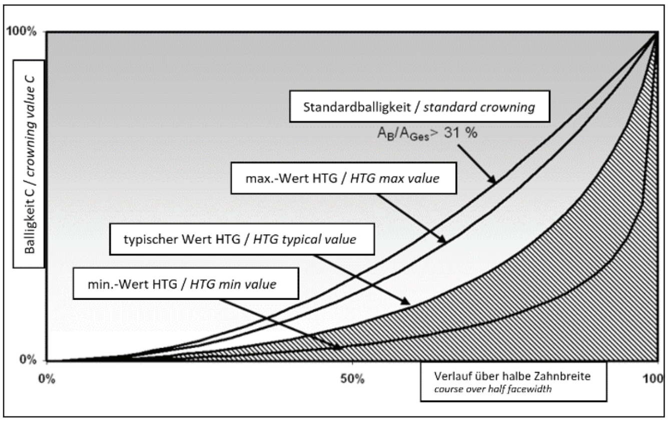

*Figure 19: Qualitative comparison of the flank modifications of standard vs HTG gear* (*Image: Schottel)*

In combination with the asymmetrical base shape of the bevel gear toothing, a theoretical performance improvement in torque load capacity of up to 30 per cent can be proven. In practical terms, a combination of performance and safety enhancement is normally chosen. Performance increases of 5-15 per cent have been realised in the applications so far, but stronger gears will follow in the near future. By using the

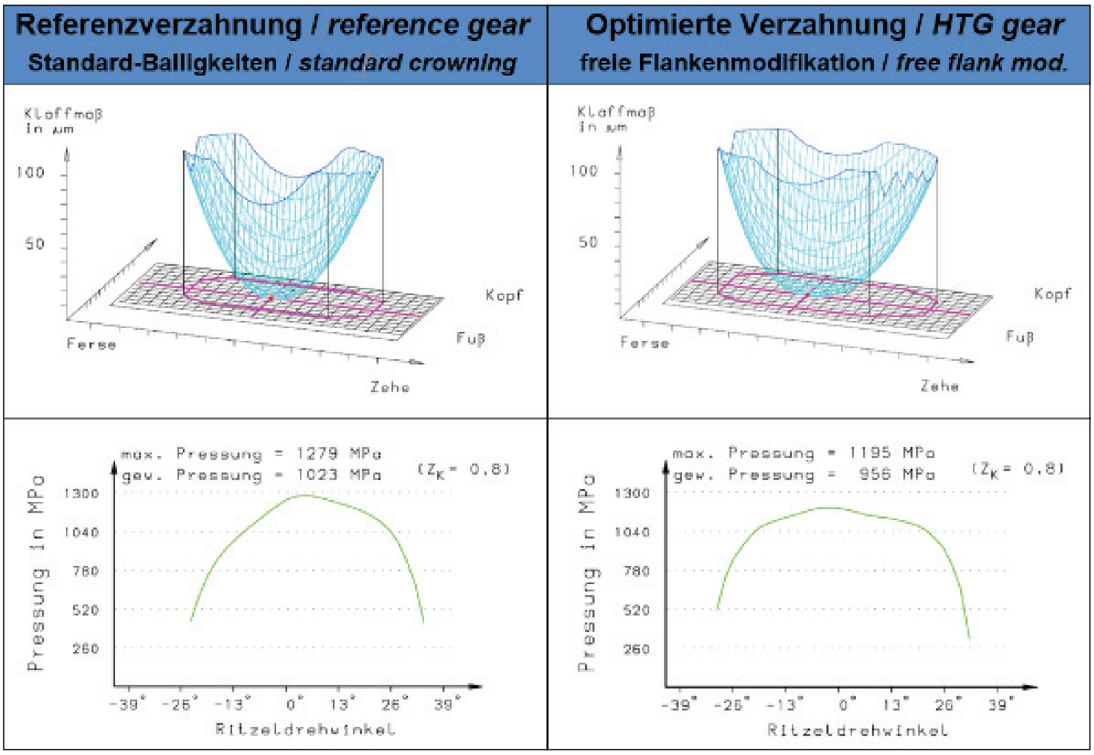

*Figure 20: Flank topography 'ease-off' of standard versus HTG toothing* *(Image: Schottel)*

GearDesigner software developed in co-operation with TU Dresden, gear design engineers have a powerful evaluation tool which allows targeted modification and optimisation with the same security for all the damage characteristics shown above.

The tooth surface can be modified using stored supporting curves (in particular, logarithmic and elliptical curvatures), which form the flank, specifically in the width and height directions. Through suitable modification, the highly-loaded centre of the flank is relieved and the high pressure zone falls flatter in the direction of the flank edges. Figuratively speaking, the standard flank topography is flattened like a cushion *(Figure 21)*.

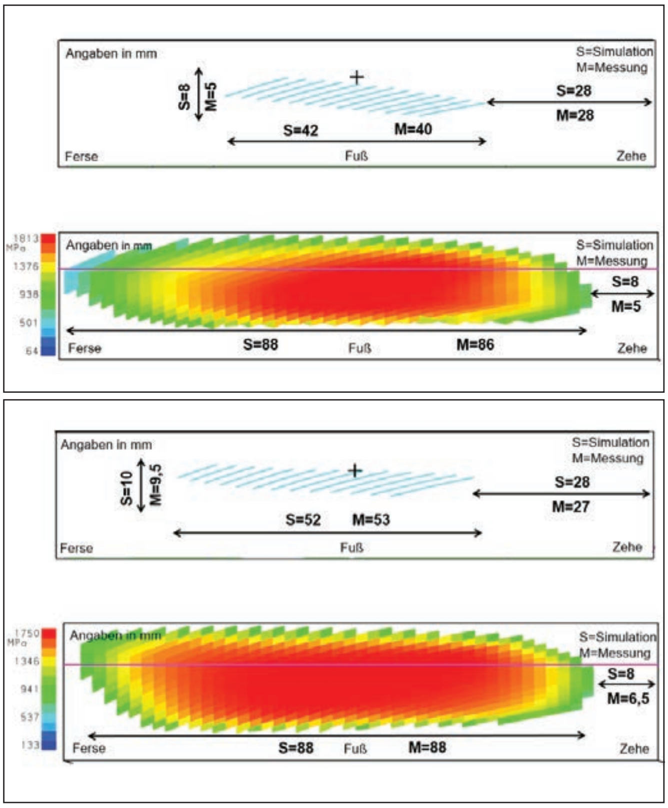

*Figure 21: Contact pattern development, comparison of load-free and loaded patterns standard crowning (top) vs logarithmic crowning (bottom)* (*Image: Schottel, Potts*[1])

For bevel gear sets of transverse thrusters with monoblock propellers (moulded from a single-piece propeller), free flank topography modification is of particular importance. With these drive systems, thrust direction can only be changed from the starboard to port side and vice versa by changing the propeller's direction of rotation. This means the bevel gear is operated with both directions of rotation and, consequently, on both flanks of each tooth.

Asymmetrical toothing is therefore not possible and the free flank topography modification remains as the relevant performance and safety enhancement measure, possibly even combined with an increase in the tooth height. Another advantage of 5-axis milling can be used here: both flanks can be individually designed, as the machine shapes the flank topographies independently of each other, in contrast to a standard bevel gear milling machine.

## FEATURE: ADAPTED FOOT CURVATURE, E.G. ELLIPTICAL FOOT CURVE

As shown above, damage risks such as sub-surface fatigue, pitting, scuffing and grey staining can be reduced and aligned through targeted design strategies using asymmetry and free flank modification. However, the thus-far unexamined criterion of foot breakage is negatively affected by the asymmetrical tooth design with its sharper tooth ground and wider pressure distribution (the design result of the overall higher tooth force of the HTG gear set). So the higher load on the flank area may cause problems in the notch of the foot radius *(Figures 22 and 23)*.

*Figure 22: Foot breakage of a bevel gear toothing*
*(Image: Schottel)*

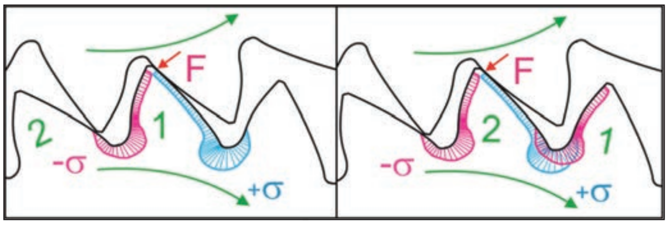

*Figure 23: Increased alternate bending stress in the foot ground of the asymmetrical toothing*
*(Image: Schottel, Potts/Schäfer*[3]*)*

The measure needed to mitigate this higher alternating stress load is simple, however, using the geometric freedoms of 5-axis gear milling. The given standard tooth foot radius, which is inevitably formed by the cutter head radius of the generating standard tools, can be replaced by suitable tooth foot curves of any shape with a lower notch effect, because in the 5-axis process even the foot curve consists of multiple cutting movements of a finger cutter or ball-shaped cutter.[3]

In earlier studies, especially for standard cylindrical gears, the means to increase the load capacity of the tooth foot have already been examined. Corresponding publications give recommendations for appropriate foot curves, including, for example, tangent or elliptical foot curves that are well known from the relevant literature (eg Mattheck, Voith, Linke, etc).[5,6,7] In principle, all these three named foot curvatures offer sufficient stress reduction potential to compensate the notch effect in the tighter foot ground of the asymmetrical HTG toothing.[3]

Using one of these favourable shapes resolves the tooth foot issue. In the GearDesigner software, the calculation engineer can check for the tooth foot stress load and safety factors after final design of the macro and micro geometry of the teeth, and then simply apply an appropriate size of foot curvature. In most cases, an elliptical shape is chosen.

The comparison in *Figure 24* shows the stress reduction potential of the various possible foot curvatures of similar dimension.

Further to the three features of asymmetrical toothing covered above, free flank modification and alternative foot curves, several other unique modifications can be used as a result of the new machining method. Schottel uses these various modification features of HTG technology in different ways. Depending on the objectives of the product development or product improvement process, selectively targeted modifications are applied. Safety can be increased, higher power can be achieved or gear dimensions can be reduced to obtain hydrodynamically favourable forms.

Other well-known beneficial technologies, such as shot peening of the tooth root and vibratory grinding of the tooth flanks, are often used in combination *(see Figures 25 and 26, overleaf)*.

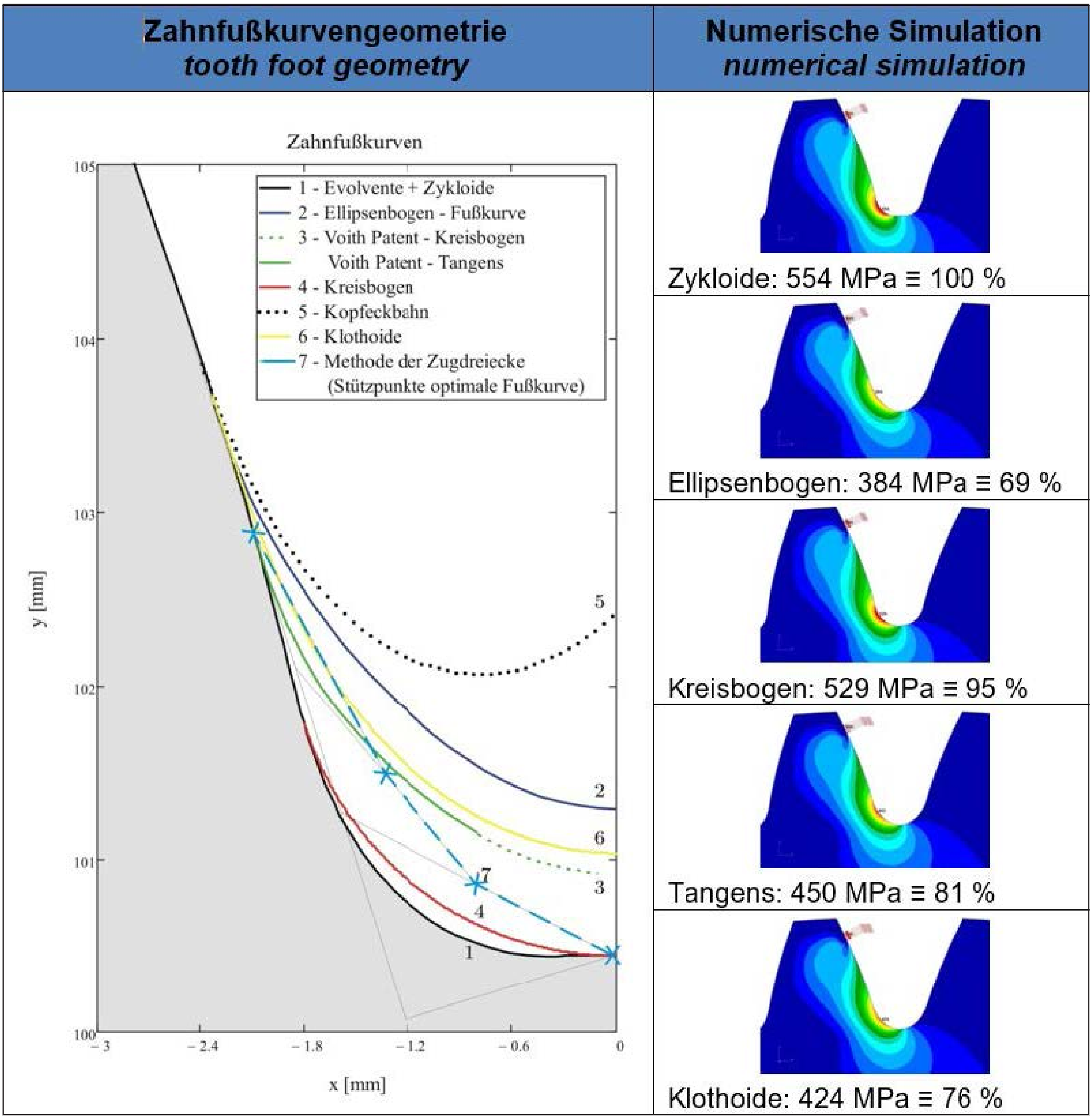

*Figure 24: Stress reduction potential by the elliptical foot curve of the HTG toothing* (Image: Schottel, TU Dresden)

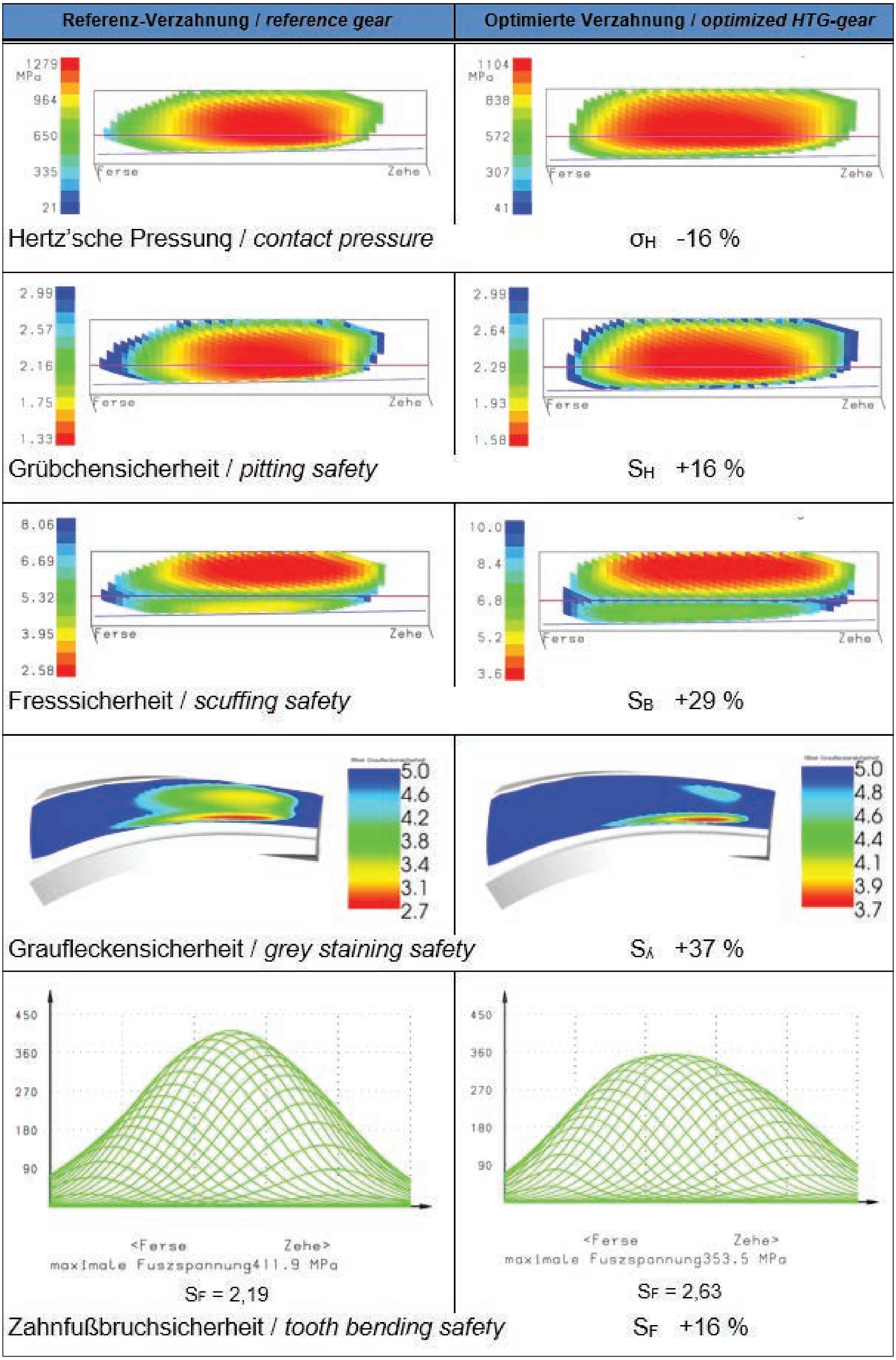

*Figure 25: Load and safety parameters of an optimised Rudderpropeller gear stage (Image: Schottel, Potts[1])*

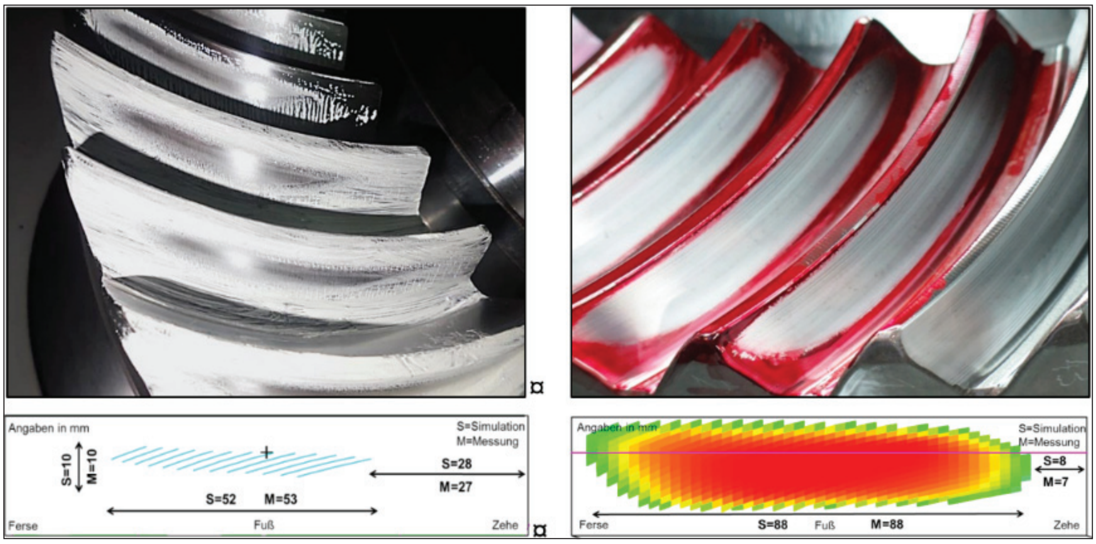

*Figure 26: Typical no-load and loaded contact pattern of an HTG flank at high load* *(Image: Schottel)*

## HTG = MORE POWER WITH GREATER SAFETY

### Patent right achievements

This paper describes some of the many novel features of the innovative HTG toothing technology. In particular, the combination of asymmetry and defined free flank topography modifications of the tooth flanks offers such a huge increase in performance that patent applications have been made for these and other features worldwide. HTG toothing currently enjoys legal patent protection in many countries around the globe, and patents have already been granted for Europe, Japan, USA, China and Korea. Other national applications are in the verification process or close to being issued.[8]

*Figure 27: Intentionally produced sub-surface fatigue damage (Schottel Hellbox)* *(Image: Schottel, Potts[1])*

### Practical experiences

From the beginning of the project it was clear that a development with such a high increase in performance could not be placed on the market without extensive testing to verify the theoretical studies. In addition to various tests on standard gear testing machines, the new gears have been tested in different sizes in parallel since 2011.

In a joint undertaking by the R&D department at Schottel, Spay and at TU Dresden, tests were carried out on different self-developed test machines in a power range up to about 2,000kW. All essential test parameters such as torque, speed, oil temperature and purity, vibrations (online FFT) were permanently monitored and recorded for later evaluation. Over a number of years of tests with specifically modified gear set batches, all the essential characteristics of damage could be checked and comparatively tested with standard gears under controlled conditions *(Figure 27)*. This main testing phase lasted from 2011 to 2015. A parallel test programme with structurally different test setups and on different scales in Spay and Dresden enabled independent assessment of the performance increases achieved.

Based on these experimental findings, a pilot series of technically safe HTG-equipped thrusters was put into use from 2013 onwards. These thrusters were introduced into deliberately selected harsh applications where conventional bevel gears were brought to their performance limit. HTG bevel gears can today be found in a variety of Schottel products, both new developments and proven products which have been upgraded in the wake of ongoing maintenance.

A current focus of development is to produce HTG technology on conventional bevel gear machines (cutter head and cup grinding wheel machines) from the current machine generation. Initial production operations have already been performed successfully, and by the end of 2016 an overall production possibility for such gear sets over the entire size range was available. The performance of the new toothing will therefore be combined with the productivity of the most modern specialised gear production machines. Following this developmental step, it will be possible for the HTG technique to be generally implemented.

Looking more closely at tug applications, where thrust is the main metric, the increased torque load capabilities of the HTG technology can be transformed into increased thrust values generated

*Figure 28: Schottel Rudderpropeller SRP 610 with HTG*

by the propulsion system. This meets new market requirements demanding higher bollard pulls while reducing environmental pollution. Applications with increased propeller diameter at lower rev/min to keep the tip speed level naturally lead to higher torques in the power train. These can be addressed by using HTG instead of increasing the outer dimensions of the bevel gears.

In combination with one of Schottel's new nozzles, such as the SDP 55 Schottel PowerDuct to maximise bollard pull, or the SDV 45 Schottel VarioDuct to generate high bollard pull while maintaining efficiency during transit operations, optimised tug propulsion is available for any application. HTG technology can also be used to increase bevel gear safety in order to meet impact overloads – such as rough environments or exceptional incidents like tree trunks hitting the propeller – with improved gearing safety.

*Figure 28* shows the new SRP 610, which benefits from the advantages discussed in this paper. The new SRP 360 has the same underwater housing size as the lower-powered SRP 340, thanks to the increased power density of the HTG. New developments at Schottel now always take into account the availability of HTG, and existing products can be upgraded, which is the case for the SRP 630 (formerly known as SRP 3030). The SRP 150 (the smallest representative among the HTG thrusters) and SRP 510, SPJ 220 and SRP 560 can also be assigned to the HTG family. In addition to the latest generation of sealing technology for propeller shafts and azimuth shafts with sealing solutions for bio-oils and alternative leakage discharge systems, this gear technology satisfies the needs of today's high-end performance tugs.

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