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AGMA Fall Technical Meeting Papers: 2012

12FTM01. *Balancing – No Longer Smoke and Mirrors* 1
Author: **R. Mifsud Hines**

In the late 1970's a balancing machine salesman visited a customer's plant who had just received a new balancer from the salesman's competitor. The plant manager said they were very happy with their automatic balancing machine and offered to show it to the salesman. The manager walked the salesman out on the floor and the two of them watched the operator and balancer in action.

The operator placed a part on the balancer and closed the door. The balancer spun up the part, welded on a weight, spun up again, and displayed "good part." The operator removed the balanced part, put in a new part, and closed the door. The balancer spun up the part, welded on a weight, spun up again, and displayed "good part." This scenario was repeated several more times as the salesman and the manager watched.

The manager commented, "We just love our new machine. All day long it balances parts by welding on weights and puts out good parts." The salesman suggested having the operator place a "balanced part" back in the balancer again just to see what would happen. So the operator placed the previously balanced part back in the balancer again and closed the door. The balancer spun up the part, welded on a second weight, spun up again, and displayed "good part." The manager had the operator take another balanced part and put it into the balancer again. Again, the balancer spun up the part, welded on another weight, spun up again, and displayed "good part." Suddenly the manager was not so happy with his balancing machine. It seems this machine was not balancing the parts at all. They had purchased an expensive welding machine to weld weights on their parts.

12FTM02. *Power Loss and Axial Load Carrying Capacity of Radial Cylindrical Roller Bearings* 11
Authors: **S. Söndgen, W. Predki**

The application of cylindrical roller bearings (CRB) is widely spread in mechanical engineering. CRB can carry comparatively high loads and are usable in high speed ranges. These bearings have been proven to be variously applicable and economic. With lipped inner and outer rings CRB permit the transmission of axial loads in addition to radial loads. The axial load is induced on the lip of the inner or the outer ring and transferred by the roller end face contacts to the opposing lip. In comparison to an only radially loaded bearing there are additional friction losses in the contact between the lip and the roller ends as a result of sliding.

The limiting factors for the permissible axial load are high temperatures which can cause smearing and seizing, lip fracture, fatigue failure and wear. In consequence of the axial loading the stresses in the contact between the roller and the raceway rise and the fatigue durability of the bearing is reduced.

At high speeds the permissible thrust load is dominantly limited by high temperatures. At low speeds the limiting factors are lip fracture and wear.

Within the examination an extensive test program with different bearing geometries is carried out. Thereby the decisive measurand is the friction torque of the bearings.

The friction torque of a thrust loaded radial cylindrical roller bearing is mainly dependent on the parameters speed, load, size and design of the bearing.

An analytical simulation model which has been developed at the institute allows calculating the lubrication conditions, the stresses within the lip - roller contact and the axial load dependent friction torque.

The intention of the study is to enlarge the application range of radial cylindrical roller bearings by means of a more precise determination of the thrust load capacity and to allow more economic designs.

12FTM03. *Gear Lubrication — Gear Protection also at Low Oil Temperatures* 22
Author: **M. Hochmann**

To find out if the high-performance gear oils of today are able to reliably protect gears and rolling bearings in gearboxes against damage also at a reduced oil temperature of 40°C, different high-performance gear oils were examined on an FZG back-to-back gear test rig as well as on an FE8 bearing test rig by modifying the standardized test methods. It has been shown that the advanced additive technologies used in today's high-performance gear oils are capable of inducing the required reactions on the surfaces of gears and bearings also at 40°C, thus providing reliable damage protection even under these operating conditions.

12FTM04. *Energy Efficient Industrial Gear Lubricants* 37
Authors: **D. Blain, A. Galiano-Roth, R. Russo, K. Harrington**

Global energy demand is predicted to be about 30 percent higher in 2040 compared to 2010. Energy demand growth will slow as economies mature, population growth moderates and efficiency gains accelerate. This paper will focus on the third factor: energy efficiency. The industrial sector consumes almost 48% of global energy, with the remainder being used for residential/commercial and transportation. Clearly, improvements in energy efficiency in the industrial setting can have a major impact on overall global energy use and resultant CO_2 emissions.

There are multiple sources of lubricant-related energy loss in industrial equipment in general, and gearboxes in particular. These include frictional losses due to metal-to-metal contact, frictional traction losses under elasto-hydrodynamic lubrication conditions and windage/churning loses in the bulk oil. All three of these factors can be improved by using a properly formulated lubricant, with carefully selected base oils and additives to improve efficiency.

ExxonMobil has developed a series of industrial lubricants that can reduce energy usage by up to 4% relative to conventional lubricants. These savings have been documented in both carefully controlled laboratory testing and in extensive evaluations in actual industrial equipment in the field. Experiments to measure lubricant-related energy efficiency benefits are inherently challenging. Valid determinations of these benefits require precise measurements and controls, meticulous attention to detail and appropriate statistical analysis. In addition to the energy efficiency benefits, these oils can reduce equipment operating temperatures, resulting in increased component and lubricant life. This leads to longer oil drain intervals, and less used oil disposal.

ExxonMobil defines sustainability as having three components: social development, economic growth and environmental protection. In addition to discussing all of the points above, this paper will also describe how the new energy efficient lubricants contribute to each of these sustainability attributes.

12FTM05. *Combined Effects of Gravity, Bending Moment, Bearing Clearance, and Input Torque on Wind Turbine Planetary Gear Load Sharing* 53
Authors: **Y. Guo, J. Keller, W. LaCava**

This computational work investigates planetary gear load sharing of three-mount suspension wind turbine gearboxes. A three dimensional multi-body dynamic model is established, including gravity, bending moments, fluctuating mesh stiffness, nonlinear tooth contact, and bearing clearance. A flexible main shaft, planetary carrier, housing, and gear shafts are modeled using reduced degrees-of-freedom through modal compensation. This drive train model is validated against the experimental data of Gearbox Reliability Collaborative for gearbox internal loads. Planet load sharing is a combined effect of gravity, bending moment, bearing clearance, and input torque. Influences of each of these parameters and their combined effects on the resulting planet load sharing are investigated. Bending moments and gravity induce fundamental excitations in the rotating carrier frame, which can increase gearbox internal loads and disturb load sharing. Clearance in carrier bearings reduces the bearing load carrying capacity and thus the bending moment from the rotor can be transmitted into gear meshes. With bearing clearance, the bending moment can cause tooth micropitting and can induce planet bearing fatigue, leading to reduced gearbox life. Planet bearings are susceptible to skidding at low input torque.

12FTM06. *Virtual Optimization of Epicyclic Gearbox Planet Bearings in Wind Turbines* 69
Authors: **S. Vasconi, D. Raju**

Demand for higher reliability, robustness and performance in epicyclical gearboxes have led SKF to develop Design for Six Sigma (DfSS) based simulation tools and methods.

This paper will illustrate the advantages of using simulation driven design in the development of planetary gearboxes for multi megawatt wind turbines. The simulation example will show the influence of the housing flexibility and of the non-linear bearing and gear stiffness on the gearbox performance under transient load. In particular the load distribution and deformation of the planetary gears and bearings will be analyzed.

The flexibility and accurate stiffness description led to non-intuitive results. The gear deformation and load distribution led to significantly different results compared to results obtained by using traditional calculation tools and methods. A comparison between advanced and standard calculation methods is given as evidence that advanced analyses should be used to design reliable, robust and high performing gearboxes.

A virtual design of experiments was used to determine the most influential parameters affecting the gearbox performance. This paper will highlight the results of this DfSS study.

12FTM07. *Validation of a Model of the NREL Gearbox Reliability Collaborative Wind Turbine Gearbox* 85
Authors: **C.K. Halse, Z.H. Wright, A.R. Crowther**

Gearboxes in the wind industry have been suffering from a poor reputation due to major issues with reliability. There has been a long list of issues; e.g. grind temper, material inclusions, axial cracking in bearings, poor load sharing on shaft-bearing arrangements, significant gear misalignment, bearing ring creep, gear scuffing, gear and bearing micropitting; all of which are common and often serial problems. There has been improvement in the last few years for some of the products, yet it is not uncommon for wind sites built as recently as 2008 to have 20 - 40% of gearboxes requiring a component replacement (such as a high speed pinion or intermediate shaft bearing) already (by 2012) and 5-10% complete gearbox failures. An important program for the industry, "*The Gearbox Reliability Collaborative*" (GRC), has been funded by the US Department of Energy and run by the National Renewable Energy Laboratory for several years to aid the industry in improving the reliability of this key component. The collaborative has brought together manufacturers, academia, national laboratories, engineering consultants and gear and bearing software providers as part of a program to model, build, simulate and test gearboxes with a goal to improve reliability and reduce the cost of energy.

The team at NREL have instrumented two gearboxes with over 125 channels, for measurements such as planetary tooth load distributions, annulus gear hoop strains, planet bearing load distribution, sun orbit and carrier deflection. They were then subjected to a rigorous testing regime, both up-tower and on the NREL 2.5MW dynamometer. Romax Technology have been a collaborator in the GRC Analysis Group and have developed detailed computer simulation models of the gearbox including gear macro and micro-geometry, bearing macro and micro-geometry, structural stiffness of gearbox housing, carrier and annulus gear, system clearances and preloads, and surrounding boundary conditions (such as main shaft, rotor hub and bedplate). The model is used for accurate simulation of the whole system deflections and the prediction of the resulting gear and bearing contact conditions under various loading conditions.

The focus of this paper is a comparison between measurement and simulation for key parameters including gear load distributions, annulus deflection and sun motion. The simulation results that are robust and those that are sensitive to hard-to-predict parameters that include significant effects from manufacturing and assembly variations will be outlined. Lessons learned in how best to apply computer-aided-engineering tools to improve wind turbine gearbox reliability will be described.

12FTM08. *Combined Marine Propulsion Systems: Optimization and Validation by Simulation* 97
Authors: **B. Pinnekamp and F. Hoppe**

Modern Navy and Coast Guard Vessels usually have combined propulsion systems using gas turbines, diesel engines and electric motors as main propulsors. Desired operating profiles demand for individual optimization of the gear propulsion system with respect to efficiency, noise, operational flexibility and capital cost.

Combined systems are complex and therefore sensitive to dynamic excitation and resonance. To avoid unfavorable dynamic effects, it is necessary to validate candidate arrangements using modern tools like multi body simulation.

The paper describes the evaluation process for optimized combined marine propulsion systems and system validation by dynamic simulation.

12FTM09. *Systematic Approach for the Psychoacoustic Analysis of Dynamic Gear Noise Excitation* 117
Authors: **C. Brecher, M. Brumm, C. Carl**

The sound quality of technical products is an increasingly important quality criterion and has a significant influence on the product acceptance. But sound quality does not only depend on the physical attributes of the sound signal. It is defined to a large extent by human sound and noise perception. This perception is based on a physiological and psychological signal processing. These aspects depend on complex properties of the physical signal like the spectral distribution and a relative comparison. However, today the sound design of gearboxes is mainly based on the physical reduction of the noise level that is detected by absolute and objectivized parameters. The noise oriented gear design is based on a fundament of physical key parameters like the reduction of transmission error in compliance with achievable manufacturing tolerances. Nevertheless, these design rules may lead to a minimal sound pressure level but cannot solely be applied for an optimal sound quality in every case. Under economic and technical aspects there is no excitation free gear set. Furthermore, modern tendencies such as lightweight design and masking noise reduction (engine downsizing and electrification) lead more and more to scenarios where the sound of a gear set, which is only designated to have low transmission error, can be perceived as annoying. This requires design guide-lines which take also the human related aspects of gear noise into account. Nowadays the gear design does not yet consider human noise perception sufficiently.

Thus, a research project at the WZL has been established that investigates the correlation between gear mesh excitation and the evaluation of gear noise. The objective of this project is to deduce a method for the consideration of perception-based noise evaluation already in the stage of gear design. Therefore, psychoacoustics metrics are used to analyze the gear noise of different gear sets in the dimensions of air-borne noise, structural vibration and the excitation due to meshing. The aim of this paper is to discuss the correlation between the signal properties of the excitation and the radiated noise in order to investigate the possibilities to transfer the perception related evaluation from sound pressure

to the gear mesh excitation. The paper firstly shows central psychoacoustic parameters that are most relevant for the properties of gear noise. Furthermore, a new test fixture will be introduced that allows a dynamic measurement of gear mesh excitation directly adjacent to the meshing. Regarding these aspects two different gear sets are discussed concerning the calculated transmission error and the experimentally determined excitation, surface vibration and noise radiation. These aspects are accordingly examined with respect to human noise perception, which is described by psychoacoustics . It is shown that operating conditions, order distributions as well as the gear geometry are the main influences on the signal evaluation. The influence of dynamic aspects and especially the influence of resonance effects on the noise characteristics are additionally considered.

Authors: **U. Sridharan, S. Kompella, S. Ji, J. Fiecoat**

The unique requirements of an electroplatable superabrasive CBN grit used in profile grinding of hardened steel gears as well as the attributes and grinding behavior of a new CBN developed specifically for this application are discussed. Profile gear grinding parameters were simulated in through-hardened AISI 4140 steel (56 HRC) and the grinding performance of the new CBN was compared against a competitive CBN grade widely used in the application. Consistent with field criteria, grinding performance was characterized based on occurrence of 'burn' or 'form' failure. The 'burn' or metallurgical phase transformation failure was detected by Barkhausen Noise Analysis (BNA) and corroborated by microstructural and microhardness evaluations. The 'form' failure was simulated by tracking average radial wheel wear to a threshold value where form loss was expected to occur. Grinding tests indicate that the new CBN grit can grind 35% more parts compared to the competitive CBN grade before burn failure. In addition, the new CBN displayed a lower wear rate. The new CBN grade also exhibited a unique ability to grind with lower grinding power, resulting in a near constant BNA response on the ground surface throughout the test. This implied minimal microstructural change on the ground part from start to end of the test compared to the progressive softening of ground surface noticed with the competitive CBN.

Author: **C. Kobialka**

Depending on production volumes, batch sizes and workpiece geometry, several gear manufacturing technologies are used for industrial gear production. Most frequently applied is the hobbing process, followed by broaching, shaping, sintering and rolling processes. Upcoming gear manufacturing processes are power skiving, forging, precision blanking and cold forging. Due to improvements to the numerical control of direct drive technology, the power skiving process has become a competitive gear manufacturing process in comparison to shaping, blanking and broaching. The potential of the reinvented power skiving process will be explained by production volume analyses, achievable gear quality and gear geometry modifications. Also the economical and environmentally friendly aspect of the power skiving process will be explained.

Authors: **I. Tsuji, K. Kawasaki, H. Gunbara, H. Houjyou, S. Matsumura**

In this paper, a manufacturing method of the pinion member of large-sized skew bevel gears using multi-axis control and multi-tasking machine tool considering that the gear member is provided is proposed. First, the tooth surface forms of skew bevel gears are modeled. Next, the real tooth surfaces of the gear member are measured using a coordinate measuring machine and the deviations between the real and theoretical tooth surface forms are formalized using the measured coordinates. It is possible to analyze the tooth contact pattern of the skew bevel gears with consideration of the deviations of the real and theoretical tooth surface forms expressing the deviations as polynomial equations. Moreover, the deviations of the tooth surface form of the gear member are fed back to the analysis of the tooth contact pattern and transmission errors, and the tooth surface form of the pinion member that has a good performance mating with the gear member. Finally, the pinion member is manufactured by a swarf cutting using multi-axis control and multi-tasking machine tool. Afterward, the real tooth surfaces of the manufactured pinion member were measured using a coordinate measuring machine and the tooth surface form errors were detected. As a result, although the tooth surface form errors were large relatively on the heel side, those were small on the other side. In addition, the tooth contact pattern of the manufactured pinion member and provided gear member was compared with those of tooth contact analysis. As a result, there was good agreement.

Author: **F.C. Uherek**

For gears larger than 3 m (10 feet), construction of gear blanks tend to divide into cast steel, ductile iron, and forged rim welded web structures for use in cylindrical grinding mills and kilns. This paper will review the application, various

options for material selection, and the impact of selection on tooth geometry. A group of sample gears are developed to compare each of the materials and method of blank construction. Each sample is discussed in light of structural stress, deflection, expected life, handling weight, material origin, fabrication method, inspection requirements during construction, and impact of selection on field performance. Based on the above, a roadmap is developed listing critical considerations and optimal use of each material and method of construction in this application.

Author: **M. Pasquier, and F. Wavelet**

Most of the large open gear sets for mining industry are designed according to AGMA 6014-A06 and AGMA 2001-D04. and rating according to AGMA standard (service factor) involve the final design of the pinion such as: material and heat treatment (through hardening or case carburized pinion), and the finishing process of the teeth (to achieve the design geometry).

Basically, customer specification and rating according to AGMA standard (service factor) involve the final design of the pinion such as: material and heat treatment (through hardening or case carburized pinion), and the finishing process of the teeth (to achieve the design geometry).

Moreover, the increase of applied load for a single meshing becomes a new challenge.

In addition to the mechanical properties for the material used and its associated heat treatment requirements given in standards, elastic and thermal behaviour and resulting accuracy, as well, have to be taken into account at design stage, even for large open gears.

Beside design consideration, such increase of single meshing load cannot be achieved by using conventional manufacturing and quality control methods.

Therefore, improvements in manufacturing process and in quality inspections for such heavily loaded single large parts, as already performed for smaller parts in batch are now mandatory to achieve these new design requirements.

Based on examples, in this paper, it is presented such manufacturing and the associated quality controls improvements from steel fabrication to final machining for heavy parts, to ensure the customer that the result meets the specification requirements.

Authors: **C. Wirth, B.-R. Höhn, C. Braykoff**

A failure mode called "flank breakage" is increasingly observed in different applications of cylindrical and bevel gears. These breakages typically start from the active flank approximately in the middle of the active tooth height and propagate to the tooth root of the unloaded flank side. Crack initiation can be localized below the surface in the region between case and core of surface hardened gears. This failure mode can neither be explained by the known mechanism of tooth root breakage nor by the mechanism of pitting. Even bevel gears in truck and bus applications are at the risk to suffer from subsurface fatigue, if the optimum utilization of the material should be achieved. In this case a balance between the flank breakage and pitting risk has to be found. The purpose of this paper is to describe a new material physically based calculation method to evaluate the risk of flank breakage versus the risk of pitting. The verification of this new method by experimental tests is exemplarily shown.

In cooperation with "ZG - Zahnräer und Getriebe GmbH" (ZG) "MAN truck and bus AG" (MTB) developed a new method for the calculation of the risks of flank failure by flank breakage and pitting. The calculation method has been adjusted and approved by experimental tests on powertrain test rigs of MAN. The ten different test gear variants had an outer diameter of d_{e2} = 390 mm to 465 mm, a ratio i = 4,5 to 5,7 and a normal module of m_{mn} = 6 mm to 8 mm. Also variants with the same main geometry but different Ease-Off designs were examined. All gear sets were tested under a defined load spectrum. Based on the research work at the FZG (Gear Research Center at the Technical University of Munich in Germany) of Oster, Hertter and Wirth a calculation method for bevel gears was established. The principle of the calculation model is the local comparison of the occurring stresses and the available strength values over the whole tooth volume. Therefore it is possible to evaluate the risk of initial cracks beyond the surface of the flank. Close to the surface cracks may grow and cause pitting - especially in the flank area with negative specific sliding. Cracks in the transient area between case and core lead to a high flank breakage risk.

First the local stresses and forces on the flank are determined by a loaded tooth contact analysis followed by the calculation of the maximum exposure (regarding yielding) and dynamic exposure (regarding fatigue) of the material inside the tooth. Thereby the stress components from the Hertzian contact, bending, thermal effects (flash temperature) and friction are considered. Furthermore the positive effect of residual compressive stresses and accordingly the disadvantageous effect of the residual tensile stresses can be implicated. Finite elements method investigations have been carried out in order to achieve a sufficient approximation of the residual stress distribution in the transverse tooth section. The strength values are locally considered, depending on the material depth and the position on the flank.

The recalculation of the test gears showed a good correlation between the occurred type of damage and the determined material exposure inside the tooth. The variants failed with flank breakage could be reliably distinguished from the variants failed by pitting by the new material-physical method. With this knowledge it is now possible to optimize the main geometry parameters of the gear set (e.g. number of teeth, spiral angle, pressure angle) as well as the micro geometry (Ease-Off) that influences the load distribution on the flank. Altogether this new method leads to an insured increase of the permissible material utilization and hence to smaller gear sizes while keeping the load capacity on a constant level.

12FTM16. *Gear Design Optimization for Low Contact Temperature of a High-Speed, Non-lubricated Spur Gear Pair* 232

Authors: **C.H. Wink, N.S. Mantri**

This paper presents a gear design optimization approach that was applied to reduce both tooth contact temperature and noise excitation of a high-speed spur gear pair running without lubricant. The optimum gear design search was done using the RMC (Run Many Cases) program from The Ohio State University. Over 480 thousand possible gear designs were considered, which were narrowed down to the 31 best candidates based on low contact temperature and low transmission error. The best gear design was selected considering, also, its manufacturability. The selected optimum gear design was compared to an existing gear set using LDP (Load Distribution Program) from The Ohio State University. Tooth contact temperature was calculated for both designs using dry a steel-on-steel coefficient of friction. Predicted contact temperature correlated well with results observed on dynamometer tests with the existing gear set. Predictions with the optimized design showed a 48% contact temperature reduction and a 79% noise excitation reduction. The low contact temperature of the optimized design will significantly contribute to preventing tooth surface damage under no lubricant operating conditions.

12FTM17. *Dynamic Analysis of a Cycloidal Gearbox Using Finite Element Method* 241

Authors: **S. Thube, T. Bobak**

Speed reducers incorporating cycloidal technology as their primary reduction mechanism have always been active topics of research given their unique trochoidal tooth profile. A cycloidal reducer is recognized for its strength and mainly studied for rotational performance improvement. Nowadays, this study can be performed by digital prototyping, which has become a valuable tool for simulating exact scenarios without experimenting on actual model.

This paper discusses the stress distribution, modeled in a dynamic simulation environment, on the rotating parts of Cycloidal reducer. A three dimensional finite element model is developed using Algor FEA commercial code to simulate the combined effect of external loading and dynamic as well as inertial forces on one-cycloid disc system. This model utilizes surface-to-surface contact to define interaction between rotating parts of the reducer assembly. The results are analyzed for the variation in stress and deformation with respect to time for a certain simulation period. This study gives an insight of internal load sharing of rotating parts and their capability of carrying shock loads.

12FTM18. *Analysis of Ripple on Noisy Gears* 254

Author: **G. Gravel**

A low noise level is an important quality feature in modern gearboxes for passenger cars. But a troublesome noise can have many causes. The noise origination and transmission is amongst others affected by the design layout, by the actual deviations of the components, by the assembly of the components and also by the mounting situation of the complete gearbox.

Damages, form errors and displacement errors or ripples are often present on the flanks of a gear, if it is found to be the cause of problems in a noise check. Especially ripples or 'ghost frequencies' of a gear are problematic, because up to now they rarely can be detected on a gear measuring device but only in a relative complex single-flank roll checking procedure.

A new evaluation method now allows to identify and to describe ripples on the flanks of gears based on the results of a normal gear measurement. The deviation curves were approximated by sine functions, the results are displayed graphical and by characteristic values. A combination of the deviation of each measured point with its rotation angle allows an evaluation equal to a rolling with the mating gear. The results show a very good correlation to a noise check and to a single-flank roll check.

The application of the software is demonstrated by practical examples of the manufacturing methods generating grinding, honing, broaching and shaving. Vibrations of machine tool and ripple generating influences in the manufacturing process can be verified down to a level of a few tenth micrometers. At the same time this method is well suited to describe long-wave form deviations like an ovality or a 3- or 4-fold ripple caused by the clamping or by a square blank.

With this new evaluation method gears can be tested in an early state of production for known, critical ripples and conclusions can be drawn on the state of machine tool, cutting tool and clamping device.

12FTM19. *A Field Case Study of "Whining" Gear Noise in Diesel Engines* 265
Author: **Y. Kotlyar, G.A. Acosta, S. Mleczko, M. Guerra**

The proposed paper is a field case study of diesel engine .whining. gear noise. The paper will describe the development work performed to reduce the gear whining noise. It will include the problem definition, inspection of BOB & WOW engines, design of experiment, development and review of gear geometry modifications, inspection charts, sample size for a statistically significant analysis, and correlation of noise measurement results and tooth profiles.

12FTM20. *The Effect of the Surface Profile on Micropitting* 278
Authors: **M. Bell, G. Sroka, R. Benson**

A wide choice of surface roughness parameters is available to characterize components, such as gears or bearings, with the goal of predicting the performance of such metal-to-metal contacting parts. Commonly in industry, the Roughness Average (R_a) or the Mean Peak-to Valley Height ($R_{z\,(DIN)}$) is chosen to calculate the Specific Film Thickness Ratio for both superfinished and honed surfaces. However, these two surface roughness parameters fail to adequately predict the performance properties of surfaces that are superfinished or surfaces that are honed. In this paper, a superfinished surface is defined as a planarized surface having a ≤ 0.25 μm R_a. A honed surface is not considered to be planarized, even with a finish of ≤ 0.25 μm R_a. Thus, one is falsely led to predict that a planarized surface or a honed surface, having an equivalent R_a or R_z, will perform similarly. Nothing is further from the truth. Experimentally, an isotropic planarized surface delivers superior performance. The following discussion utilizes another roughness parameter, $3\sigma_{50}$, to further explain this phenomenon.

12FTM21. *Typical Heat Treatment Defects of Gears and Solutions Using FEA Modeling* 293
Authors: Z. Li, B.L. Ferguson

Steel gears are heat treated to obtain enhanced properties and improved service performance. Quench hardening is one of the most important heat treatment processes used to increase the strength and hardness of steel parts. Defects seen in quenched parts are often due to high thermal and phase transformation stresses. Typical defects include excessive distortion, surface decarburization, quench cracks, large grain growth, and unfavorable residual stresses. Gear geometries with large section differences may suffer high stress concentrations and crack during quenching. Surface decarburization before quenching may lead to high surface residual tension and possible post heat treatment cracking. In this paper, the commercial heat treatment software DANTE is used to investigate three examples of heat treatment defects. Improved processes are suggested with the help of modeling. The first example is an oil quench process for a large gear. Peeling cracks were observed on the gear surface during grinding of the quench hardened gears. Computer modeling showed that surface decarburization was the cause. The second example is a press quench of a large face gear. Unexpected large axial bow distortion was observed in quenched gears, and computer modeling indicated that an incorrect press load and die setup were the reasons. The third example is an in-process quenching crack caused by high concentrated tensile stress from unbalanced temperature and phase transformations in a spiral bevel pinion gear. The quenching process was modified to solve the problem. This example also emphasizes the need for heat treatment modeling in gear design to reduce the possibility of heat treatment defects. The three examples illustrate how to effectively use heat treatment modeling to improve the quality of the gear products.

12FTM22. *Crack Testing and Heat Treat Verification of Gears Using Eddy Current Technology* 307
Authors: **D. DeVries**

While eddy current technology has long been used in the testing of bar, tube, and wire stock, advances in electronics, automation, and coil design have paved the way for a new generation of testers specifically designed for component testing applications. This includes the testing of gears and bearings which go into automotive and industrial applications. These testing systems easily integrate into production processes allowing for in-line testing at production line speeds. In addition to enabling 100% of production components to be inspected, it can help monitor upstream processes notifying operators that something is not functioning correctly. This greatly reduces scrap and warranty costs for gear and bearing manufacturers.

Eddy current crack testing is performed by passing a small pair of coil windings over a section of the component to be tested. These coil windings are small enough to test between gear teeth, and with multi-coil probes can test very complex shapes. Most crack test applications require only one test frequency since most tests require the detection of only surface flaws. Simultaneous testing with multiple frequencies allows for testing of both surface and sub-surface defects when inspecting nonferromagnetic parts.

While not an absolute hardness test like a Rockwell test, eddy current heat treat verification can achieve sorting results on par with Rockwell testing. This has been demonstrated with both forged and powder metal gears. Eddy current heat treat inspection coils come in both standard encircling coil configurations and multi-coil custom configurations. The custom configurations allow for precise location testing verifying that induction heating parameters were correctly applied. Defects to be tested include misplaced case, shallow case, short quench, delayed quench, air cooled, non-heat-treat, and ground out conditions. When performing heat-treat inspection, multiple test frequencies are used to reliably detect these various heat-treat anomalies.

Eddy current testing offers fast, repeatable testing of gears and bearings. Testing data on each component can be stored electronically and re-analyzed off-line at a later date. Eddy current test instruments are designed to integrate with PLC's in material handling stations to set up real-time rejection capabilities. These are all features that complement modern QC requirements.

12FTM23. *Enhancing Control Of Distortion Through "One Piece Flow – Heat Treatment"* 316
Authors: **V. Heuer, D. Bolton, K. Löser, T. Leist**

Proper control of distortion has become even more important on new powertrain designs. To answer the demand for fuel-efficient vehicles, modern transmissions are built much lighter, therefore the components of the transmission exhibit less wall thickness which makes them more sensitive to distortion. Distorted gear components can create noise in the transmission, require post heat treat machining processes and may even create problems during transmission assembly.

By applying the technology of Low Pressure Carburizing (LPC) and High Pressure Gas Quenching (HPGQ), the distortion caused by heat treatment can be significantly reduced. This technology has been successfully established in serial production for many different gear applications.

With the introduction of 'One Piece Flow - heat treatment', the distortion control can be further enhanced. This 'One piece Flow – heat treatment' allows for a rapid case hardening where the components are low pressure carburized at high temperatures (1050 C) followed by gas quenching. The components are not treated in conventional big batches with multiple layers, but they are treated in small batches consisting of one layer only. The quench intensity is controlled more precisely to allow for processes which are customized individually for each gear-component. The single-layer treatment provides

- homogenous and rapid heating of the components,
- homogenous and rapid carburizing of the components,
- homogenous and precisely controlled gas quenching.

All the variations from layer to layer are eliminated, which leads to reductions in distortion-variation within the load.

In addition, this new technology allows strong costs-savings for logistics. The manufacturing-line can be completely automated since the parts are 1^{st} taken one by one from the soft machining unit, then 2^{nd} heat treated in time with the cycle-time of soft machining ("Synchronized heat treatment") and then 3^{rd} passed down one by one to the hard machining unit. The paper presents applications for enhanced distortion control when using 'One Piece Flow - heat treatment'.

12FTM24. *Recent Inventions and Innovations in Induction Hardening of Gears and Gear-like Components* 330
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Presentation focuses on recent inventions and innovations (last 4-6 years) in induction hardening of gears and gear-like components, including but not limited to:

- "Know-how" in controlling distortion of induction hardened gears.
- Simultaneous dual-frequency induction hardening.
- Advanced induction hardening process recipes when hardening small and medium size gears.
- Novel inductor designs to minimize a distortion when induction hardening of hypoid and spiral bevel gears.
- IFP technology for induction gear hardening.
- Induction tempering and stress relieving of gear-like components with improved temperature uniformity.

Presentation also provides a review of basic principles and applications devoted to induction hardening small, medium and large size gears using tooth-by-tooth techniques and encircling method.