Introduction

Gears for e-drives require tighter tolerances and specific geometrical modifications. Advanced gear grinding technology meets these requirements. The presentation focuses on hard-finishing technologies that increase load-bearing capacity, control the gears' macro and micro geometry, modify the surface structure and cope with geometrical interference contours

Scope of Presentation

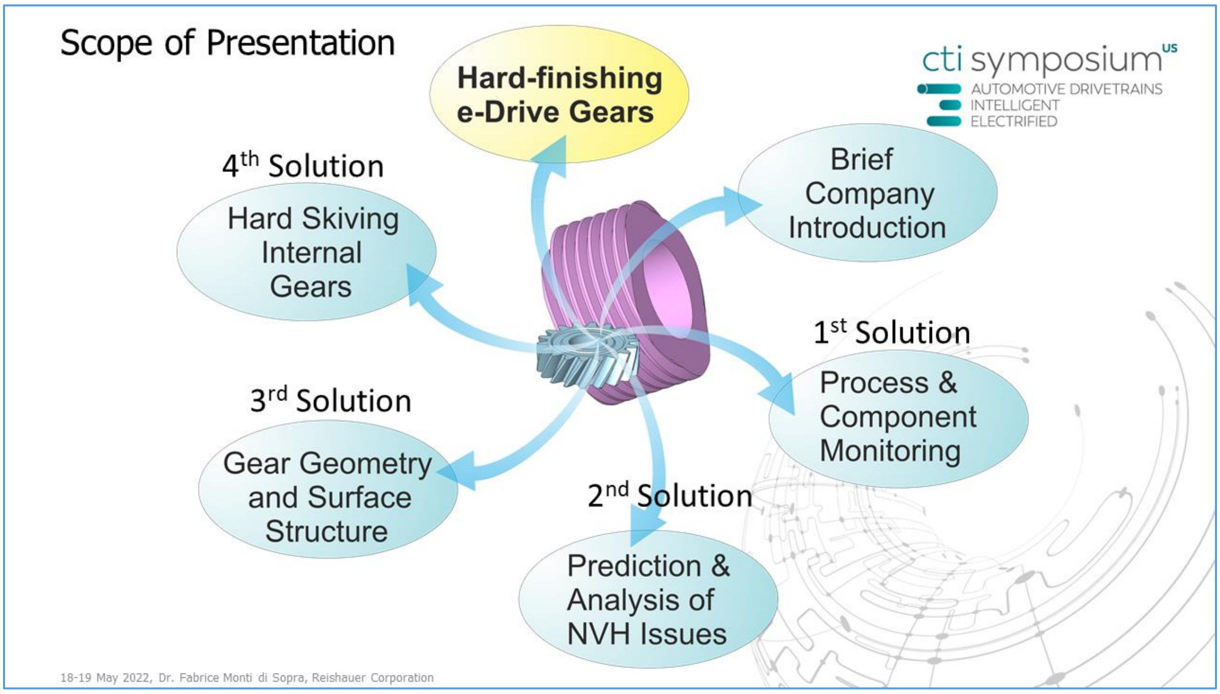

Figure 1 - Scope of presentation

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The presentation starts with a brief introduction of the company and subsequently highlights four solutions for generating gear grinding of e-drives:

1. Process and component monitoring
2. Prediction and analysis of NVH
3. Gear geometry and surface structure (Low Noise shifting, polish grinding, Twist Control grinding)
4. Hard skiving of internal gears

Brief Company Introduction

Reishauer AG is a Swiss company with an American subsidiary, Reishauer Corp, in Elgin, IL. While Reishauer produces gear grinding machines for the automotive transmission industry, its scope of activity is much wider than just building machine tools. Reishauer's "Circle of Competence" encompasses machine, automation, grinding wheels, diamond dressing tools, workholding, grinding technology support functions, process monitoring equipment, and digital products such as ARGUS. Having the complete portfolio, all of which is manufactured in-house, gives Reishauer the full understanding and control over the complete process of hard finishing gears.

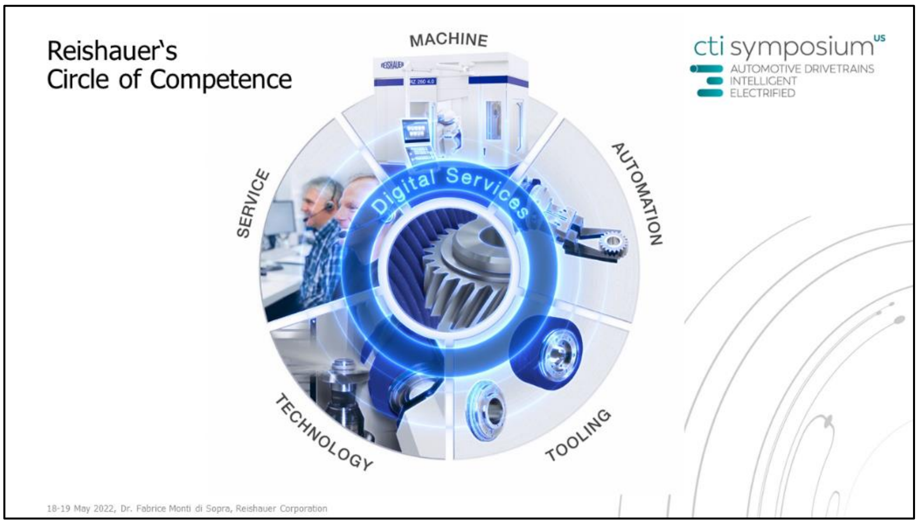

Figure 2 – Circle of Competence

Reishauer has invented the process of continuous generating gear grinding in the 1940s and has improved on the process ever since. It would be fair to say the continuous generating gear grinding process has proven itself the most efficient way of hard finishing precision gears.

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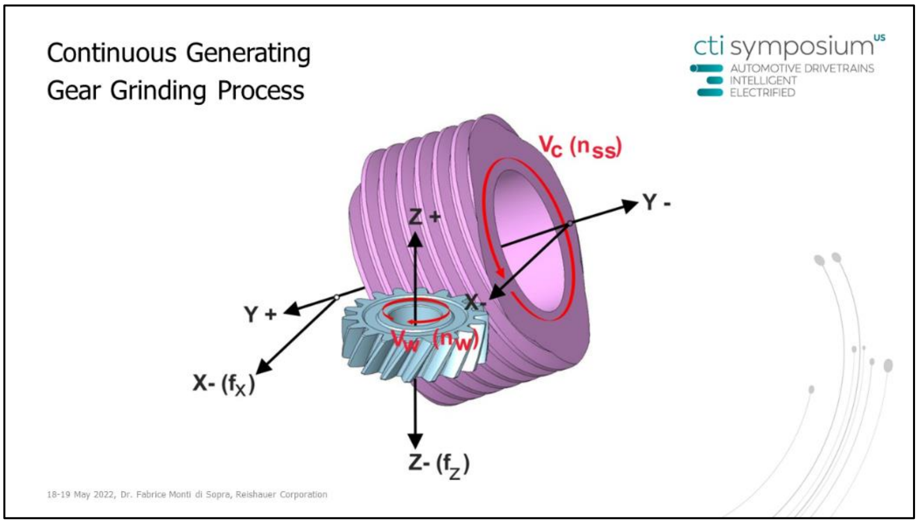

Figure 3 – Continuous generating gear grinding process

In principle, the kinematics of the continuous generating gear grinding process, as shown in Figure 3, can be understood as a worm drive, as shown on the slide, with an additional abrasive machining process consisting of an infeed X, a vertical feed-rate Z, and a lateral shifting motion Y, all working together simultaneously.

Grinding Process and Machine Component Monitoring

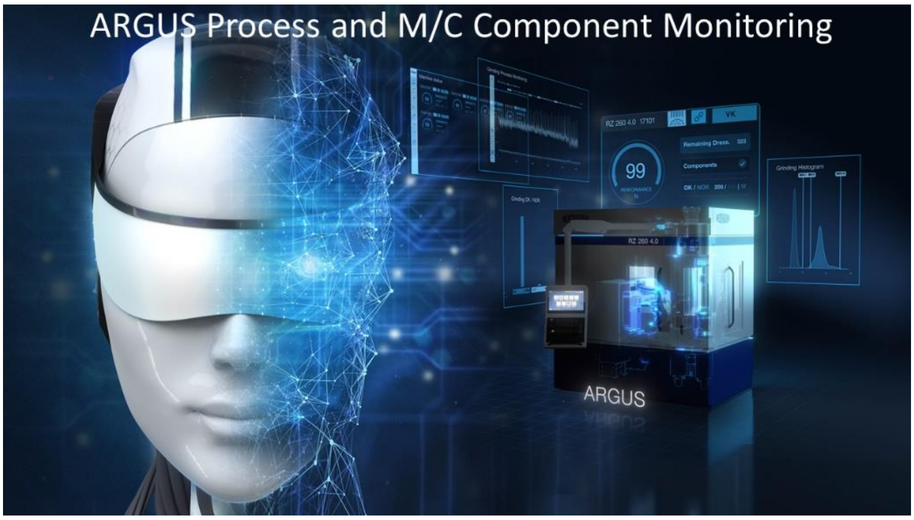

Figure 4 – Argus process and component monitoring

One of the essential features of the generating gear grinding machine is the high output within a brief period. For example, for automotive transmissions, grinding cycle times range from 8 seconds for small pinions to one minute for ring gears. For this reason, not all ground parts can be measured by CMMs due to the measurement times being much higher than the grinding times and the prohibitive costs this would incur. For this reason, the automotive gear industry relies on sample measurements, which represent only a tiny fraction of the total manufacturing lot, generally not

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higher than five percent.

The continuous grinding process is considered stable and robust as repeated diamond dressing, and the shifting during grinding guarantees a constant high-quality level. However, new gear testing methods are investigated, given that the gears are subjected to ever-increasing quality demands. More significantly, a 100% checking and constant monitoring of the grinding process gains in importance. The sample testing processes used in the automotive gear industry carry the remaining risks that gears of insufficient quality may end up inside transmissions. Furthermore, the tactile measuring methods of CMMs are, as a rule, not capable of picking up minor waviness on the surface structure of gear flanks that may cause detrimental noise (NVH) in transmissions.

The remaining risk of introducing workpieces of insufficient quality can be substantially lowered if the grinding intensity generated during the machining process is used as an evaluation criterion. The real-time analysis of the intensity signal identifies a faulty workpiece during the grinding process if the set signal thresholds have been exceeded. Moreover, this method translates into a 100% checking of the workpieces. Consequently, faulty workpieces can automatically be removed from the manufacturing process. Reoccurring defective workpieces are recognized as a systematic error that leads to a stoppage of the grinding process with a corresponding error message to the operator.

The cause of exceeding the grinding intensity could be too much or too little grinding stock, hardness distortions, or excessive out-of-roundness from the pre-machining process. The system features integrated sensors to check the dimensions of the pre-machined gear parts. Excessive out-of-roundness or cumulative pitch errors automatically results in an additional grinding stroke or the rejection and removal of the workpiece if the system determines that additional grinding strokes would not produce a good part.

"Grinding intensity" in the ARGUS system is a force model to calibrate and standardize the grinding forces. The force model considers the continually changing chip forming zone, including the local cutting kinematics during changes in the grinding wheel diameter, the changing grinding condition due to variations in wheel RPM, and the prevalent lever ratios across the grinding wheel width in relation to the grinding spindle bearing which supports the wheel on one side only. This standardization and calibration allow the setting of very narrow thresholds, which can be detected and automatically evaluated during the process. A typical progression of a 2-step grinding intensity signal is illustrated in Figure 5, as it appears on the machine tool's CNC monitor. The higher dark blue area on the left corresponds to the roughing pass, and the lower dark blue area on the right corresponds to the finishing pass. The upper limit of the roughing grinding pass is set at 55, while the process runs at an intensity of 48. For the finishing pass, the upper limit is set at 33, with the process running at an intensity of 25. Hence, roughing and finishing are well within limits. The workpiece is

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automatically removed from the production cycle if the roughing or the finishing limits are exceeded. The limits are either suggested by the process monitoring system itself, based on statistical analysis, or set by the user who may have made their own experience over time and many production lots.

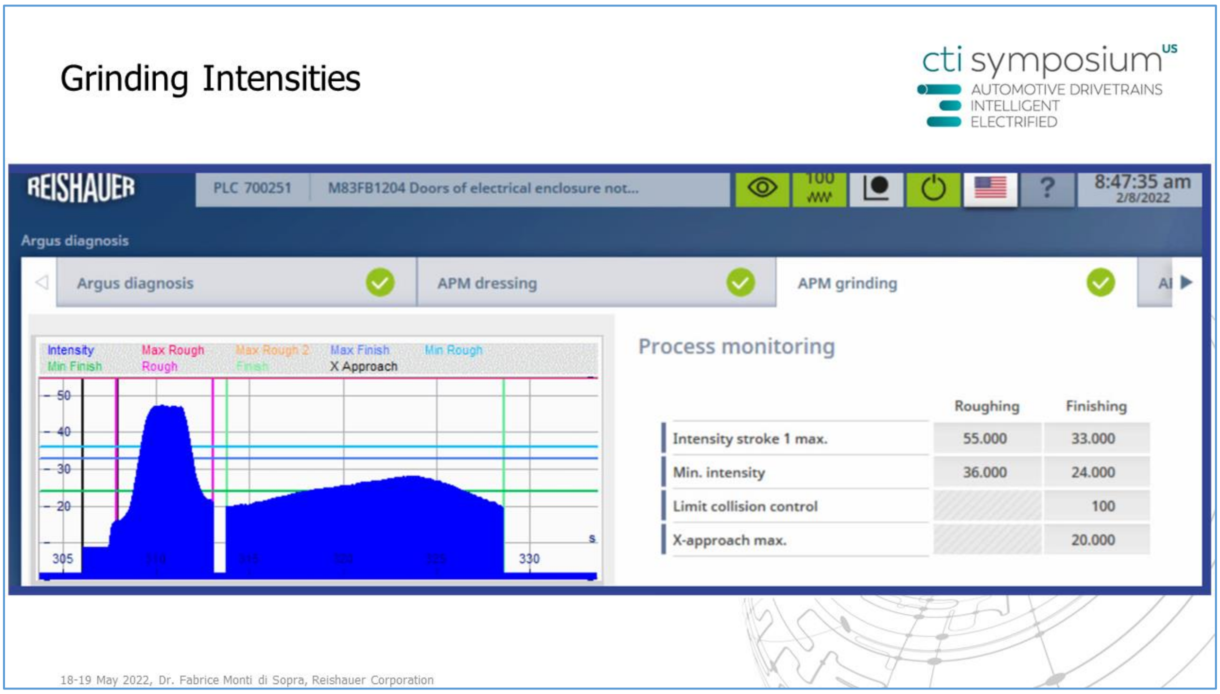

Figure 5 – Grinding intensity progression

Recording and analyzing the grinding intensity over time shows if a threaded grinding wheel maintains a consistent cutting performance across its entire width and usable diameter. As a rule, the operators evaluate grinding wheels subjectively as empirical data is unavailable. The inhomogeneous hardness variation can only be indirectly assessed via deteriorating gear flank profiles, even though this deterioration may have other causes. The system allows the hardness gradient across the grinding wheel width and the changing diameter to be made visible, measurable, and classified, as shown in Figure 6.

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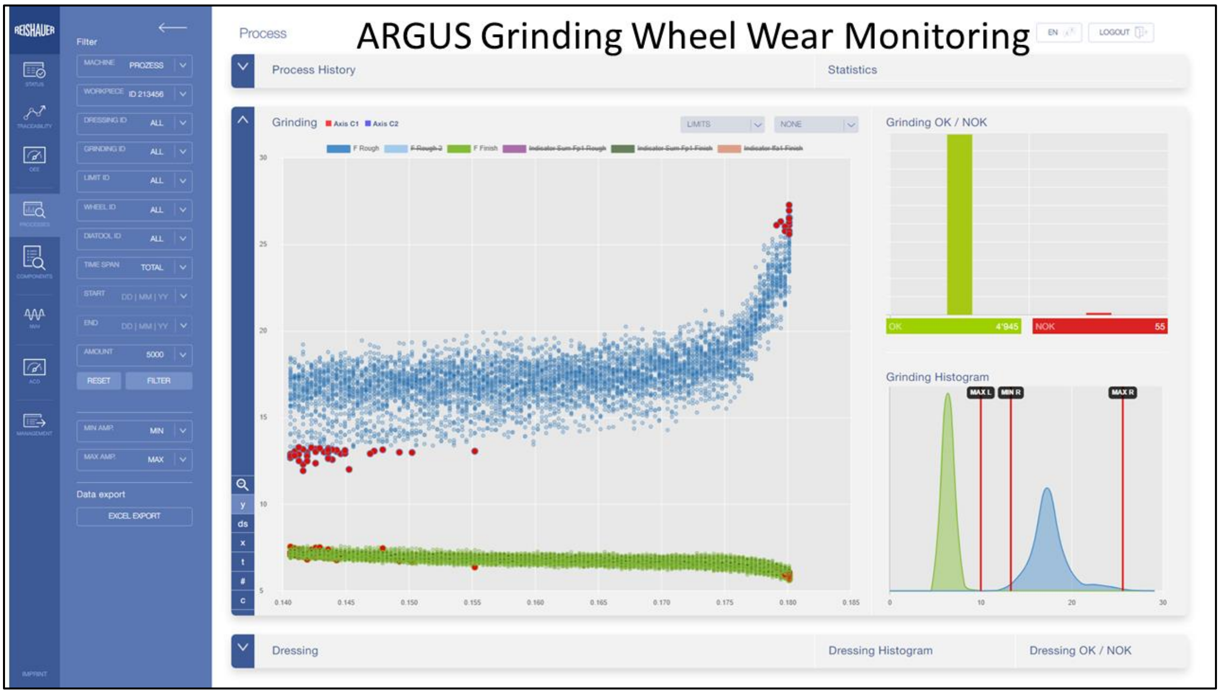

Figure 6 – Hardness variation across the threaded grinding wheel width

Figure 6 shows the changing for roughing and finishing grinding intensities across the shifting axis width Y over some 5,300 workpieces. The upper point cloud represents the roughing strokes, and the lower, denser point cloud represents the finishing strokes. The roughing stroke illustrates a diminishing grinding intensity from right to left. In contrast, the finishing strokes show the reverse, i.e., an increase in the grinding intensities from right to left. The decrease in grinding intensities during the roughing indicates process-induced wear of the threaded grinding wheel. As a rule, the underlying calibrated force model guarantees an almost constant level of grinding intensities across the full grinding wheel width and diameter.

For this reason, it is reasonable to conclude that the drop in the intensity levels during the roughing process is exclusively due to a continuous microscopic deterioration of the bond-grain matrix of the threaded wheel. This deterioration leads to a gradually lower material removal on the workpieces. The increase in grinding intensity during the finishing strokes indicates the concomitant compensation of reduced material removal of the preceding roughing strokes. The described wear effect on the threaded wheel leads to an unstable process and rejected workpieces. These rejects had to be removed during the process and are shown as dark red dots on the lower left side of the point cloud of the roughing stroke. The user had to change the grinding wheel specification to stabilize the process in this instance.

The grinding intensity also offers an insight into the out-of-roundness levels of clamping fixtures or roundness deviations of the pre-machined workpieces. Figure 7 illustrates the roundness indicator of the system, which, in this case, shows a situation where there is a marked roundness differential

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between the machine's two work spindles, C1 and C2. Both identical spindles are mounted on the revolving machine turret and alternatively rotated by 180° into the grinding position. For a straightforward interpretation of the dynamics effects of the out-of-roundness of the workpieces on the grinding intensities, the system uses proven algorithms to process the time signals captured by the measuring sensors. Using these intensities offers several significant advantages to the operator. The simple interpretability ensures that the analysis of even a complicated process no longer requires the services of highly trained and expensive specialists.

Additionally, even high data volumes generated by large production lots can be visualized. Academic studies are often based on time and frequency analysis of vast data sets, reaching several gigabytes. The system's scalar format of the data parameters makes the graphical representation easy, even with thousands of measured data points. Moreover, the system does not require specific evaluation software and hardware. It can be operated with a simple web application on standard web browsers. Given the small data size, it can be transferred any time via the internet or internal networks, even on networks of small bandwidths, and can be efficiently uploaded or downloaded.

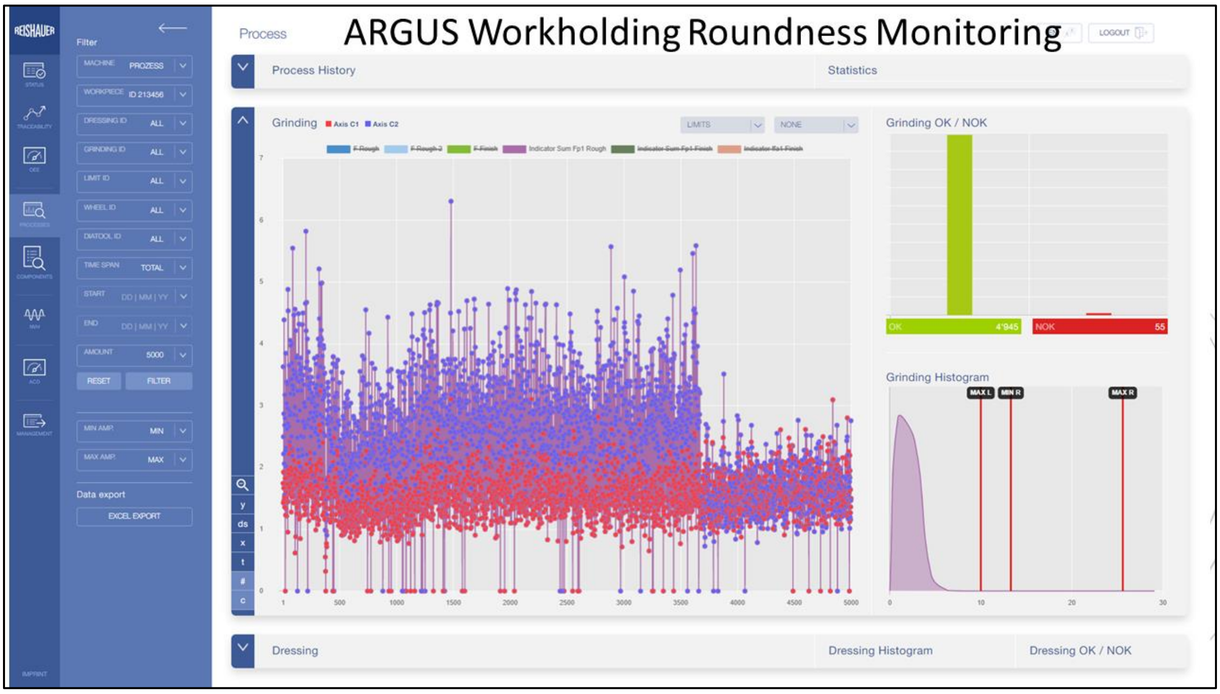

Figure 7 - Out-of-roundness on one clamping fixture

The red dots in Figure 7, representing work spindle C1, show a consistently small out-of-roundness across 5,300 workpieces. The scattering within the bandwidth of the red dots is typical and acceptable due to variation in the pre-machining quality. However, within the first three-quarters of the bandwidth from left to right, the blue dots, i.e., from workpiece 1 to 4,000, show a much broader scattering. This higher spread is clearly due to a higher out-of-roundness of the clamping fixture on the C2 axis and could not have come from the workpieces. Once the clamping fixture was clocked

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into the correct position, the process became stable and identical for both work spindles, starting at workpiece 4,000, as shown in Figure 7. It is essential to point out that even the blue dots up to workpiece 4,000 were still within an acceptable pre-machining tolerance. Nevertheless, the system would lead to the removal of workpieces if these were outside the set levels.

The application of this system has significant economic benefits. Besides monitoring geometrical inconsistencies, detecting grinding burns is essential to ensure stable production conditions. Grinding burns must be avoided at all costs. Therefore, one of the most common strategies to prevent thermal damage is to reduce feed rates, as thermal damage thresholds are unknown. However, suppose the grinding intensities are calibrated with ground components and proven free of thermal damage. In that case, the process can be optimized with higher feed rates and lower shifting rates. This process optimization leads to shorter grinding cycle times and increased tool life of grinding wheels and diamond rolls, translating into better process economics. Furthermore, as mentioned in the introduction, the principal aim of the process monitoring system is to achieve zero-error production.

EOL NVH Prediction

Modern and future transmissions face new demands in today's industrial conversion of conventional drive concepts from internal combustion engines to electric drives. On the one hand, there is the need for high power densities because of the higher torque of electric motors and, on the other hand, the increasing demand for quieter transmissions even at a higher rotational speed. Electric drives are devoid of noise masking, as known in combustion engines. Furthermore, gear developers and process engineers in gear machining today face new challenges given the higher RPM of electric drives. This section discusses and offers solutions to these challenges.

In producing hard fine-machined gears, NVH behavior is a relevant and established criterion for assessing the suitability of high-performance gears. This assessment takes place on an EOL test bench after the final assembly of the gearbox and as a last step of the manufacturing chain. Of course, detecting any defect is of particular importance at that stage. However, an earlier assessment and detection of defects can reduce higher potential costs caused by NVH issues.

Cyclic machine component analysis of the ARGUS system sets the basis for an inline assessment of the real-time machine condition. Based on cyclically repeated and standardized tests, the general and actual machine conditions can be assessed and recorded. As shown in Figure 9, for example, ARGUS makes it is easy to predict or analyze the wear behavior of a bearing of the shift axis Y as the detected order matches its typical order signature. As a rule, representing the measurement signals across the frequency range is advantageous for resolving specific problems. Looking back in time, as

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shown in Figure 8, the bearing wear of the shift axis Y had increased since April 2021 and reached its peak in June 2021. The problem was solved by replacing the faulty bearing component. In summary, it can be shown that component damage can be detected at an early stage. This early detection means that potential machine component-related EOL problems can be remedied and avoided early.

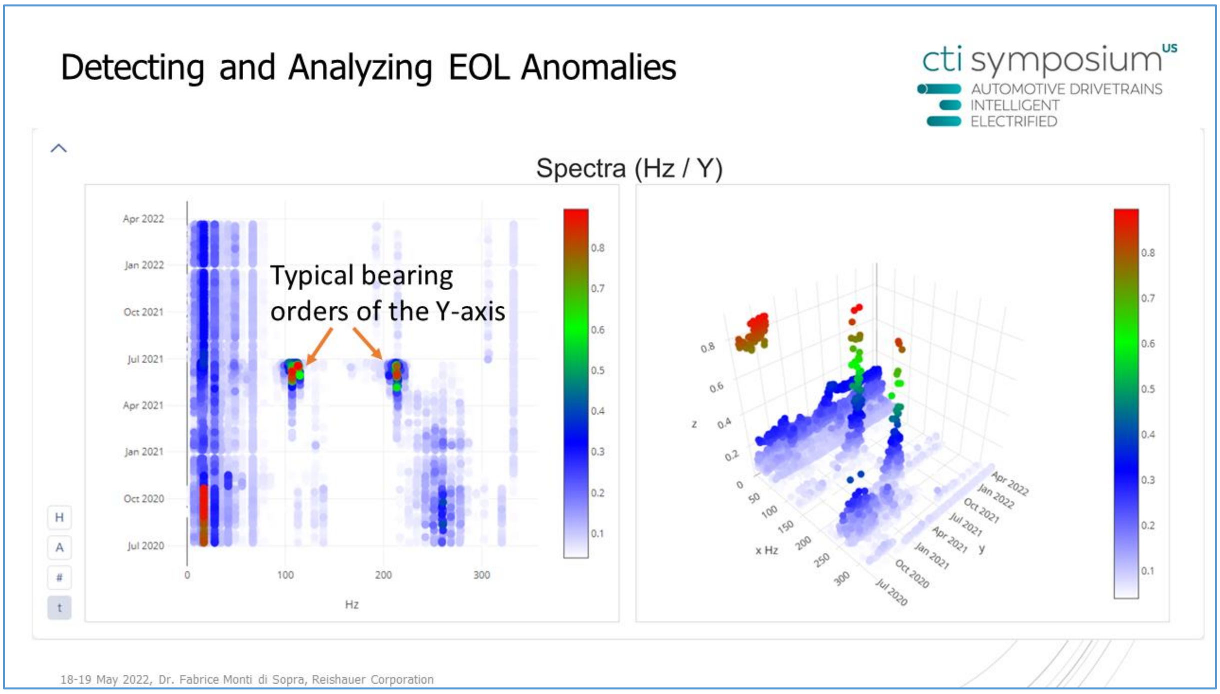

Figure 8 - Components cycle measurements of the Shift Axis Y across time, shown in Hz

EOL NVH Analysis and Remedial Measures

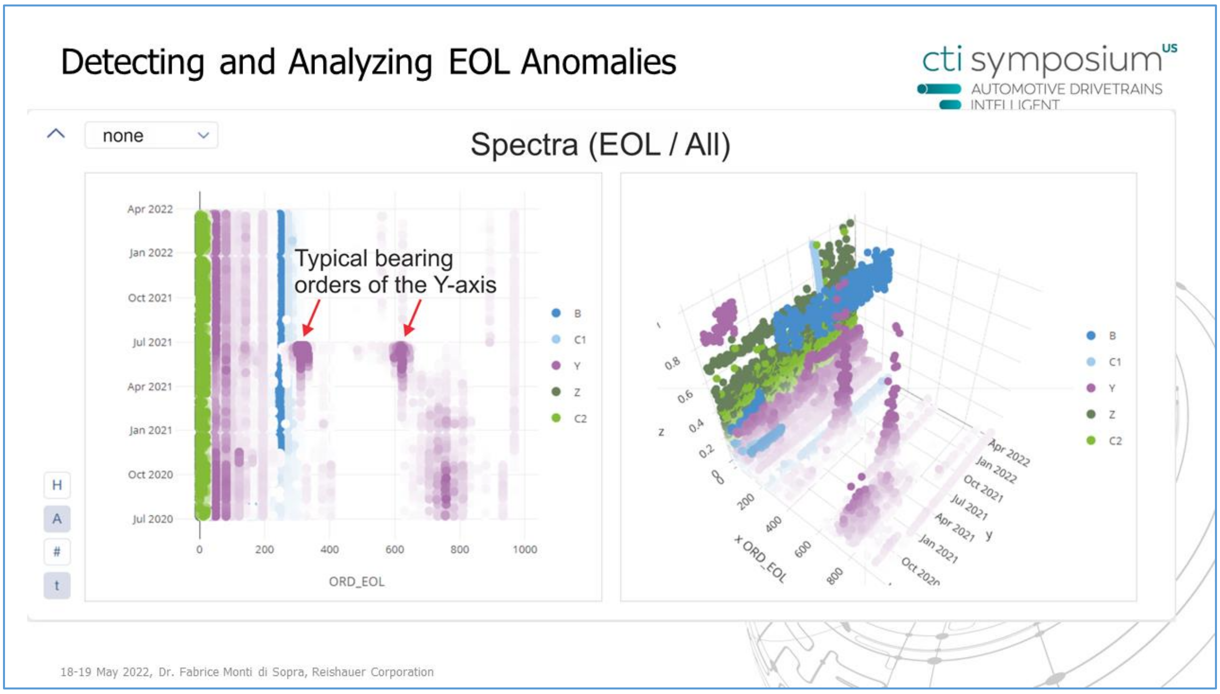

Figure 9 - Typical bearing orders of the Y-Axis

The crucial issue in analyzing EOL problems is, of course, to interpret the selected issues. A standard solution is reverse engineering. However, despite all the efforts and measures taken, noise issues can still occur in the EOL test bench, even though this is rarely the case. Once a specific order is detected and identified in the gearbox, an order analysis can identify the machine problem. (Shown in an example of a test bench measurement in Figure 10).

In the case shown here, the gear test bench shows a conspicuous order of 313, see Figure 10, which corresponds to excitation at the 313th multiple of the gear rotation frequency. Subsequently, this EOL excitation must be attributed to potential component damage. The Reishauer Argus system allows a back-calculation of the component measurements based on a WEB-NVH analysis. As all the grinding technology and geometrical data have been tracked and recorded in a cloud stationed database, a back-calculation based on patented methods can be executed to show the component measurements and behavior relevant to an EOL excitation in the gearbox. A data set of the available machining technology and geometrical data is used to generate the data of all the axes and their EOL orders. Hence, it is easy to identify a problem originating in the Y-axis, which has led to excitation in the gearbox in order 313. Alternatively, and even more simply, detailed searches for correlating NVH inciting orders can also be conducted via the Argus WEB system. In this example, a thorough examination was carried out for an order of 313. As shown in Figure 11, the output was a clearcut table, identifying the wear-related bearing damage of the shift axis Y.

Representation of the component cycle measurements of relevant machine axes in the generating grinding process with occurred bearing damage in the shift axis Y; shown in orders of the gears of an End of Line (EOL) test bench over a given course of time.

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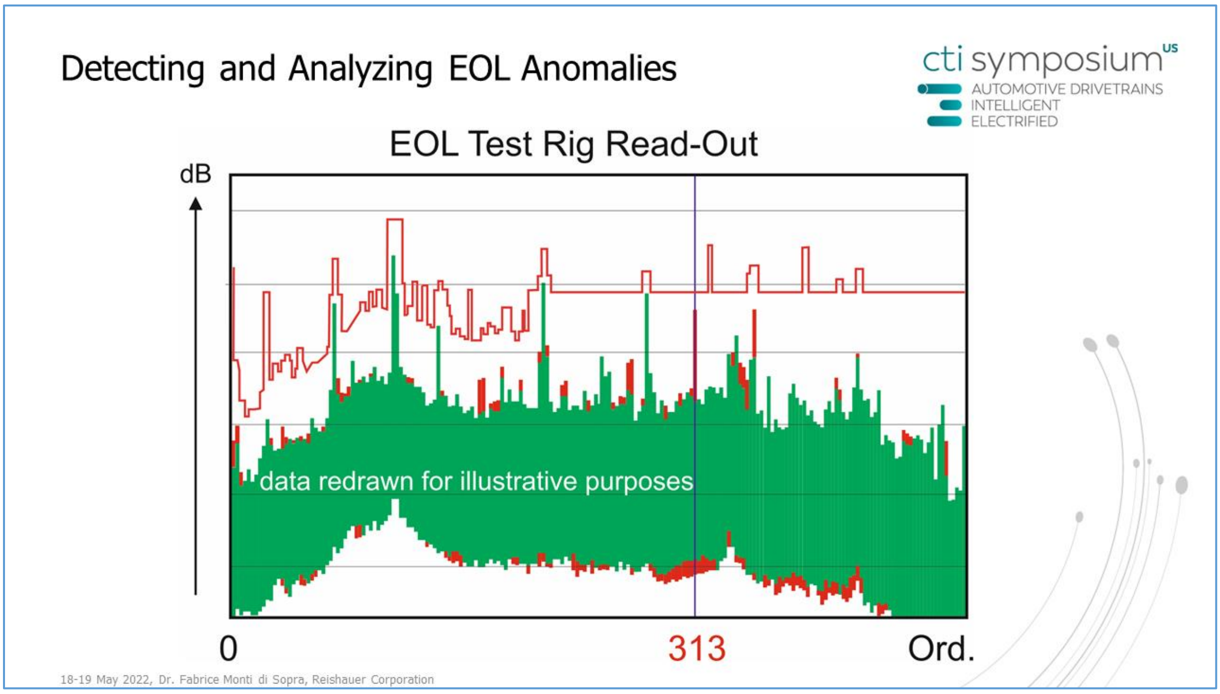

Figure 10 - EOL spectrum from the transmission test bench

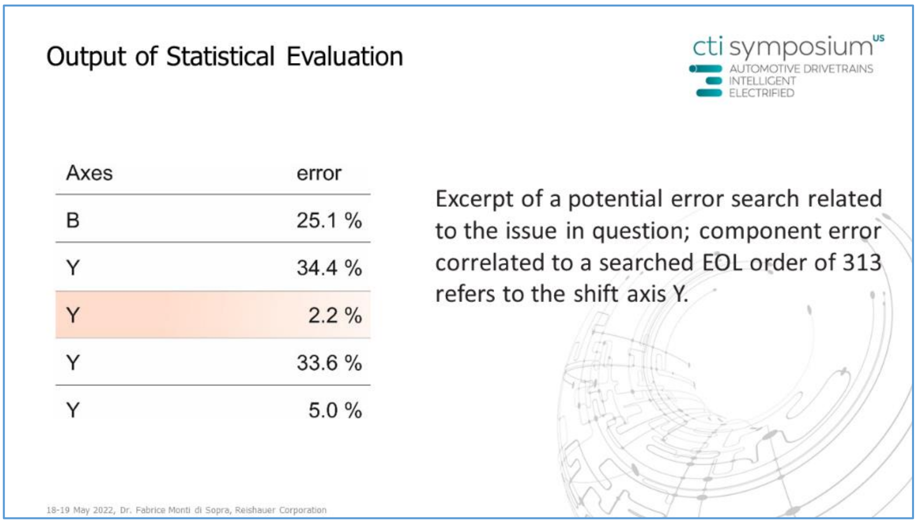

Figure 11 - Excerpt of a potential error search related to the issue in question; component error correlated to a searched EOL order of 313 refers to the shift axis Y.

In summary, the ARGUS EOL feature can predict NVH issues by analyzing the state of the entire machine components according to standardized and cyclical measurements. Inversely, supposing an NVH problem had been discovered on the EOL test rig, patented algorithms help identify worn-out parts of the machine tool.

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Gear Surface Structure and Geometry

Low Noise Shifting

Demands placed on today's automotive e-transmissions include, among others, low gear noise levels (NVH), weight reduction, economy, increased longevity, and high power density. According to these demands, modifying the surface structures and flank geometry can improve transmission performance. Continuous generating grinding can contribute to higher transmission performance in several ways. This paper touches on three relevant features that generating grinding contributes to ground gears and, by extension, to the entire transmission. Low Noise Shifting (LNS) and Polish Grinding are two features that alter and improve the surface structure. The third, Twist Control Grinding (TCG), adds control over the gear flank geometry by increasing the surface bearing ratios.

Low Noise Shifting (LNS) is an additional machining movement within the grinding kinematics of continuous generating grinding. As LNS runs unobtrusively in the background of the grinding process, most users are unaware of the existence of this feature. The machine's software automatically defines and sets LNS parameters. In principle, the kinematics of continuous generating grinding can be understood as a worm drive with additional abrasive machining properties (see Figure 3). This process consists of an infeed X to set the depth of cut, a vertical feed-rate Z, and the lateral shifting motion Y. This lateral motion ensures that the abrasive worm shifts continuously sideways by a small amount for each mm of vertical feed-rate. In this manner, the grinding always takes place with fresh, unused abrasive grits.

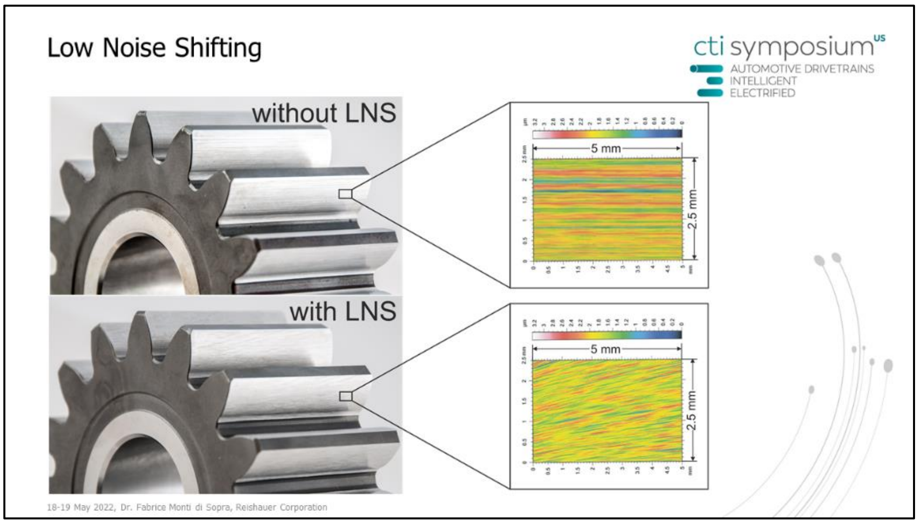

Figure 12 – Low Noise Shifting

The operator-defined shifting motion Y is used for the roughing stroke, whereas the LNS shifting motion is calculated and defined by the machine and applied in the finishing stroke. Continuous generating grinding creates grinding traces of a uniform axial waveform across the gear flank in the

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direction of the lead (see Figure 12, chart top right). Since the orientation of these waveforms is at right angles to the plane of rotation, this may cause high-frequency excitation during gear meshing, which vehicle occupants may perceive as unpleasant. To put it simply, the effect of LNS is to shorten and reduce axial waveforms. LNS results in irregular surface structures (see Figure 12, the chart on the bottom right) that prevent the generation of tonal excitations and allow the pairing of sets of ground gears.

Polish Grinding

Figure 13 – Grinding and polishing wheel structure

As emissions and energy efficiency are becoming more stringent in all significant markets, automotive companies face substantial technological and economic challenges. These requirements can only be met by improvements in all aspects of motor vehicles, and specifically to the powertrain, i.e., the engine and the transmission. Polish grinding reduces the friction of meshing gears and increases the bearing ratio of gear flanks. For these reasons, transmissions can be made more energy-efficient. The established continuous generating grinding method is the base technology for the polish grinding process. Polish grinding is performed as a final machining sequence on the manufacturer's existing continuous generating gear grinding machines without interrupting the gear grinding cycle. At the time, the workpiece remains clamped on the part holder during both grinding and polish grinding. As a rule, polish grinding consists of one polish grinding pass with the resin-bonded section integrated into the end section of the 2-zone grinding worm, which performs the grinding operation (Figure 14).

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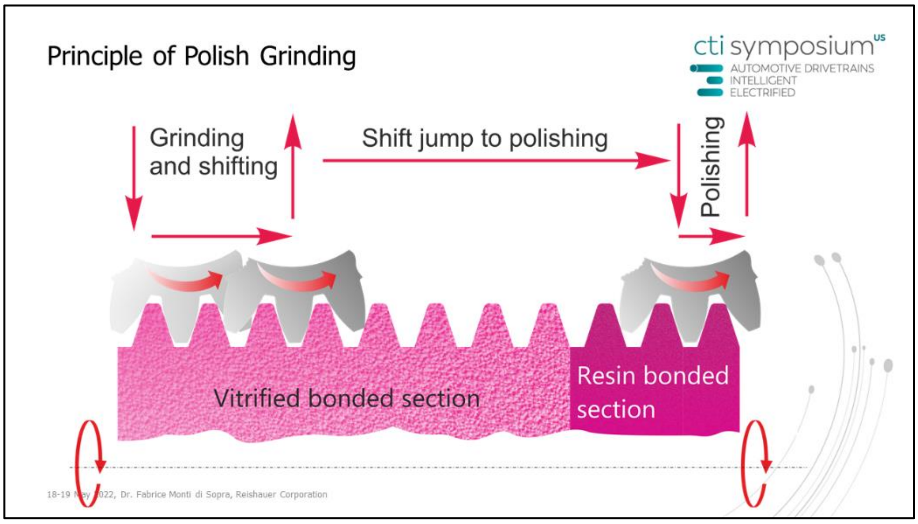

Figure 14 – Polish grinding principle

During polish grinding, only the roughness peaks are removed, reducing the roughness profile height and, therefore, this method increases the contact bearing area of the gear flanks. In contrast, the geometrical accuracy of the gear flanks is not affected. The polish grinding process delivers surface qualities with mean roughness values of Ra 0.15 µm compared with the standard values of R_a 0.4 µm used in industry on continuous generating grinding machines. It is important to note that R_a surface values are only of limited utility. The reduced peak height (R_{pk}) is a valuable indicator of a surface's functionality. Often, there is a misunderstanding that polishing should produce mirror finishes. However, polish grinding should only remove the surface roughness peaks for engineering purposes. It must leave intact the valley surface roughness such that oil films can adhere to the polished ground surface. With the roughness profile height removed, the contact area of the gear flanks is increased. Consequently, the augmented surface contact area allows transmission designers to increase the power density of transmissions.

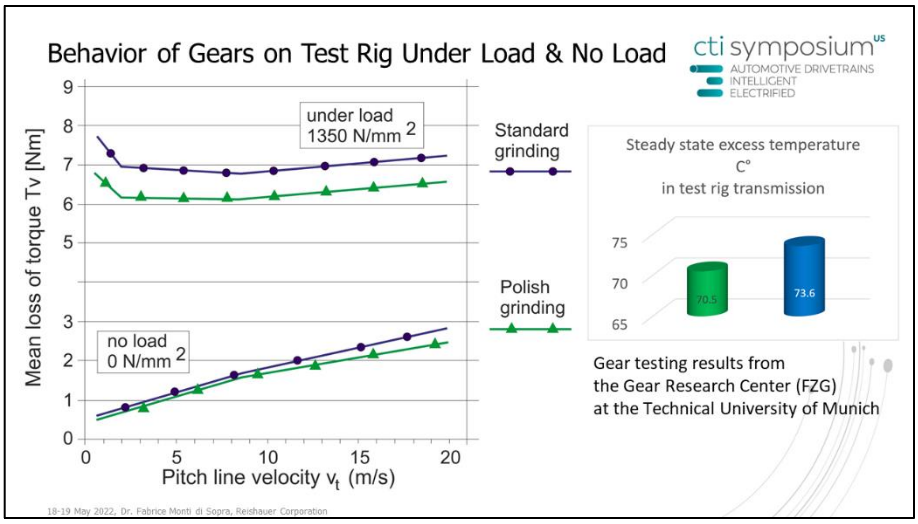

Figure 15 – Behavior of polished gears under load

Figure 15 shows test rig trials at the Gear Research Center (FZG), University of Munich, where polished ground gear sets were subjected to a load of 1,350 N/mm^2. Compared to the conventionally ground gears, the polished gears showed a reduction in friction of about 15%. Also, they resulted in a 4 degrees C lower steady-state excess temperature, as shown on the right of the graph. The reduced friction under load should translate into a better economy and proportionally lower battery usage and higher range.

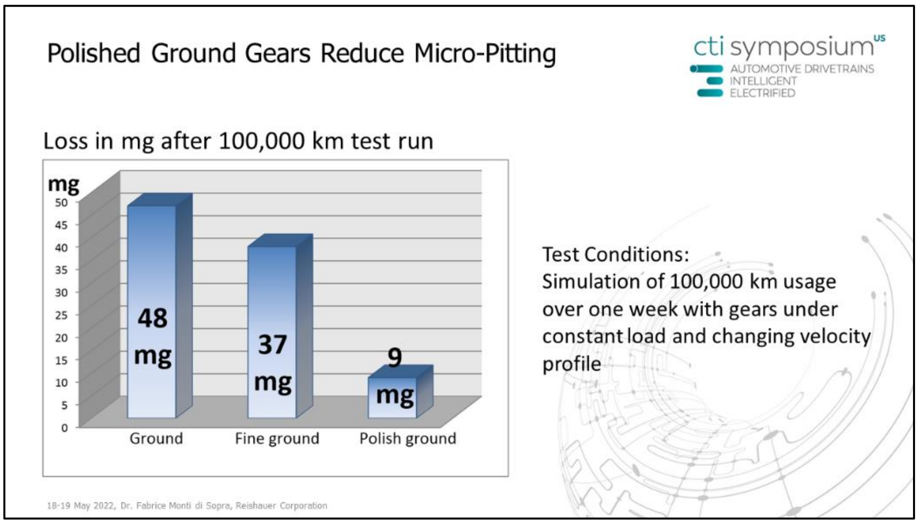

Figure 16 – Polished ground gears reduce micro-pitting

Scientific studies have shown that improved surface finishes increase the overall performance of transmissions as the resulting higher bearing ratios reduce micro-pitting and thus increase the longevity and efficiency of transmissions. Subsequent customer trials have confirmed the research results using the Reishauer continuous generating polish grinding processes. Micro-pitting leads to early gear failure, an overall reduction in transmission efficiency, and noise problems (NVH). In this example, Figure 16, standard ground, fine ground, and polished ground automatic transmission planetary gears were subjected to a simulation test of 100,000 km on a test rig under changing load and velocity profiles. The 100,000 km could be condensed into one week. Subsequently, the initial gear weight was compared to the weight after the simulation. Apart from a marked visual difference, the polished ground gears showed less micro-pitting as borne out by the marked lower loss in weight, as shown in Figure 16.

Twist Control Grinding

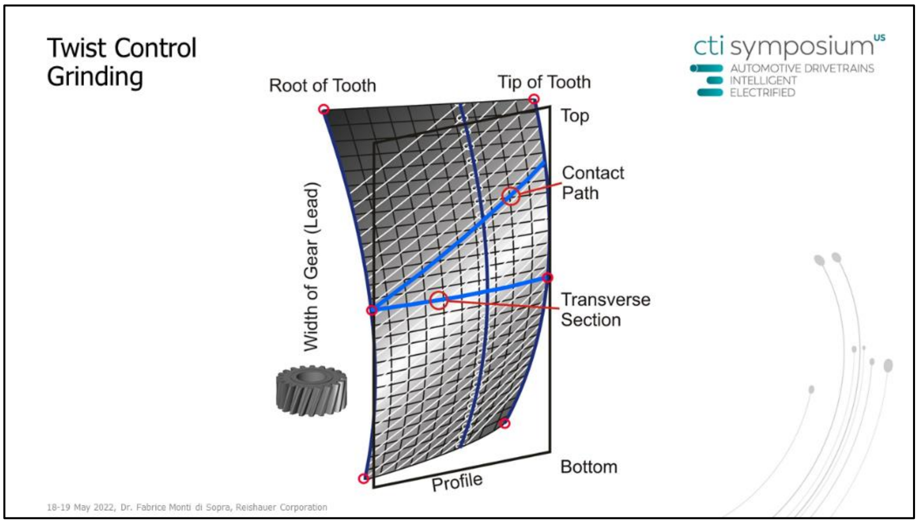

Figure 17 – Gear twist

Flank twist occurs as a matter of course when machining helical gears that feature lead modifications such as crowning, see Figure 17. Eliminating twist increases the bearing surfaces of meshing gears. Twist control grinding (TCG) aims to either eliminate twist, introduce a counter-twist on purpose, or add a specific twist to counteract the deformation of gears under load. By controlling twist, the contact bearing surfaces of meshing gear sets can be fully optimized, and therefore, the forces acting on the bearing surfaces can be ideally distributed. Twist control leads to more efficient gears, i.e., for power density and energy consumption. Today, in terms of grinding times, twist control grinding is on par with the standard continuous generating grinding, which is well-established in the industry. High volume TCG production of twist-free gears, or gears with a defined twist, is now standard production practice at several automotive gearbox manufacturers.

Twist Control Grinding (TCG) aims to either eliminate twist, deliberately introduce a counter-twist, or add a specific twist to counteract the deformation of gears under load. Often, twist has some negative connotations attached. However, with TCG grinding, the word "twist" should be seen positively, as it allows gear designers to use this phenomenon to fine-tune the gear geometry. Furthermore, the process allows separate TCG on the left and right flank in the same grinding pass.

By controlling twist, the contact bearing patterns of meshing gear sets can be fully controlled. Therefore, the forces acting on the bearing surfaces can be ideally distributed, which leads to higher power density, more efficient transmission of power, and increased longevity of gears. The TCG method gives gear design engineers a high degree of freedom to design gear flank geometries to match the demands made on e-drive gears and translate desired design features into an economical manufacturing process. Hence, modifying the flank twist by Twist Control Grinding allows modification to the contact pattern of gear teeth, thus leading to higher power density and allowing

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a reduction in the overall weight of gears in general and, by extension, a weight reduction of the transmission itself. Furthermore, TCG-ground gears have shown noise reductions of 2 to 3 decibels (dB).

One-Button Twist-free Grinding

Recently, when users wanted to grind twist-free, the machine manufacturer had to calculate the process parameters and design a gear-specific dressing tool. This process was not only expensive but also inflexible with dependence on the machine tool builder. For this reason, a customer-friendly solution was required and recently brought to market. "One-Button Twist Control" means what it says. The user pushes the button "Twist-free," and subsequently, the machine does the rest; it calculates and implements all necessary geometric and process calculations.

Furthermore, the diamond dressing tools remain the same as existing conventional processes. Also, the Twist-free process requires no additional operator training if the operators already have experience with standard continuous generating grinding. Today, regarding grinding times, Twist-free grinding is on par with the standard continuous generating grinding, which is well established in the industry. The benefits gained from controlling twist justify the small software investment and the influence of additional wheel dressing time. Following intensive research work and several years of industry application, Twist Control Grinding technology has proven itself in the marketplace. It has, in many cases, eliminated gear honing, often thought to be the only method for large-scale twist-free, or defined twist hard finishing of gears. High volume TCG production of twist-free gears, or gears with a defined twist, is now standard production practice. The minimal additional process costs over conventional gear grinding are far outweighed by the benefits of reducing torque loss, the increase in bearing capacity of TCG-ground gears, and higher resulting power density in transmissions.

Ease-of-Operation for Deliberate Twist

The same ease of operation and economy of the process as for twist-free grinding also applies to the grinding of any specific twist. Again, with standard tooling, the customer can define the desired twist with a few data points on the gear flank via the machine's graphic interface, click one button, and the machine generates a program to grind the gear's geometry accordingly.

With the three features of modification of the continuous generating gear grinding process, the users have powerful and simple tools to fully exploit required changes in geometry and surface structure to address the transmission issues of NVH, higher power density, and energy savings.

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Hard Skiving with Tools Made of Superhard Materials

Figure 18 – Hard skiving

While the main body of this article has focused on grinding external gears, the concluding part of the article addresses a novel process of hard-finishing internal and external gears: Hard skiving.

Skiving is a continuous generating chip forming process where the tool meshes with machined gear. It can be applied to both external and internal gears. The cutting speed is generated by an inclination between the axis of the gear and the axis of the cutting tool, as shown in Figure 19.

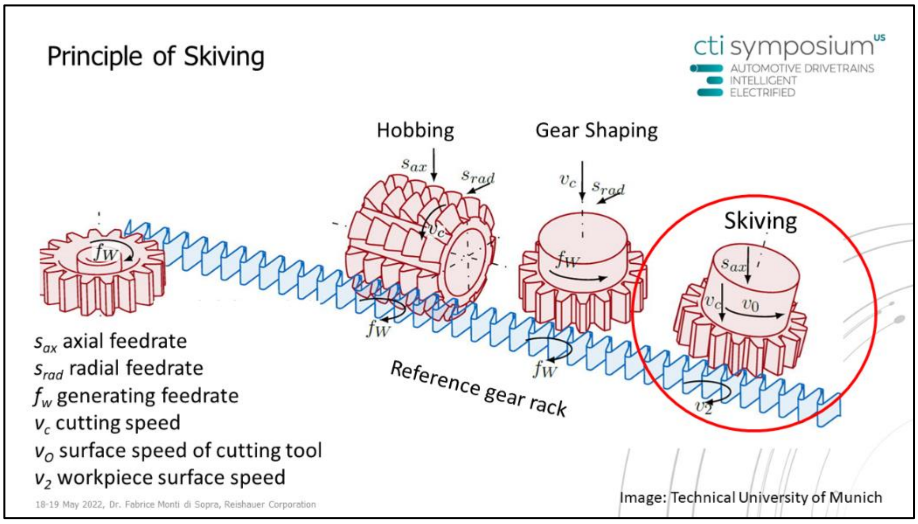

Figure 19 – Skiving process

Skiving can be seen as a combination of gear hobbing and shaping by continuous hobbing with axial feed. While the process has been around since 1909, in terms of hard-finishing, it could not gain much traction in the industry due to shortcomings of CNC software, machine tool stiffness, and the most crucial factor, inadequate tooling. Even tungsten carbide tools are subject to too much wear; the process is seen chiefly as uneconomical and of insufficient quality for critical gears used in e-drives. However, it should be mentioned that the new process needs case-hardened workpieces as

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nitrided materials presently used for internal gears cannot be machined. The extremely stiff machine tool design and the development of skiving tools featuring superhard cutting edges deliver the required process stability, surface quality, and geometrical accuracy for high-quality e-drive gears.

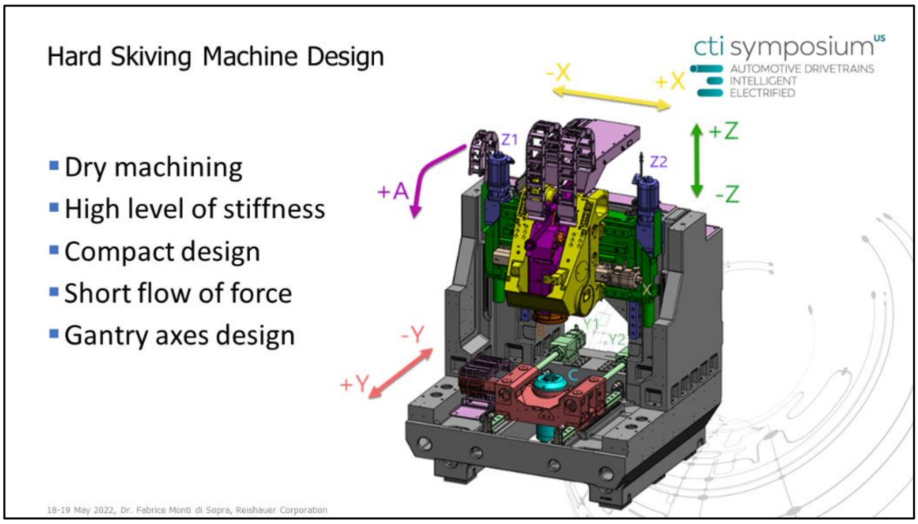

Figure 20 – Hard-skiving machine design

Conclusion

The presentation showed an overview of advanced gear grinding technologies that meet the requirements of e-drive gears. It focused on hard-finishing technologies that increase load-bearing capacity, control the gears' macro and micro geometry, modify the surface structure, and cope with geometrical interference contours.

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