# Complete Measurement of Gearbox Components

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## Introduction

In today's production environment, a variety of different measurement devices is used to assess the quality and accuracy of workpieces. These devices include CMMs, gear checkers, form testers, roughness testers, and more. It requires a high machine investment and a high handling effort — especially if a full end-of-line measurement is needed.

One approach to reduce quality costs is to include all measurements in one single machine that is suitable and robust enough for use in production. This reduces machine investment, handling efforts, and set-up time. Being able to measure in production also helps to reduce idle times by reducing transport ways to climate-controlled measuring facilities. Klingelnberg combines the experience from machine tool development and high-precision measurement.

This report describes how a CCMM (circular CMM) can be integrated into a production environment. The main challenges are dust and oil fog contamination, temperature changes throughout the day, and vibrations from production machines. Operator qualification is also an issue, since the measuring machine is handled by production machine operators.

The result is a measuring machine showing the capability and necessary accuracy in measuring gear components. This accuracy applies to all features of rotational, symmetric parts within a gear box. Finally, it will be shown how capital-intensive gauges can be substituted using the full flexibility of a modern CNC- controlled measuring machine. Compared to gauges, much more useful information can be gathered and statistically evaluated to support production control. Furthermore, component design changes only require slight software modification — at no cost. Using gauges, expensive parts need to be reworked or reinvested, including their high costs and lead times.

## Productivity Improvement in Measurement Technology

In manufacturing gearbox components, such as gears and shafts, a multitude of measurement tasks occur at different points in the process chain. The results of all these measurements are either used for process monitoring or documentation of the final state of a component. Various measuring instruments are used for the various measuring tasks. These range from gauges for a simple test of component features to complex measuring machines. Which measuring or checking instrument is used depends on many factors; the environmental conditions, measurement time, qualification of the operator and, of course, investment and operating costs, play a decisive role.

In the area of pure production monitoring, simple and also more complex gauges are often used, which are easy to handle and very robust against the environmental influences of a typical shop floor environment.

However, the low flexibility of gauges is a big disadvantage.

Gauges are often exactly designed for one characteristic only. Design changes to this feature require a new gauge, resulting in high costs and lead times. On the other side, high-precision measuring machines are used. CMMs typically require the clean and air-conditioned environment of a measuring room. Measuring machines are characterized by a higher degree of flexibility — compared to gauges — while being operated by trained staff.

Increasingly, system manufacturers and OEMs are shifting their quality control to suppliers. The component suppliers are required to measure and document all relevant features classified by their customer as part of a final inspection. For this purpose, an overall measurement of all relevant features at the end of the production chain is necessary; but this requires the use of different measuring devices present in the measuring room. This inevitably requires time- and personnel-intensive set-up and clamping processes.

One approach to increasing the efficiency in quality control and documentation is to integrate different measurement tasks on one single measuring machine in an automated process in order to reduce the number of setups and clamping processes to a minimum. For this purpose a measuring device is required in which all measurement tasks of the coordinate, form and surface inspection are integrated as much as possible. However, no compromises can be made with regard to the accuracy of the measuring medium. Ultimately, the measuring equipment's capability for the required accuracy must be given for each individual characteristic.

A further step towards improving productivity is the integration of a measuring machine directly into production. As a result, in the first step — the transport distance to the measuring room — and often also the costly measuring room itself — can be omitted. For this purpose a measuring machine must be consistently designed to the requirements of the shop floor environment. The essential components are the compensation of temperature fluctuations, environmental influences caused by dust and oil mist, as well as floor vibrations at the installation site. This allows shifting shop floor checks from gauges towards a high-accuracy coordinate measuring machine. This enables us to use all advantages of a CMM, including accuracy, documentation, and statistics.

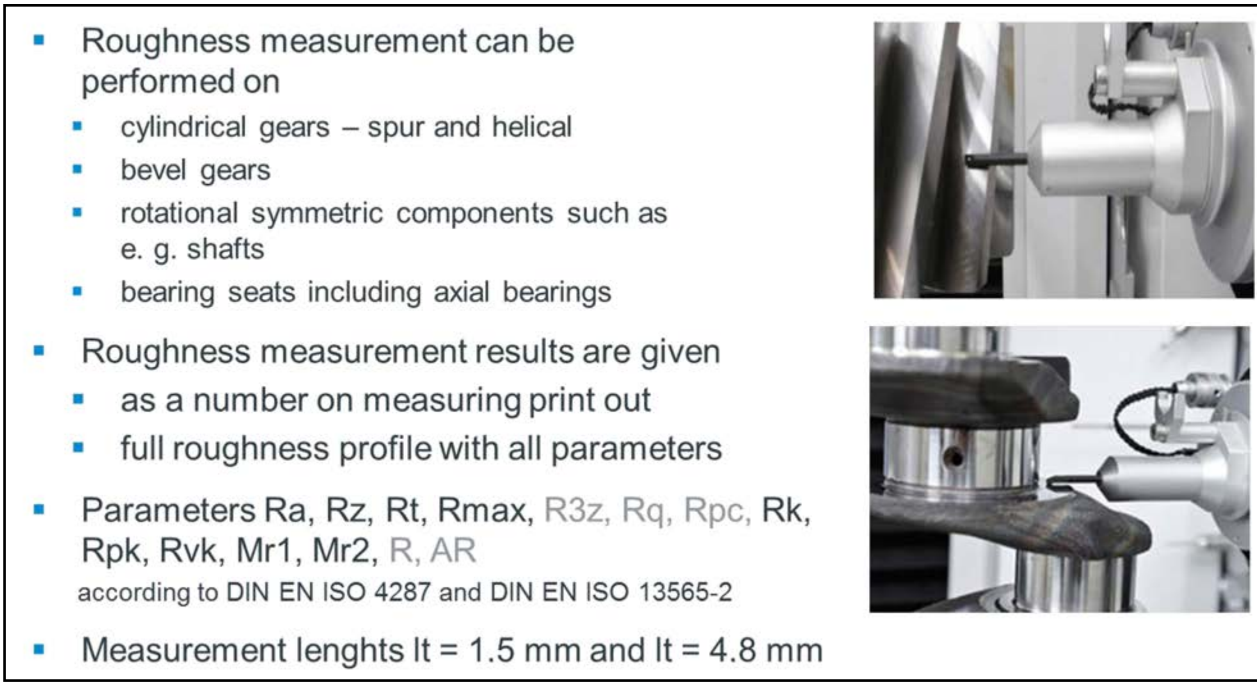


**Figure 1** **Surface roughness measurement on precision measuring center.**

## Integrating Surface Roughness Measurement into the CMM

The roughness measurement is typically carried out on special measuring devices with linear feed. In this case the component and the roughness sensor are manually positioned relative to one another for every measurement. So, a lot of manual adjustment and set-up process for each component is required. Since the positioning is done manually, the position at which the roughness measurement is performed cannot be absolutely identical, and thus the reproducibility of the measurement result is impaired.

Integrating the roughness measurement on a coordinate measuring machine offers several advantages. The highly accurate axes of the coordinate measuring machine are available for positioning the probe. The measurement can therefore always be carried out at exactly the same position. In addition, the roughness measurement can be integrated into the measuring sequence. In conjunction with an automatic probe changer, set-up and set-up times are completely eliminated. Figure 1 shows the roughness measurement on the tooth flank of a cylindrical gear (upper photo) and on the axial bearing seat of a crankshaft (lower photo).

A skidded system for roughness measurement is used. Thus, the reference plane for the measurement result is the surface of the component and not the feed axis of the machine. This is an important difference from standard surface roughness measurement systems using a straight axis as the reference plane. With a straight reference, the involute curve of a gear flank is part of the measurement. This has two main disadvantages; one is that the involute is part of the measurement and has to be filtered, including the risk of also filtering information about the surface. The second disadvantage is that the probe cannot be kept perpendicular to the surface as the standards call for, which can, depending on the curvature, also influence the measurement result. Using the four axes of the measuring machine, a generating movement can be realized by always keeping the probe perpendicular to the surface. The downside of a multi-axes movement is that the control quality of the axes can influence the measurement result. This can be avoided by using a skidded system where the skid forms the reference.

The skid itself has a large radius so that the measuring results cannot be falsified by the reference plane. The blade with the probe tip is rotatable-mounted. The rotation to the measuring position is automatically controlled by the measuring software. As a result, the left and right tooth flanks of a gear can be measured without a manual set-up effort with only one probe. In addition, it is also possible to directly measure other different geometry elements on the clamped part. By means of this design, different gears and bearing seats can be measured on a component in one clamping. The usual characteristic values of the roughness measurement are calculated (Fig. 1).

Especially for the measurement of small contours with small measuring lengths, it is important that as little measuring distance as possible is lost by the skid as a reference system. Therefore the skids and stylus can be integrated in such a way that the full available measuring range can be utilized as far as possible. An example of this integrated solution is shown in Figure 2. With this very small-sized roughness probe, the roughness measurement on tooth flanks of cylindrical gears is possible, starting from a module of $m_n = 0.9$ mm (DP 28). The skid is positioned to the side of the roughness probe itself in order to be able to measure such small gear flanks. The photo on the lower right shows the automatic exchange of the roughness probe system. In this case there are two positions in the probe changer magazine in order to measure surface roughness on a bevel gear, and a bearing seat in one clamping and in an automated measuring sequence.

A major advantage of the skidded system on a coordinate measuring machine is shown in Figure 2. To avoid falsifying the measuring results, the probe tip must

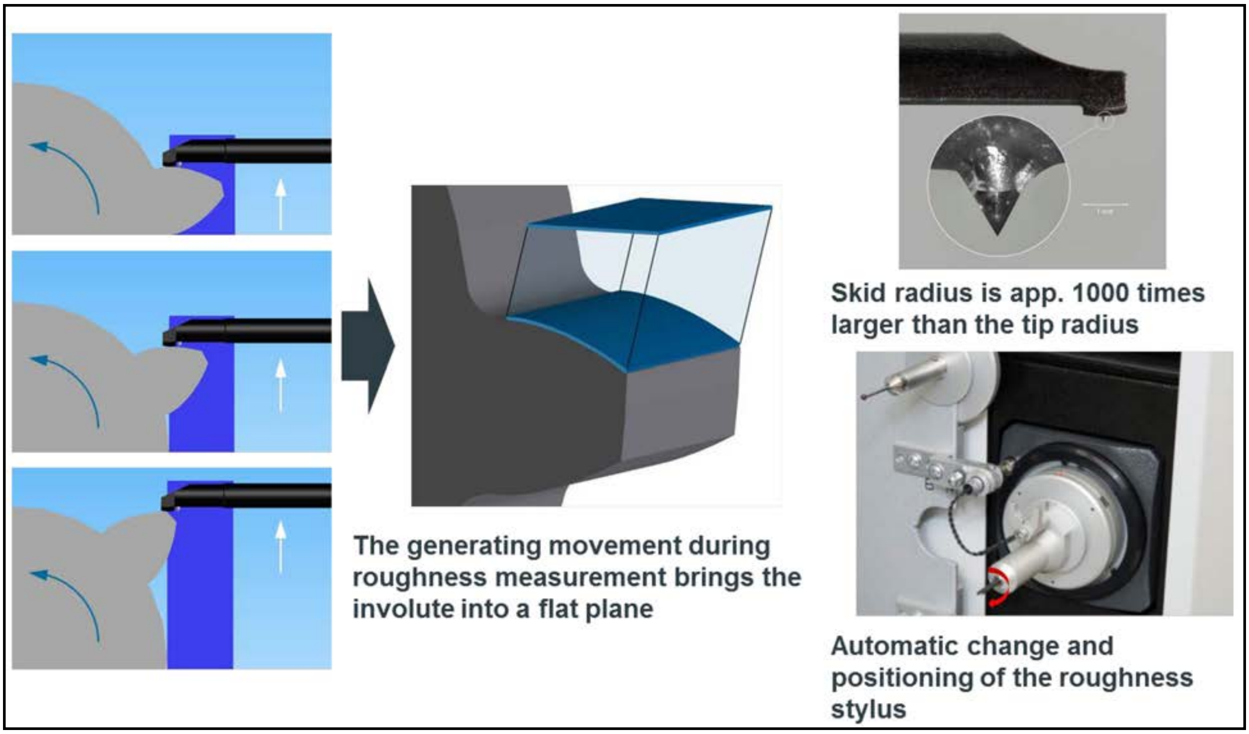


**Figure 2 Design of surface roughness probe.**

always be positioned perpendicular to the surface during the roughness measurement. Traditional roughness measurement systems with a straight reference plane cannot achieve this on curved surfaces, such as an involute gear tooth flank. In addition, in the case of involute gear flanks, the tooth curvature is in the measurement results and has to be filtered. This represents a significant disadvantage of these systems, since this makes it impossible to achieve a standard measurement perpendicular to the surface.

Measurements of involute gear flanks are carried out on four-axes, precision measuring centers. In this case, as in a standard gear measurement, the C-axis and the X-axis perform a coupled movement. This is the typical generating movement following the involute flank, i.e. — keeping the position between flank and measuring stylus constant. In this way the involute tooth flank is transferred into a flat plane relative to the touch probe. The sketches in Figure 2 show that the probe tip is always perpendicular to the measured surface. This ensures that the roughness measurement is carried out according to the relevant standards.

The possibility of automatically rotating the surface roughness probe presents the possibility of reaching many different positions and geometries on the parts to be measured. Still, the flanks of internal gears cannot be reached this way. Therefore a further extension of the surface roughness measurement is shown (Fig. 3). The surface probe is mounted to a special construction and turned by 180°. This now makes it possible to measure internal gears using the same probing system described and shown before. It can also be handled by the automatic probe changer, and gears can be measured starting with module $m_n = 0.9$ mm (DP 28).

Figure 4 represents an example of a roughness measurement. In this case,


**Figure 3 Roughness measurement — internal gears.**

three different teeth of a gear have been checked in profile direction on the left and right flank. The results are shown on a printout very similar to the printout for a standard involute check. On the right flank, it is clearly visible that the characteristic profile features can be found at identical positions of the profile. One such example is marked in the printout. In conjunction with the very reproducible machining result from a generating grinding process, it is also clearly visible that the measurement and the measuring position are very reproducible.

Finally, it can be stated that a roughness measurement on a coordinate measuring machine offers many advantages. The first is the fully automated integration into the measurement cycle. This eliminates the need for setting up the measurement each time a new part needs measuring. Another important advantage is the reproducibility — not only of the measuring result — but also of the measuring position. The user influence on the measuring result is completely eliminated. Finally, however, the possibility also exists of placing curved surfaces, such as a tooth flank, in a measuring plane and thus testing it in a standardized manner. Still, it is important to note that the reference is always a straight plane. So there is a clear separation between the roughness measurement only reflecting the surface, but not the involute or lead with corrections. Involute and lead are still represented by the standard gear measurements; surface roughness is always additional information.

## Precision Measurement on the Shop Floor

The precision measuring centers are uncompromisingly developed for use in production. Here the experience gained in machine tool development is combined with the expertise in precision measurement technology. The main success factors are the robustness of the machine in conjunction with a temperature model in order to compensate for the influence of temperature gradients on the shop floor (Fig. 5). In combination with vibration isolation, this is the basis for Klingelnberg ambience neutral technology.

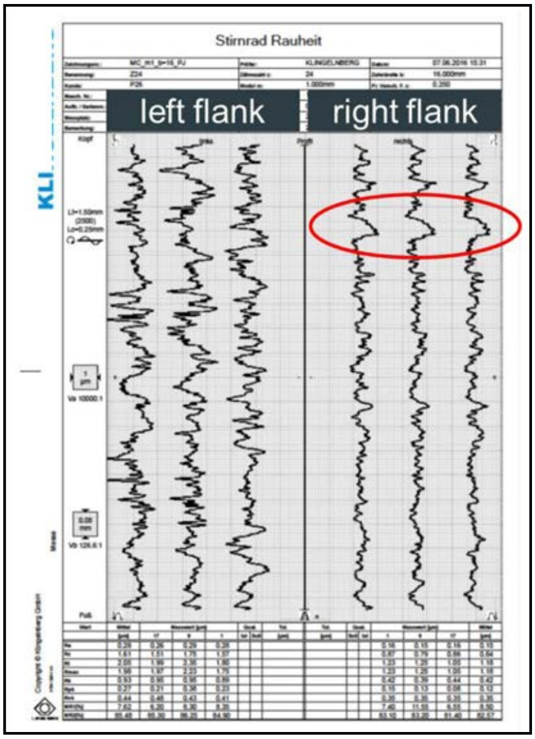

**Figure 4** Example measuring sheet for surface roughness measurement.

The production environment is characterized by contamination of the air with oil and dust. A measuring machine used on the shop floor has to be designed to operate in this environment. The main components in need of special attention are the guides, bearings, and scales. Though robustness is the key factor, accuracy cannot be compromised. In the production environment, the only option is to use roller bearings instead of air bearings, and also roller guides instead of air guides. For a machine with form

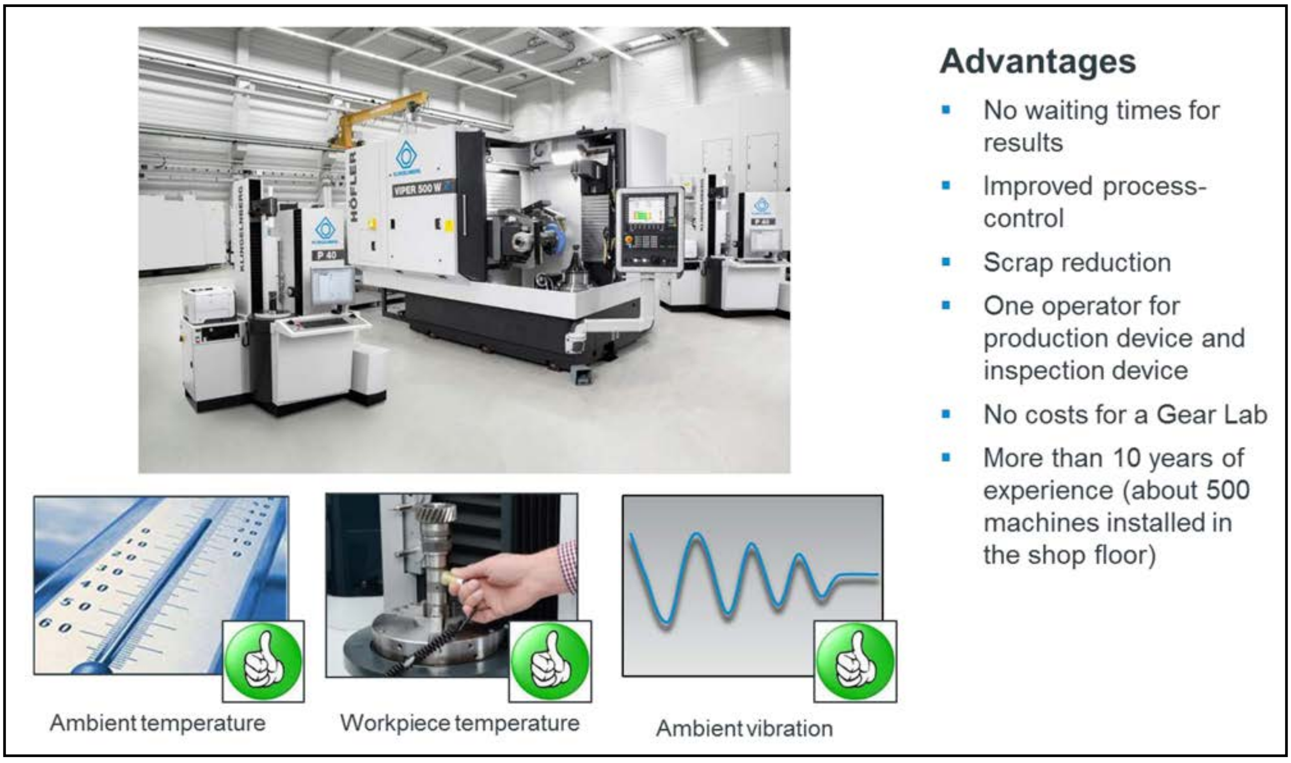

**Figure 5** Precision measurement on the shop floor.

testing capability, the design and also precision manufacturing of a precision roller bearing is a challenge. Basically, for a good gear measuring machine being capable of form testing on shafts, a radial runout of the rotating axis of less than 0.5 mm is necessary. Also, it is rather difficult to keep the glass scales absolutely safe from any dust. Therefore the best solution is to strike a compromise between isolation and accessibility — thus enabling the user to include the glass scale cleaning into the yearly maintenance. Experience shows that a yearly cleaning is sufficient in approximately 90% of the cases, and increasing the frequency to twice a year has proven to be sufficient in all cases.

On the shop floor, vibrations induced into the floor by different sources, such as manufacturing machines or fork lifts, are another challenge; those floor vibrations are often below 15 Hz. In order to isolate a machine against such low frequencies, very soft damping isolation material is required. Since this would result in a "shaking" machine when axes or masses are moved, an active controlled system with pneumatic springs is absolutely necessary. In this way it is possible to achieve the necessary isolation against low-frequency vibrations below 15 Hz from the shop floor, while keeping the machine stable and avoiding all influences on the measurement results.

Another aspect of the production environment is temperature fluctuation. The main challenges are the compensation of the machine changes due to temperature change, and ensuring that different materials used in the machine with different temperature growth do not cause inner tension, and so influencing machine performance. In order to keep the system simple, one good way is to ensure that all components of the measuring machine have the same temperature growth. This can be achieved by limiting the material choice to steel and cast iron. Therefore, the machine bed is made from cast iron instead of granite. By measuring the temperature of the machine, the environment, and the workpiece, all necessary information is there in order to use an analytical temperature model for the compensation. This model has been proven in a temperature range from 15° C up to 35° C. Still, the temperature gradient throughout the machine is another important factor. Therefore, the maximum temperature change per hour to make the system work has been set and proven to $\Delta T = 2°$ C/h.

## Complete Measurement of All Features

In addition to roughness and gear measurement, numerous other measuring tasks can be carried out on a precision measuring center. Basically, it is a coordinate measuring machine with a rotary table for rotational symmetric components — which we like to call a circular coordinate measuring machine (CCMM). In addition, important features are required to significantly increase the accuracy. The rotary table bearing has a radial runout deviation of significantly less than 0.5 µm, and thus has a sufficient accuracy for form measurement. This is achieved by a highly accurate probing system with low masses, which is well suited for both form testing and rapid coordinate measurement. This means that all requirements are fulfilled in order to carry out nearly all measurement tasks on shafts, in addition to the roughness and gear measurement.

Figure 6 shows examples of measurement and evaluation options along the process chain in gear production. Before green machining of the gear teeth, the blank can already be measured completely with all relevant features. Both dimensional measurement tasks, as well as form measurement tasks, can be integrated. The same also applies, of course, to the measurement of all elements after heat treatment and before hard-machining of the gear teeth, such as gear grinding.

In addition to classical gear

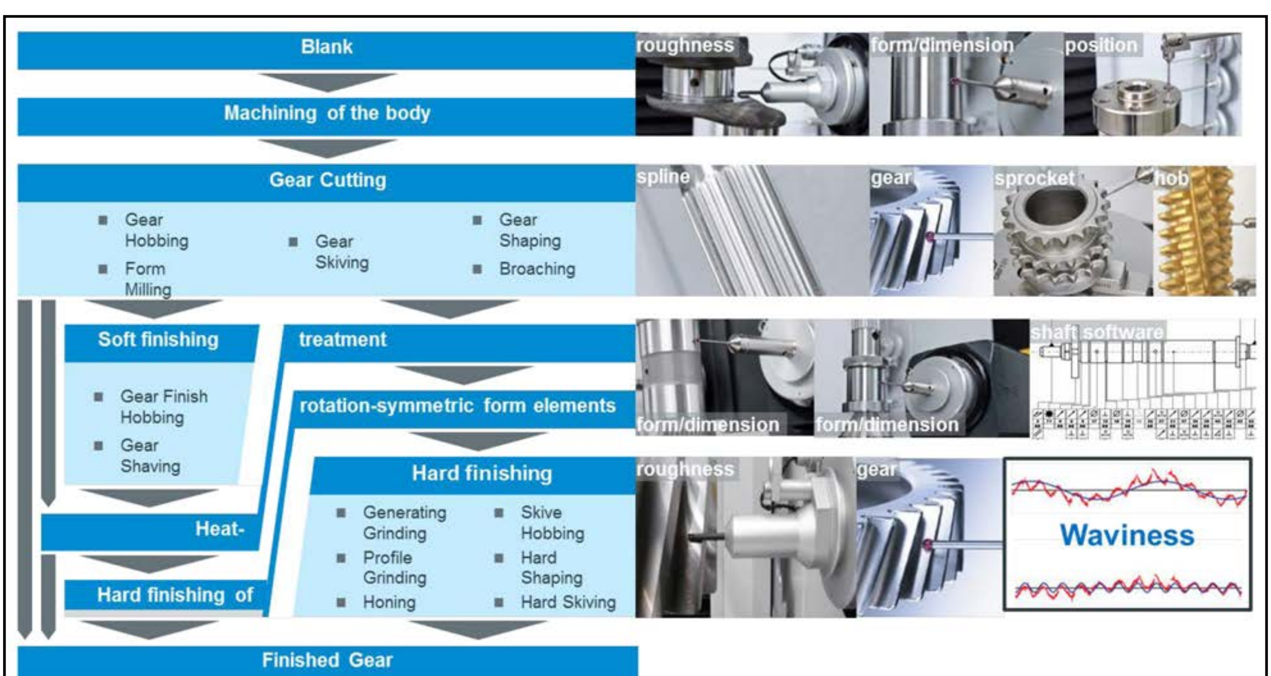


**Figure 6** Measuring possibilities along the process chain of gear manufacturing.

measurement, tools used can also be measured; shown here (Fig. 6), for example, on a hob. The advantages of roughness measurement on a coordinate measuring machine were described in the previous section. What's more, the evaluation of ripple on the tooth flanks after the gear grinding process is possible in order to assess gear noise issues. The capabilities of the precision measuring centers for form measurement make a highly precise measurement of the ripples possible. With the corresponding evaluation software "deviation analysis," sound phenomena, such as so-called ghost frequencies, can be analyzed and important information for their avoidance in production can be gathered.

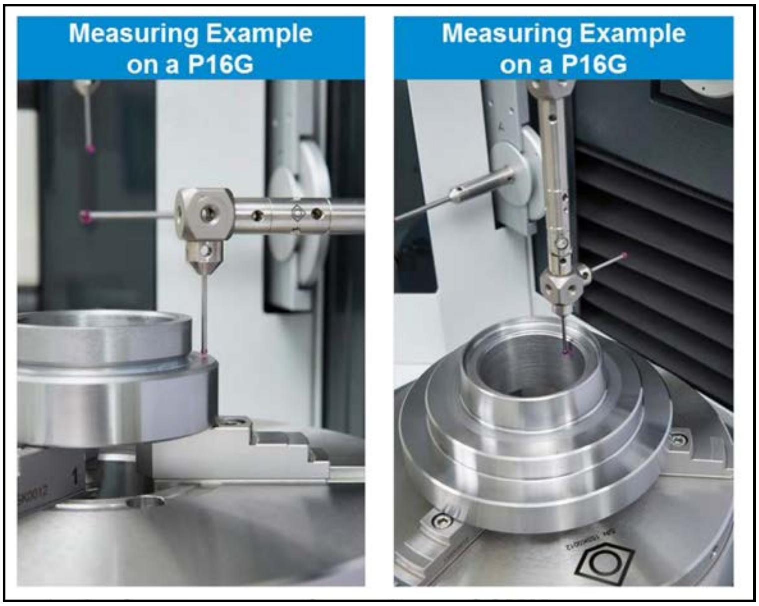

**Figure 7 Typical measuring tasks for gauges performed on a CCMM.**

## P 16 G: Replacing Gauges in Production

On today's shop floor, gauges are used for quality assurance of different process steps. Gauges can be used, without restrictions, directly on the shop floor and close to the machine tools. They are characterized by a high robustness against the shop floor environment and "built-in temperature compensation." If the gauge consists of a material with the same coefficient of thermal expansion as the workpiece, and has the same temperature, the thermal influence on the test result is thereby excluded or compensated. The test is also very simple and can be performed directly by the operator of the machine tool itself.

The main drawbacks of gauges are the individual adaption to the component and the test task combined with a high investment and long delivery times. Basically, this makes gauges very inflexible. Design changes are especially critical since they require a new gauge, resulting in another high investment combined with the long lead time. In addition, documentation of the test result is only qualitative and cannot be used for process control. It is therefore desirable to have a measuring machine that has the advantages of gauges and is suitable for use in production, showing a much higher flexibility.

In the previous sections it is shown that nearly all measurement tasks on rotational-symmetrical components can be carried out on a Klingelnberg precision measuring center. There also exists the possibility of using the measuring machine directly on the shop floor. The necessary robustness, in combination with temperature compensation and vibration isolation, makes this possible. So with these preconditions, it is possible to replace gauges as described before by a measuring machine.

Figure 7 shows typical measuring tasks for gauges carried out on a P 16 G. In this case, for example, diameters, distances and lengths, positions to a reference, and many other different parameters are measured. These can be realized as measurement tasks on a coordinate measuring device. The flexibility of the measuring device is much higher compared to a gauge. Any number of different components can be checked; only the appropriate measuring program has to be created. The adaptation to geometrical changes of existing components can be realized by only small changes of the measurement program.

Figure 8 shows the P 16 G — a measuring machine for disc-shaped components and short shafts. This represents a high number of typical parts in the automotive industry. Measuring on the shop floor allows improvements for process control. By means of the statistical evaluation of measured values, for example, trends can be detected at an early stage, thus an intervention can take place before the first component is out of tolerance and needs to be scrapped.

Another important factor for moving a measuring machine on the shop floor is the qualification of the operators. In the measuring room, experienced measuring machine operators are typically available. A CMM on the shop floor used for replacement of a gauge is normally used by the machine operators; they have a lot less experience in measuring technology. Still, the quality and reliability of the measurement results must be ensured. For this purpose a system called *EasyStart* has been developed. This is software that consequently separates the setup of the measuring program and the measurement itself. In order to start an already-programmed measuring cycle, very little knowledge is required; this helps to reduce training efforts. The operator finds the necessary measurement program for his specific part directly on the start screen. In order to start the cycle, only one click on the button is necessary. This procedure can be further simplified by using a scanner in conjunction with an identifier on the component. This identification can be handled in multiple ways; the most common today is a QR-code on the surface of the part.

## Conclusion

The measurement technology is an integral part of the production of transmission components. Quality control is an important part of the process chain and, like the manufacturing process itself, should be part of continuous efforts to

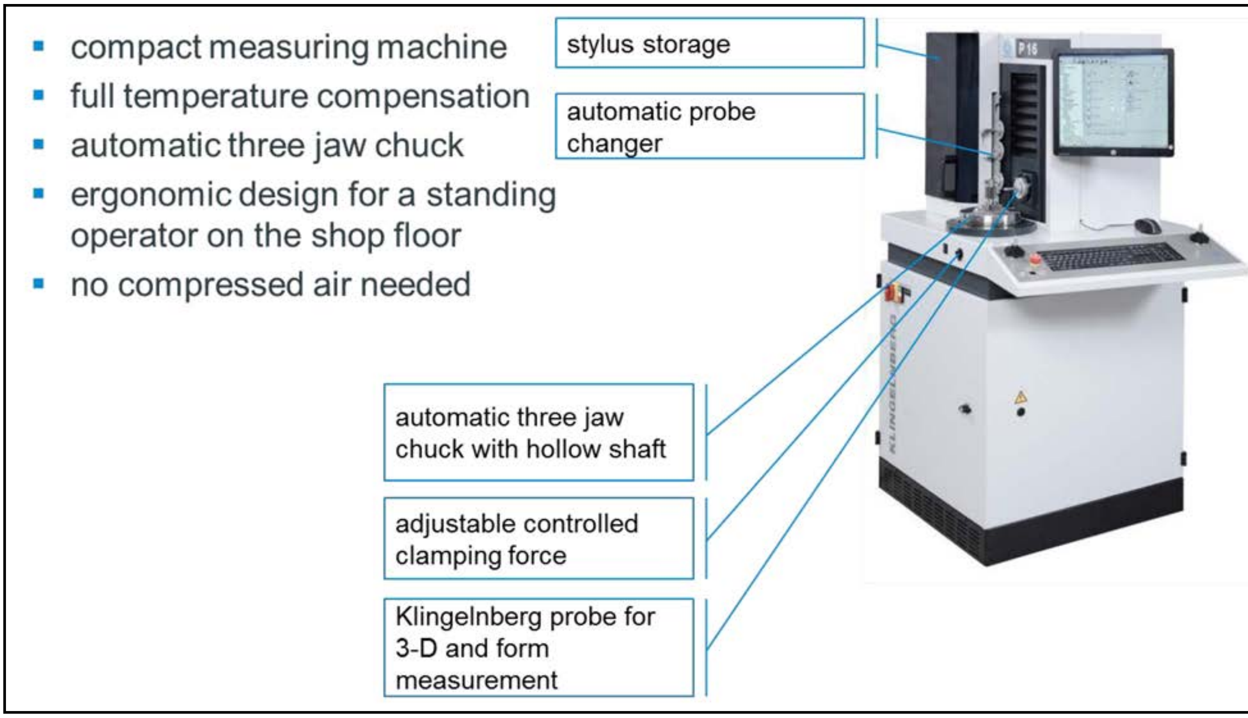


**Figure 8 P 16 G as a replacement for gauges on the shop floor.**

improve productivity. On the one hand, costs for the measurement processes can be saved. On the other hand, important information for an optimization of production processes can be collected by utilizing measurement capabilities.

It is shown in this paper that the process integration of different measurement tasks — which typically take place on multiple machines — is possible on one machine. On a precision measuring center, all coordinate measuring tasks, as well as form testing, can be carried out in addition to the classical gear measurement. This is supplemented by the roughness measurement, which results in both efficiency advantages and starting points for improving the reproducibility of the measurement result.

If the measuring machine is moved out of the measuring room and placed on the shop floor, further productivity increases can be achieved. In addition, cost savings are possible if the number of measuring rooms can be reduced. With a measuring machine on the shop floor, gauge checks, and thus the investment into gauges, can be replaced by CMM measurements. In this way the possibilities of statistical process monitoring can be used more intensively. Qualitative measurements have to be carried out within the scope of quality documentation, so that a gauging test is often an additional process step anyway. Ultimately, measurement in production, coupled with statistical process control, also enables the acquisition of trends, for example, so that intervention can take place in the process before the first part is out of quality and needs to be scrapped.



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