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# CAPABLE PROCESSES BY OPTICAL METROLOGY

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**Abstract -** Today, optical metrology is already an essential factor for manufacturing processes. Within different tasks optical metrology guarantees increasing capability of processes. Optical measurement techniques secure fast and precise process steps. Therefore, optical methods integrated into manufacturing lines are well suited for measurement tasks. Their setups are modular and they have defined interfaces to the electronic periphery. Further, optical measurement techniques are very versatile, flexible and most accurate. They are used more and more for non-contact distance measurement, shape and surface inspection as well as for analysis of dynamic processes. Due to their ability for miniaturisation optical sensors are well suited for the direct use in manufacturing systems and production environment.

Thus, the goal of this article is to illustrate the efficient use of optical measurement systems in different manufacturing processes. Detailed examples show that optical metrology is a key factor for sucessful manufacturing. Finally, perspectives and trends of optical measurement techniques in the field of production technology will be presented.

Keywords: Optical Metrology, Manufacturing Process, Quality Control

## 1. INTRODUCTION

Quantified statements about different characteristics of a product are essential in all phases of the product emergence beginning with the development, via the manufacturing up to the service. An even more important role comes to the measuring technique, since it is embedded into a strongly changing production environment, which is characterized by sinking product development times, increasing product renewal rates, increasing degree of automation, highest claims of quality, new materials and finishing techniques as well as sinking response times to identified quality faults.

Into this environment not all measuring procedures, which worked satisfactorily under classical manufacturing conditions, can be transferred. The rationalization of the measuring process by the use of modern microprocessor technology was an important step into the correct direction, yet the necessary profit at robustness, accuracy and cannot be achieved by this alone. Thus e.g. the comparison of nominal and actual values of a relatively simply formed body part of an automobile with a given sample requires more than the fast processing of individual, mechanically recorded measuring points, if the adept view of the quality tester is to be substituted by an automated testing facility. Thus, it is necessary to find new solutions concerning metrology and qualify them for the use under industrial conditions.

## 2. OPTICAL METROLOGY

### *2.1. Process chain oriented optical metrology*

The primary goal of manufacturing processes is the economic production of high-quality products. The past showed that modern production strategies are not sufficient, in order to secure enterprises a competition advantages on a long-term basis. Short running times and optimal machine utilization are possible only if the assigned processes are technologically expenditure-provoked and controlled qualitatively. A condition for it is however a founded knowledge of the processes and thus the use of modern measuring procedures.

Production metrology embedded into quality control loops is the basis for controlled and capable manufacturing processes. The potential of these control loops can be exhausted however only if the quality relevant product characteristics can be examined close to manufacturing. In order to avoid errors, a clear correlation between quality criterion of the product and the causing parameters of the manufacturing processes involved must exist. A consistent use of the quality and measuring data can be ensured only on this way.

The process-chain-oriented measuring technique (fig. 1) pursues this approach. In order to control the production procedures all quality relevant characteristics of the processes and products in production must be recorded, evaluated and be given back to the process as manipulated and/or controlled variable.

The use of the measuring procedures during the process are focused thereby on three temporally sequential phases:

- Prae-process measuring technique
- In-process measuring technique
- Post-process measuring technique.

Measuring procedures during the prae-process serve the process preparation and are used in the run up of individual manufacturing steps of a process chain. Rising accuracies with the production of complex components and systems require e.g. an even more accurate positioning of construction units, which cannot be ensured alone by devices. Additionally the increasing degree of automation in the production plants places new challenges against the measuring technique. By prae-process measuring systems construction units can identify, whose position determined and which geometrical data are acquired. These measuring data serve as basis for the following process and inspection planning and resuming automated working steps.

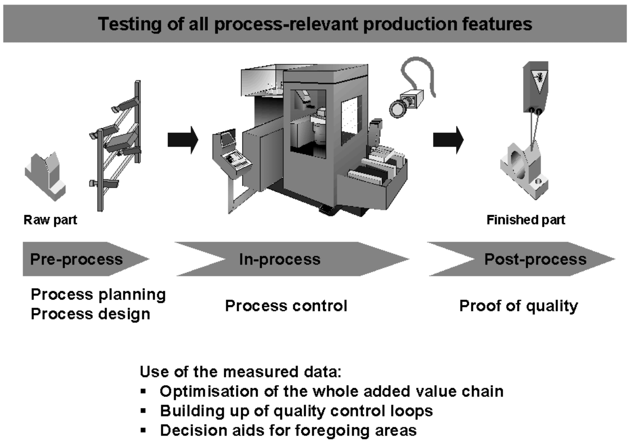


Fig. 1: Process chain oriented measurement technique

In process measuring technique is used in the process, in order to make results of measurement available without time delay and for a process feedback control. In this way a manufacturing-integrated quality automatic control loop arise, which permits a fast reaction to changes of processes. The connections between measured characteristic and process parameters must to be known, so that due to the determined data the correct measures can be introduced.

The post-process measuring technique corresponds to the traditional quality control following individual processing steps and/or at the end of the entire manufacturing. Object of this measuring technique is the workpiece and/or a complete product. The classical post-process measuring technique is often used in form of the statistic process feedback control for monitoring actually capable processes. As well it serves for the quality proof opposite customers in the context of quality agreements.

Beyond the regulation of the production process all measuring data are prepared and feed back into pre-aged fields. So they can be given for example in the construction information over critical design features in the manufacturing or be consolidated to ability indices of machine tools concerning the job planning [1].

*2.2. Key factors of optical metrology*

Today and in the future the need of a fast precision measuring technique will continue to grow for the highly exact geometrical inspection of different workpieces within all ranges of the production developing process. This consequence can be derived directly from the fact of an increasing quality awareness as well as a rising automation and at the same time increasing manufacturing speeds. Generally, the measuring of geometrical characteristics such as size, position, shape or roughness parameters are the most frequent measuring tasks. This circumstance makes the meaning of process-integrateable, highly exact optical metrology clear.

Optical measuring procedures can be used thereby due to its versatility and flexibility in all ranges of a process chain. The speed of these procedures during the parallel collection and evaluation of measuring data enables a high availability of process data and a purposeful, fast regulation of production processes. Additionally, the robustness of the procedures ensures a high machine availability and small measurement uncertainty of the sensors guarantees standard conformity. An important characteristic represents the circumstance that with optical measuring technique contactlessly and thus without destruction especially sensitive objects can be inspected. At the same time procedures, which are based on optical sensor technology, can also measure smallest details of samples. Due to these characteristics the optical measuring technique possesses a high potential as quality-assurance instrument in the production engineering and creates thereby the condition for the guarantee and control of processes.

The optical measuring technique offers a wide spectrum of solutions for many of the already mentioned challenges. The goal of the paper will be to illustrate on the basis of concrete examples the profitable use of optical measuring technique in the production process and to point out the potentials and trends within this technology.

## 3. PRAE-PROZESS MEASURING TECHNIQUE

The use and potential of optical metrology in the preliminary stages of the production will now be presented by an example of an automation of a handliong process.

The automation of handling processes represents a challenge regarding to rapid and therefore cost efficient production processes. Secondary times can significantly be reduced by automated handling processes. This applies during the production process as well as to the process preparatio. The last one should be illustrated by means of the workpiece/tool identification and the position sensing by optical measurement technology (fig. 2).

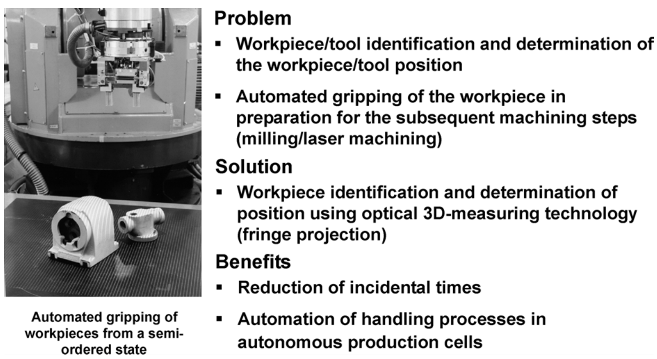


Fig. 2: Optical metrology for process preparation

In this context, the autonomy of a production cell includes the capability to execute complex manufacturing processes safely and fault free with a maximum degree of autonomy for a larger space of time. For a manufacturing process with laser or milling the process preparation can be as follows. Workpieces or tools which should be supplied to the actual manufacturing process are situated in a state of semi arrangement. From this state of semi arrangement the workpieces or tools first are identicated by optical metrology and secondly their position is sensed. This gained data permits the automated grabbing of the desired tool and thus the delivery to the following processing steps.

The identification and the postion sensing of the workpieces is provided by optical 3D sensors in order to detect in a single measurement the complete region in which the workpieces are located. Optical 3D techniques like the fringe projection technique which is applied here, excel in a rapid three-dimensional detection of a complete region with a high density of points. A high density of points is of high importance especially for a failure-free further processing of the gained clouds of points. Due to the cognition of the geometrical dimensions of the measured workpiece from the CAD data set the clouds of points can be segmented and processed in a way that identification and postion sensing of the required workpiece can be provided in a safe way.

## 4. IN-PROCESS MEASURING TECHNIQUE

Optical metrology is used in many field of manufacturing in order to control processes. In the following chapter different examples will demonstrate the successful use of optical measuring methods in the process itself.

### *4.1. Process intermitting measurement of tool wear with image processing*

Primary the application of optical metrology in the manner of camera measurement technique based on image processing permits a measurement of the tool wear of drilling, turning and milling tools (fig. 3). The prae-processing detection of the tool status – in this case the value of face and flank wear of the milling tool – supplies useful information not only for process observation but also for a possible process control and for optimization of tool life.

The wear causes are mechanical abrasion, diffusion processes, built up edges and scaling. These create geometrical changes on the the face and the flank of the tool, which can be detected by an incident light testing system [2].

The advantages of wear measurement by optical metrology compared to conventional systems for process observation, e.g. impact sound or torque sensor, are situated in the image information itself. It permits a extensive evaluation of the tool wear, detached from specific conditions and processing parameters of the respective manufacturing process. By using the image information it is possible also for the workers to apply their knowledge in the fields of production. Moreover the worker recognizes with the images at one glance, if the provided wear values are plausible.

As the metallic reflecting tool surfaces create negative effects caused by the respective illumination, the detection degree of the measurment system is reduced. By applying a variation of illumination by several controllable LEDs these negative effects caused by illumination can be detected, because they tend to displacement in the image, depending on the respective illumination direction. For the damping of such disturbance effects a image series based on a varying light source is generated. Then, this series is concentrated by an optimizing algorithm into an image corrected from disturbance effects. Thereupon, the position of the cutting edge is detected by further procedures and the region of tool wear is segmented. Based on this data a measurement of the width of the wear mark and a classification of the wear type can be conducted.

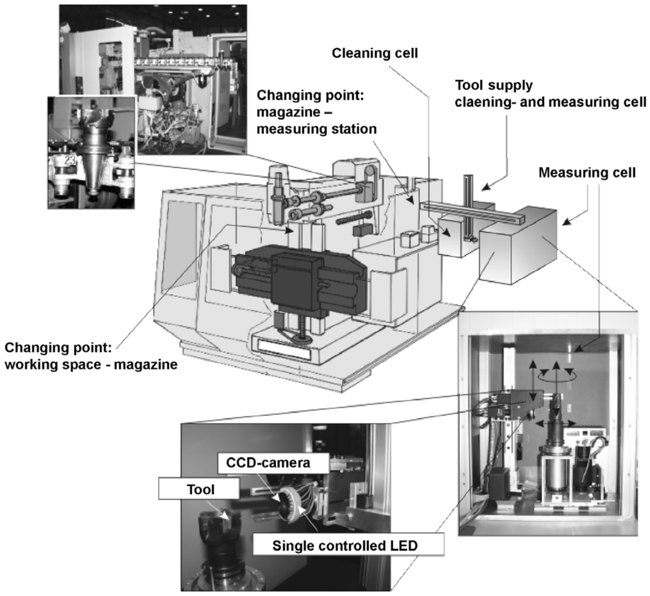


Fig. 3: Wear tool measurement on basis of a image processing supported camera inspection system

### *4.2. Process controll systemfor the automatically inspection of quality features at beverage can caps*

The Schmalbach-Lubeca AG is a global player with the manufacturing of packaging material. One of their core business is the manufacturing of beverage cans. For the quality assurance of the business segment beverage cans a fully automated inspection cell for the detection of geometrical features was intergrated in the production flow.

The system senses with an optical technique automatically ten parameters at the cap of the can, which before the workers had to collect expensively in different measuring stations with manual methods. The testing cell processes within about four minutes all the test criteria, while before for the manual testing in the measurement room several hours were necessary.

The removal magazin in which can be put up to 150 caps and which in this way can provide a stand-alone performance for 10 hours, is able to recognize autonomously the different types of caps put in it, and to create the respective inspection plans. Thus, faulty operation by the workers is excluded.

The testing cell consists of two chromatic sensors for the profile measurement of the top and bottom side of the cap, of a x-/y- positioning platform for the sensor, of an image processing-based camera system for recognition of the caps, of a Scara robot for the handling of the caps, of different magazines and of an air-conditioned test bench with safety interlock.

Inspection featrues of the beverage can cap is for example the remaining wall thickness in the scar line. That represents rated break points for the opening of the can cap (fig. 4). The remaining wall thickness is the critical feature for that the can is leak-proof in closed state, and can be opened without breaking opening clip. The test bench measures the surface profil of the cap's top and bottom side contactless at defined points. From the difference data the system evaluates the remaining wall thickness in the area of the scar line (tolerance+-2µm). Further more parameter like rivet head thickness, rivet bootom thickness and ventstop thickness can be detected.

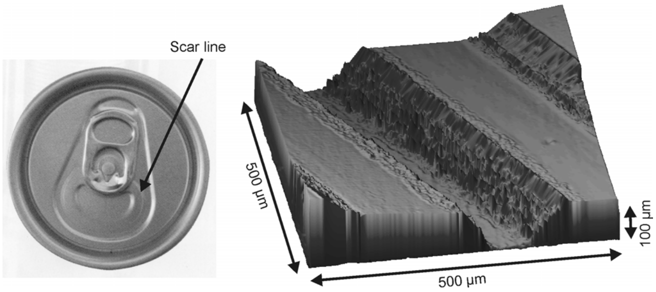


Fig. 4: Inspection featrues of the beverage can cap is for example the remaining wall thickness in the scar line [3].

*4.3. Multi-Sensor-Coordinate measuring technology in the manufacturing observation*

By the increasing miniaturization of components and units in almost all industrial sectors the conventional coordiate measuring machines working after the pure touching principle reach their performance limit.

Coordinate measuring machines with multi-sensors show the advantage that the user is able to select a sensor according to the respective measurement target [4]. At doing this there exists no limitations for adequate developed machines. Thus the possibility is given to process the complete inspection plan on one machine in one measuring procedure. Orientations and features can be determined by combination with different sensors. That creates efficiency advantages and a improved reliability.

Modern multi-sensor coordinate measuring systems are applied as well in the traditional field of production as in air-conditioned clean rooms.

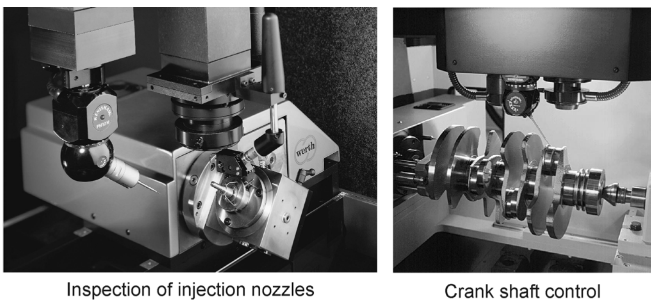


Fig. 5: Multisensor coordinate measuring systems

By a linear drive system, coordinate measuring machines are able to run up to 5 measuring positions per second and to measure there at the same time several geometrical elements. By means of the high measuring rate a efficient production observation with coordinate measuring machines is enabled for the first time in some sectors. This covers e.g. applications in the sector of electronic components and also the rapid measurement of plate bent components, moulds, and shafts in the automotive industry (fig. 5).

Multi-sensor coordinate measuring systems excel in the advantage, that apart from the available optoelectronic sensors different mechanical tracers and laser sensors can be integrated. By combined application the several sensors can fulfil different measuring tasks. A list of available optical sensors in multi-sensors coordinate measuring machines with respective field of application and respective advantages is shown in table 1.

TABLE I. Range of optical sensors in multisensor coordinate measuring systems

| Sensor | Fields of application | Advantages |
|---|---|---|
| Image processing | Edge measuring Multi-point distance measuring by contrast method | High-accuracy, rapid, independent from surface due to flexible lightening |
| Laser sensors | Path-scanning of 3D topography | Highly accurate contour measurement |
| Fibre tracers | Measurment of very small, e.g. diesel injector | High accuracy, possibility of micro-geometry measurement |
| Line and plane sensors | Free formed surfaces measurement | Very fast, large number of points |

*4.4. Trends*

The examples of optical in-process metrology presented so far show, that optical measuring systems work parallel, rapid and robust. These characteristics enable a high availability of process data and consequently a specific control within the production process.

In addition these success factors include the potential not only to apply optical metrology or optical measuring systems for a post-process quality inspection, but to integrate them directly in the manufacturing process.

In general, it can be shown that the in-process application of optical metrology represents a current trend of development. In future optical metrology will no longer be additively connected to an existing system, but it will be integrated from the beginning into the whole system even within design and development of the production equipment. With the example of a current research project such a machine-integrated complete system are presented now. Thereby, the essential innovation insists in building up within the machine tool continous data structures and interfaces from metrology over CAD/CAM functionalities and machine control up to the actual processing.

Due to continously increasing customer requirements and shorter product life cycles especially in the scope of tool-and die-making a rised flexibility and an utilization of all time and cost potentials is necessary. Thereby, tools for massive and sheet metal forming occupy a pivotal position within the production of investment and consumer goods.

Suchlike tools are often subjected to an intense wear during their application. Therefore, as well preventative measures, e.g. application of a protective layer, as efforts for restoration after use, e.g. regeneratrion of reference contour by depostion welding, are necessary. Usually the wear appears only locally at the most subjected areas of the tool. As the tools mostly are no longer applicable for production already with an abrasion of some 1/10 mm due to today's standard precision requirements, the worn areas must be built up again.

The reparation of such tools is presently provided in the separated pocessing steps tool preparation, manual deposition welding, NC programming for mill processing and the following rough and finish milling. These processing steps present a low degree of automation and a high content of manual operation. That results in high cycle times, who emerge from longer transport and holding times and as well from several set-up of different units (metrology, deposition welding machine, milling machine). In addition the multiple set-up effort causes potential error sources, which can be amplified within the process chain. Furthermore, there exists only an insufficient, in most cases even none continuity of CAD data.

The priority of this development project is the buildup of a repair-production cell for tool-and die-make, which enables an automated restoration from the detection of worn tool areas up to the repaired, applicable tool.

For this not only isolated applications for the respective processing steps

- optical geometry detection
- CAD data generation
- variance comparison
- NC data generation
- laser deposition welding
- finishing

should be elaborated, but especially an integrated complete implementation concept and its prototypical realization in a plant should be developped.

Caused by the decisive influence to the efficiency and continuity of the process chain within a tool repair-production cell a special meaning insists in the integration of optical 3D metrology into the complete system. The digitalization of the surface topography of different tools is provided by an fringe projection directly integrated into the axis portal of the manufacturing system. The advantages of these surface tracing methods contrary to tactile coordinate measuring technique are the high mesuring rate and the high denisity of the cloud of points at the digitalization.

## 5. POST-PROCESS MEASURING TECHNIQUE

In this chapter typical application for the use of optical post-process measuring techniques will be shown.

### *5.1 Laser light cutting technique for inspection of pistons*

Within the scope of quality assurance measures, like statistical process control, single features of manufactured workpieces must be controlled frequently. As an example for a typical post-process measurement, the inspection of a engine piston is described now.

Within the inspection of the engine pistons, not only macrogeometrical features like the piston diameter or the ovality have to be tested but also features of minor structures. On the piston there are grooves for the piston rings, for which the groove depth and width must be measured with a tolerance of 1/100 mm. Furthermore, there is a micro-structure applied by a lathing process along the piston skirt, which should support the improvement of the emergency operation performance of the piston. This micro-structure has the shape of a sawthooth with an amplitude of maximum 1/10 mm and must be measured with a measurement uncertainty of a few micrometers.

With optical measurement technology high requirements of measurement range and resolution can be satisfied. At the Fraunhofer IPT a light cutting technique was developped, with which two-dimensional sections can be measured and variable measurement ranges can be realized. Furthermore, that measurement system performs a high resolution independent of the selected measurement range (fig. 6). Moreover, the measuring system can be applied for object and position identification, completeness check respectively for the quality inspection of surface structures.

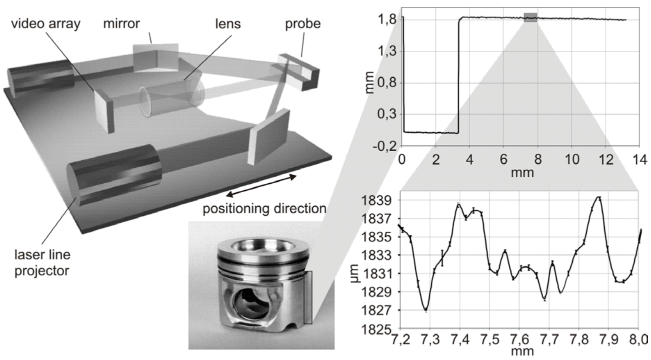


Fig. 6: Inspection of a engine pistion with laser light cutting process

### *5.2 Inspection of microscopic components and structures*

The demand for micro system components as well as for complete micro systems has significantly increased over the last years. Micro systems are successfully applied in different sectors like biology, automotive industry, telecommunication, sensor analysis and life science. This is caused by intermediately established production technologies. A similar tendency can be recognized in the field of testing and measuring technology. By having a view over the different measuring and testing techniques applied within the production of microsystems, it becomes obvious that even in the field of quality inspection a wide range of techniques is employed in order to estimate the spectrum of product features of a single micro component or of a complete micro system. For product-oriented post-process measuring technology in that ambitious field principally optical techniques like white light interferometry, confocal microscopy or autofocus technique are applied.

The most common field of application of white light interferometry is the surface characterization of optical and technical surfaces. So white light interferometry is employed e.g. for the roughness inspection of moulds for hot embossing or injection moulding, manufacured by ultra precision lathing. Especially laser mirrors or optics manufactured with the aid of the fast tool make high demands on the surface. Here mean roughness indices with values between 3 and 20 nm can be tested. Equally white light interferometry is applied for roughness testing of finished or scaled wafers. One more example is represented by the testing of diamond lathed optical surfaces of plastomer or non-ferrous metal like aluminium, copper and brass, where aimed mean roughness indices minor than 10 nm are checked.

For more detailed inspections of surfaces in the micrometer dimension, a special modification of the conventional optical light microscopy is applied: confocal microscopy. As result of a skilled combination of pinholes and optics confocal microscopy can image not only surfaces but even the three-dimensional shape of objects in a very clear and high-contrast way. Thus e.g. the width and depth of ultra precision milled channels for optical fibre connection or for fluid technical applications can be detected. Also the shape as well as the aperture angle of milled V-grooves can be measured, which are used as reflectors for purposes of illumination (fig. 7). An other application lies e.g. in the characterization of the topgraphy of grinding disks or in the evaluation of the one-grain scratch test of wafers for the analysis of material abrasion mechanisms.

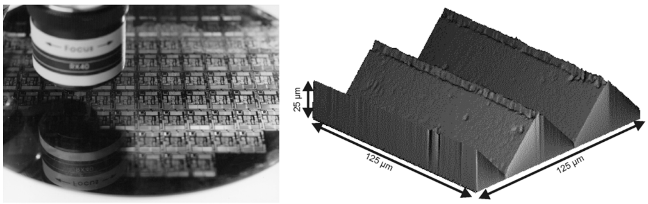


Fig. 7: Optical inspection of finished manufactured wafers (left) – 3D-topography of a V-groove in brass measured by confocal microscopy (right)

## 6. PERSPECTIVES AND TRENDS

The development of optical production metrology is largely driven by production technology. Thus optical measuring methods are continously modified, refined and optimized, in order to fulfil the continually increasing requirements regarding to tolerance and complexity of the tested gemoetries, and to permit a higher degree of integration of the optical metrology in tool machines as well as in production processes.

Future challenges and trends in optical metrology can be named as follows:

- machine-integrated integral systems
- multi-sensoric applications
- miniaturization of optical measuring systems
- scalable measuring methods
- cost reduction of optical measuring systems increase of precision and measuring rate

## 7. CONCLUSION

In all the producing branches shorter time-to-market intervals and growing demands on the quality require a reliable control of all the processes participating in the product emergence. Instable or failure prone processes cause costs for rejects and retouching work as well as rising costs for warranty, obligingness and resulting consequential costs, which affect enduringly negative the competitiveness. Low cycle times, high adherence to schedules and short production start-up times require an increase of efficiency of the applied production methods. At the same time a high option variety, complex manufacturing methods, increasing precision of manufacturing as well as novel manufacturing processes demand an efficient control of complete production processes.

In order to guarantee the required quality of process and product, mesauring methods must be applied, which also satisfy the highest demands. Thus optical measuring methods excel by rapidity, robustness, high precision, simple handling , high adherence to details and low costs. Beyond that, by optical metrology many different dimensions like geometry, extension or mechanical stresses can be detected.

The tendency of production of complex geometries and of introduction of new manufacturing methods result in the need for reaching more and more higher finishing accuracies and for satisfying more and more tighter tolerances, which in turn must be proved by adequate measuring techniques. For that, an involvement of optical metrology in the machine-integrated total system is urgently necessary in order to satisfy the requirements of the production environment. Optical measuring methods excel by a high flexibility, rapid detection of measurement values, non-contact object tracing and a brilliant adaptability to product and process parameters, which also permit a specific control of complex production processes.

Optical metrology creates the precondition for ensuring reliable and capable production processes and is meanwhile applied in all fields of the product synthesis process. The showed examples document that optical measuring methods are already established and successfully applied in the field of production, and that optical metrology also in future will represent an important factor for the succes of quality-oriented production.

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