IN-PROCESS QUALITY CONTROL APPROACH IN METAL FORMING OF SPLINED MACHINE ELEMENTS

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Abstract:

The increasing demand of high precision machine elements manufactured in mass production results in a target conflict with respect to quality control of the production lots, esp. if metal forming techniques are the production principles.

Due to high process forces, kinematic movements of forming tools and imprinted change of material properties during tool and workpiece interaction, a change of the workpiece position within the manufacturing processes generates quality losses in the resulting geometries.

Today, SPC based post-process or in-situ measurements are the basis for the quality control on such production processes. This paper will give an outlook on in-process monitoring of geometrical features based on the targeted component feature specification to be observed. The border-zone quality prediction combined with the collection of relevant process parameters, integrated into an overall in-process measurement system approach are further intellectual aspects. Initial results out of an ongoing development initiative will be presented.

Keywords: in-process metrology, metal forming of gears, precision mass manufacturing

1. INTRODUCTION

The actual trends in the field of precision manufacturing are the driving forces in the development environment in the higher accuracy coordinate metrology industry and representing their future challenges [1].

Some representative examples are the total capture of the components overall 3D-geometry using high accuracy sensing technologies, the measurement of border-zone surface properties using multi-physical principles and in-process quality control and -inspection systems in connection to calibration chains with the NMIs, delivering resilient results of relevant process quality parameters [2].

The scope of this paper is set by an in-process quality control approach, applied on splined machine elements using metal forming production techniques. This case represents a typical application of precision components mass production using non-cutting production techniques [3].

2. PRECISION MANUFACTURING OF SPLINED MACHINE ELEMENTS USING METAL FORMING TECHNIQUES

2.1 Industrial Application

Splined machine elements are mass parts to be used f.e. in the automotive industry in very large numbers. The most common application is the component combination of a gear pair represented by a spline shaft and a gear hub. This shaft-hub combination is mainly used for the transmission of torque by allowing an axial displacement within the connection. The precision of these mass parts is remarkable high, as the transmissions stages containing this components have a need of high quality central axis alignment combined with a low level of backlash over lifetime use (Fig.1).

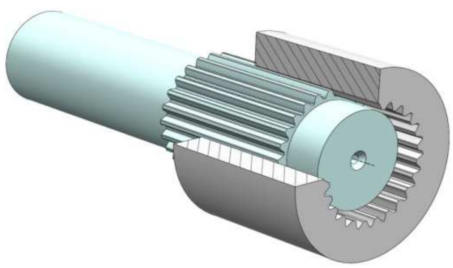

Fig. 1: Shaft-hub connection [3]

The manufacturing methods for splined machine elements are based on rolling processes using compressive stress while forming the tooth gap. The main methods can be differed into methods with a) rotationally symmetrical external toothed tools (PeeWee), b) with flat back shaped tools (RotoFlow) and c) with internal toothed tools (WPM) (Fig. 2) [4].

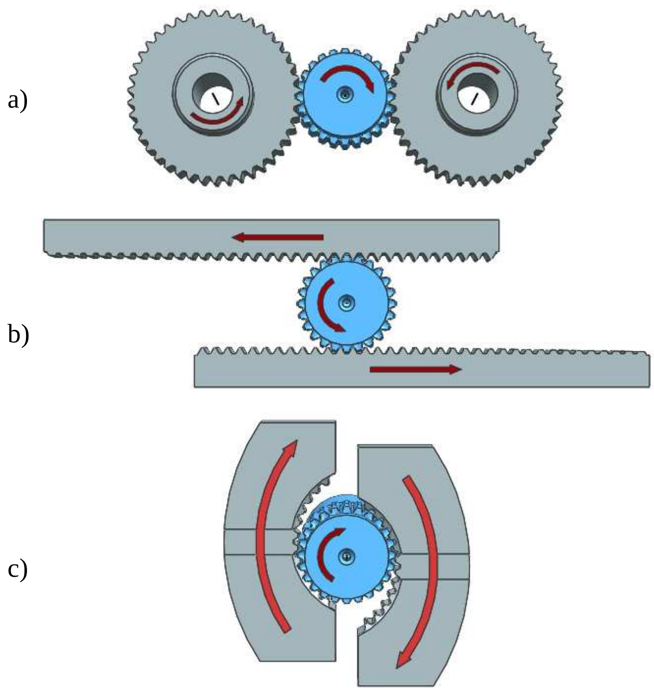

Fig. 2: Spline shaft rolling methods

2.2 Limitations and Conflicts

The rolling processes in metal forming of spline shafts provide highest performance in production throughput and a remarkable benefit in material savings (Fig. 3) which leads into a considerable economic advantage.

In contradiction to those manufacturing advantages, the industrial mass manufacturing of accurate machine elements demands a contemporary and intensive quality control. Basically the arising quality assessment efforts are representing a major contribution to the overall production cost per unit [5].

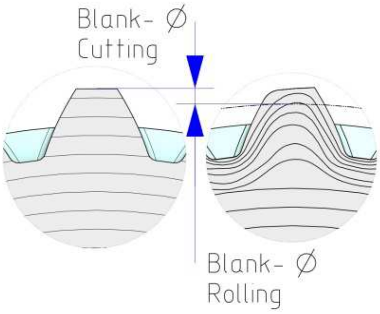

Fig. 3: Preliminary diameters [3]

The post-process quality control of components manufactured by metal forming techniques can only be considered as a process audit, even when implemented as an In-Line setup, as inspection times cannot compete with the high speed production cycles.

As the mass manufacturing is, due to cost effectiveness, based moreoften on metal forming technologies the demand of adapted quality control approaches increases in order to achieve an overall competetive advantage against cutting production techniques.

Looking more detailed into the rolling processes for splined machine elements, the achievable feature accuracy figures are interdependent from relevant process parameters like [4]:

- workpiece feedrate = actively deformed volume / time,
- linear-/rotational velocities of workpiece and work-toolsets,
- drive systems power consumption,
- preload- and process forces,
- machine frame and guideway deformations.

Due to high process forces, certain kinematic movements of forming tools and imprinted change of material properties during tool and workpiece interaction, a change of the workpiece position within the manufacturing processes generates quality losses in the resulting feature geometries. The level of quality loss can be determined within a root-cause analysis and is driven by:

- initial unbalances and weaknesses within the rolling machine mechanics or drive systems,
- workpiece excentricity caused by process forces /-torque or initiated by worktool contact within the active forming zone,
- workpiece deformations or distortions caused by process forces /- torque.

In summary the Kinematic movement of the workpiece can be described in first order as an assumption of the DOF in the external fixation and the guidance given by the work-toolsets. The imprinted geometrical gear quality is strongly depending on that circumstances and typical characteristics like:

- pitch-/runout excentricities,
- profile unsymmetries,
- flank direction errors,
- head- and root circle diameter deviations,

can be found during gear measurements acc. DIN 3960ff. (Fig. 4-5) [6].

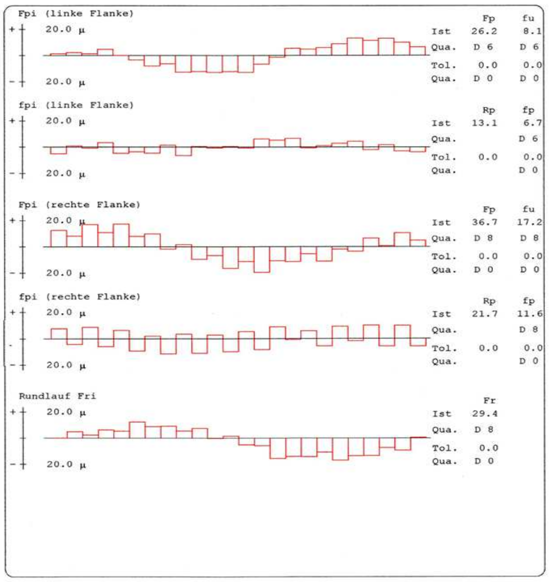

Fig. 4: Pitch- / runout excentricity acc. DIN 3960ff. [3]

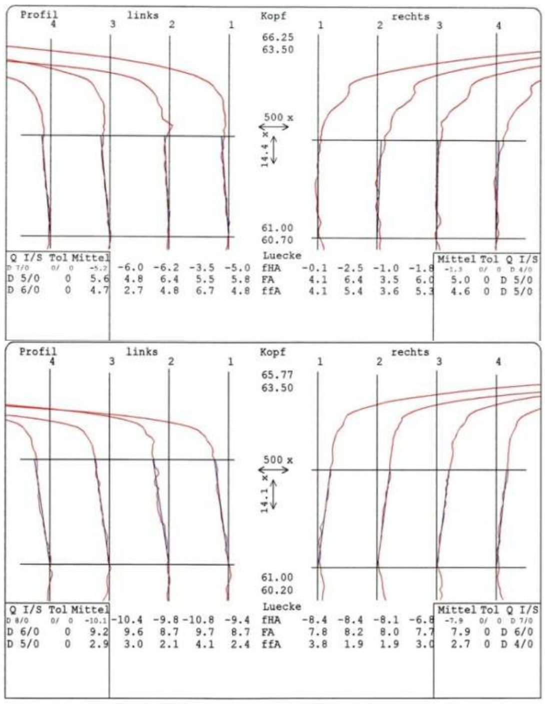

Fig. 5: Profile- and tooth trace deviations acc. DIN 3960ff. of a WPM rolled spline shaft [3]

In addition to the gear geometry characteristics, the material structure changes caused by non-linear material behaviour resulting f.e. in work-hardening based on the materials flow curve characteristics [7].

As a matter of fact, specific to feature accuracy realisation, a process internal conflict with the functional required material properties, like:

- grain texture,
- hardness and depth of hardness,
- introduced residual stress,
- roughness changes and surface damages/cracks,

cannot be avoided (Fig. 6) [8].

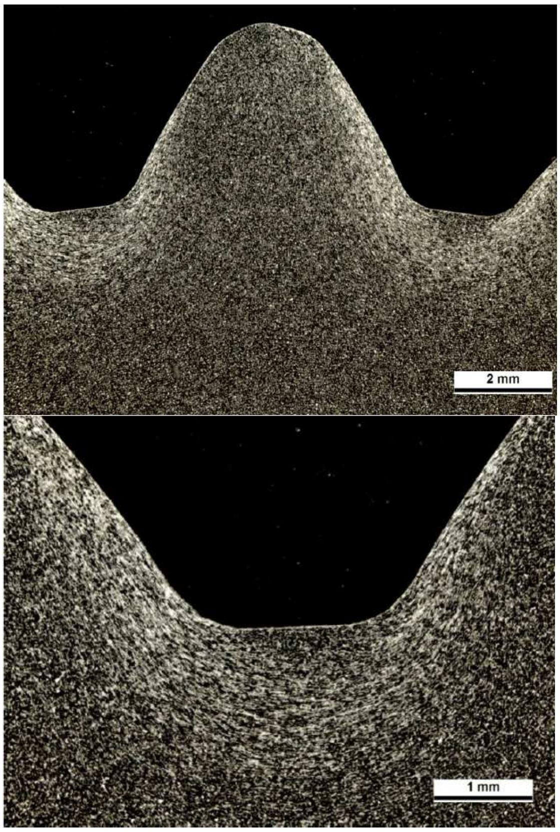

Fig. 6: Metallographic specimen of a WPM rolled spline shaft, material C15 (1.1140), scale: 10:1 / 20:1 [8]

The correlation between the geometrical characteristics (Fig. 5) compared to the analyzed material structure (Fig. 6) is significantly high in the reviewed rolling process. This observation could be amongst others a base for in-process monitoring approach [9,10].

3. IN-PROCESS QUALITY CONTROL NEW MEASUREMENT SYSTEM APPROACH

3.1 Experimental Results

The geometrical characteristics at splined machine elements manufactured by rolling processes are unique for certain classes of rolling methods and the specifics can be found in functional as well as in non-functional tooth areas [3]. The central question now is, if the geometrical characteristics are direct or indirect related to certain process parameters. If doing so, the monitoring and evaluation of these relevant process parameters allow a review of the rolling process as such and the prediction of the resulting component qualities.

The typical geometrical feature characteristics are located on the accessable surface of the rolled parts and targeted to be therefore detected by suitable sensors (non-contact) within the forming machine and during the production process. A special attention could be spent to the capture of typical shapes and edges to be recognized perpendicular to the centerline of the spline shaft (Fig. 7) [3]. This mentioned dimensional parameters are to be correlated to inherent process parameters, within this study to the feedrate of the toolset.

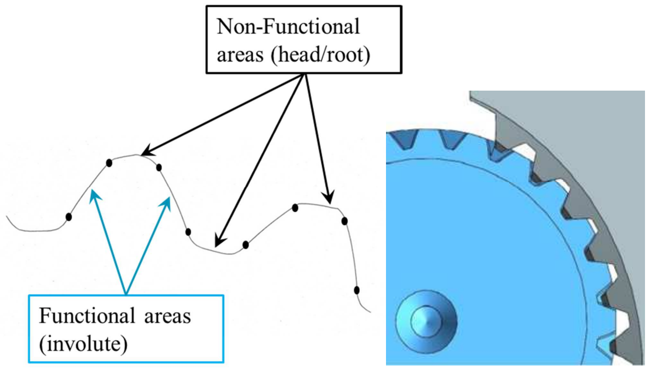

Fig. 7: Separation of tooth areas [3]

3.2 Implementation Considerations

Within the presented case study, the outcoming root-diameter deviations are being observed more accurate within the production batch (Fig. 8). So this parameter could be a stable base for referencing an in-process measurement setup.

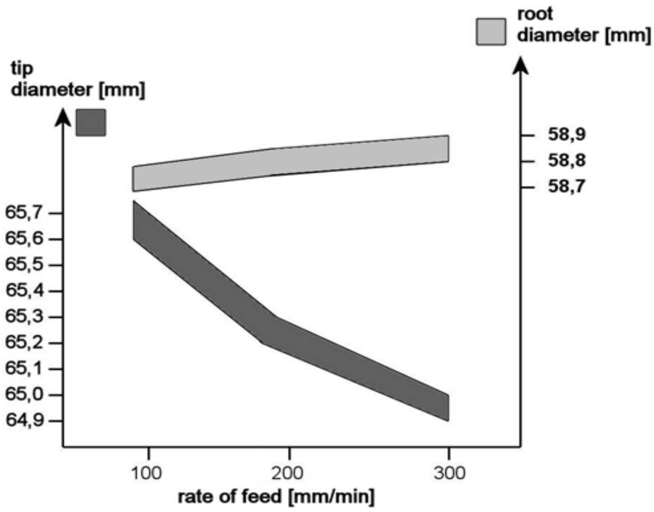

Fig. 8: Trend analysis of tip- / root diameter dependence [3]

Further aspects in the implementation context can be listed as follows:

- local specifics like already described shapes and edges of the spline geometry are to be observed within the total length of the forming zone,
- typical tooth shapes are unique to the reviewed process forming stages,
- Detectable metrological changes within the specific rolling method, geometrical features indicate

variations of relevant process parameters. These changes could indirectly being associated with a change in the component quality.

As an example regarding experimental sensor system setup in spline shaft production, the illustrated arrangement sketch (Fig. 9) can be seen as an initial idea.

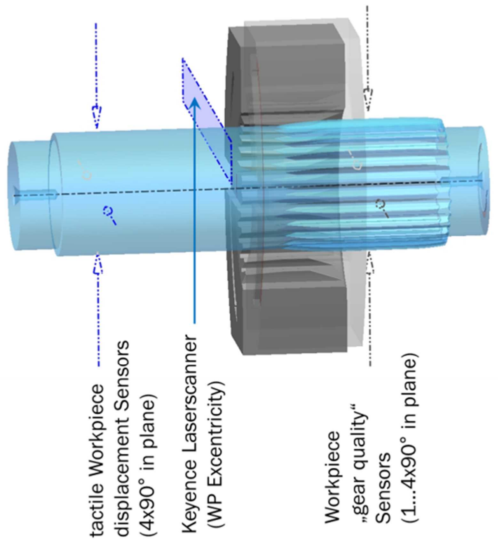

Fig. 9: Example of in-process sensor setup principle

The challenges of such an in-process measurement arrangement in precision manufacturing could be anticipated by the:

- given overall system environment in shopfloor conditions,
- multiple Sensor Systems integration into existing machine tools,
- Real-Time data aquisition and processing
- (model based or experimental) correlation function determination of multi-physical parameter combinations
- Measurement System Calibration and Measurement Uncertainty evaluation.

The future in-process quality control systems require special considerations for the integration into future machine tool concepts. Fig. 10 represents a simplified view on this topic. In the future design approach the monitoring of surface parameters, f.e. roughness, structural cracks and work-hardening additional constructive barriers remain to be overcome.

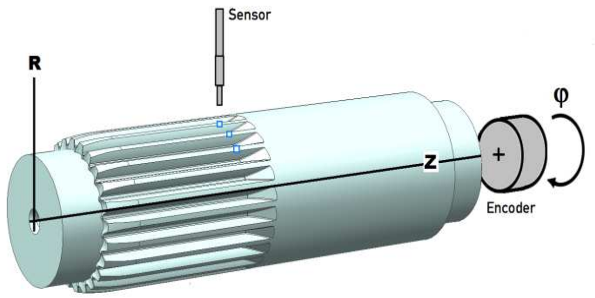

Fig. 10: Configuration of sensors / workpiece coordinate system R, Z, φ [3]

4. CONCLUSION

Changes in the specific characteristics in combination with mechanical and technical measured variables can be detected and interpreted in the individual process or the production life of many toothed components. The monitoring of the uniformity of an ongoing mass production stands in the foreground. It can be assumed, that the production takes place under the same conditions, if the results show nearly identical head and foot geometries. Fluctuations in the corresponding measured values strongly indicate that the rolling conditions must have changed [3].

The acquisition of geometrical features with non-tactile sensors based on detailed indication regarding the contact situation between the tools and the material will be set as a starting point for the application of in-process monitoring. Considering the geometric relationships on the resulting workpiece geometry, a detailed analysis of the material work hardening combined with the resulting surface characteristics lead to a comprehensive in-process quality control of rolling methods.

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