Quality and Surface of Gears Manufactured by Free-Form Milling with Standard Tools

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The recently available capability for the free-form milling of gears of various gear types and sizes—all within one manufacturing system—is becoming increasingly recognized as a flexible machining process for gears. This paper addresses the manufacturing and quality of gears made by free-form milling, with an added focus on the specific process properties of the parts. Finally, the potential for free-form milling is investigated in cutting tests of a common standard gear.

Introduction

The free-form milling of gears recently becomes more and more important as a flexible machining process for gears. Due to use of standard milling tools and universal machine tools, free-form milling of gears does not depend on special tool geometries for each gear type. This makes the technology relevant for manufacturing of gears on universal cutting machines in various applications (Refs. 1–3); (Fig. 1).

With the use of standard milling tools the application area of gear types and sizes is theoretically unrestricted; accordingly, all conventional gear types and tooth geometries can be realized. Furthermore, the technology is flexible concerning new gear types.

Study Aim and Approach

Although the technology for the process design and manufacture is readily available (Refs. 4–9), there is nothing yet published concerning the potential of free-form gear milling pertaining to *gear quality*.

Gear manufacture via free-form milling with standard milling tools on universal machine tools is a combination of conventional gear manufacturing technology with special machines and integrated NC machining of complex geometries on universal cutting machines. Both domains are characterized by specific terminologies and technical terms. The fusion of both domains requires an agreement of technical terms in a disciplinary matrix for free-form milling of gears (Ref. 10).

Process capability will be analyzed in milling trials. Therefore hard-machining of a standard gear will be done with different machining strategies.

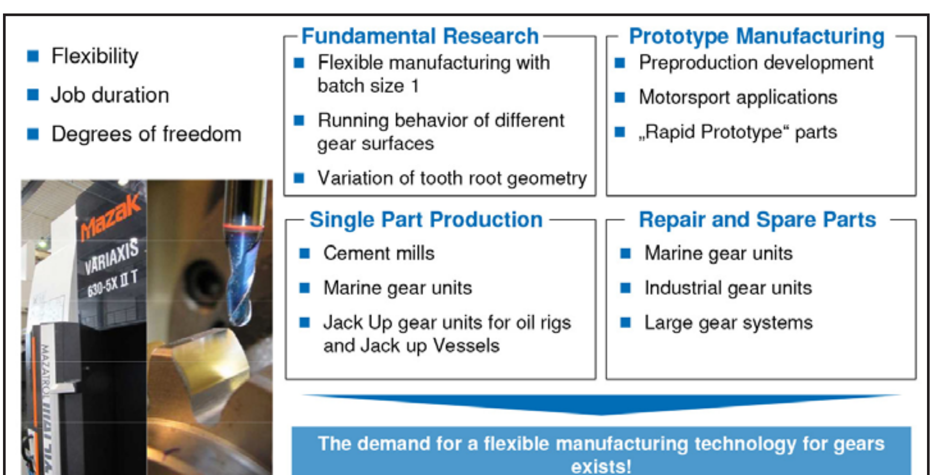

Figure 1 Motivation and area of application.

Terminology of Free-Form Milling

According to DIN 8589-3, manufacturing of gears on universal machine tools is located in the area of NC form milling (Ref. 11). The manufacturing process regarding machine tool and control unit is comparable to the manufacture of molds and dies (because of similar materials, hardness and accuracies), and to the manufacture of impellers (because of similar geometries). The process description includes the definition of process parameters, tool selection and the generation of input data (Fig. 2).

A full description of process characteristics of free-form milling of gears contains: tool selection, generation of input data and machining strategy; these three mentioned aspects will be discussed in the following sections. Characteristics beyond that are defined by terminology of gear manufacturing and NC free-form milling, and will be adapted.

Selection of milling tools. The selection of milling tools is divided into soft- and hard-machining. Between rough and fine cutting steps, a change of tools must be done because of different requirements. For the machining of tooth root, a tool change can be necessary, too. Standard milling tools are characterized by the parameters shown in the middle of Figure 2.

For stability reasons the tool diameter is chosen as large as possible. Tool length is chosen as short as possible. Tool size

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as well as the blade radius is restricted by the gear geometry.

Different types of milling tools are divided into groups by their blade geometry. Possible tool geometries are full radius, torus and shaft cutter (Fig. 2, middle). Depending on the type of tool, there is a point or line contact between tool and gear flank. The chosen machining strategy is essential for this contact condition and for restrictions of tool selection.

Generation of machine input data. In contrast to the manufacture of gears on conventional gear manufacturing machines, free-form milling of gears requires a defined geometry in the form of coordinates. Figure 3 shows the CAx process chain that is necessary for the generation of the NC code.

After gear design, the gear data is the input for the CAx process chain. In the first step, the gear data is transferred to the gear geometry. The creation of gear geometry can be done analytically or by a manufacturing simulation that includes a defined geometry off both flanks and tooth root. In the following step the gear geometry is converted into NC code. Any deviation of geometry resulting from the manufacturing process can be negated by closed-loop between manufacturing, gear measurement and generation of NC code. Depending on the correction method, different steps of the CAx process chain are necessary for this compensation (Fig. 3, right).

Machining strategy. The machining strategy includes three major aspects of the definition of the manufacturing process: 1) *lineness*; 2) *trajectory*; and 3) *indexing procedure* (see Fig. 4).

The *trajectory* defines the path of the tool in machining relative to the tooth flank. The *lineness* is the term for the quantity of tool paths required for the machining of one tooth flank and the space between the lines. The *indexing procedure* describes the systematics of machining all gaps successively. This includes the manufacturing order and movement of all axes during indexing between two teeth. All three components of the machining strategy are defined and described in detail in the following sections.

Trajectory. The definition of the trajectory is based on technological requirements for the running behavior of the

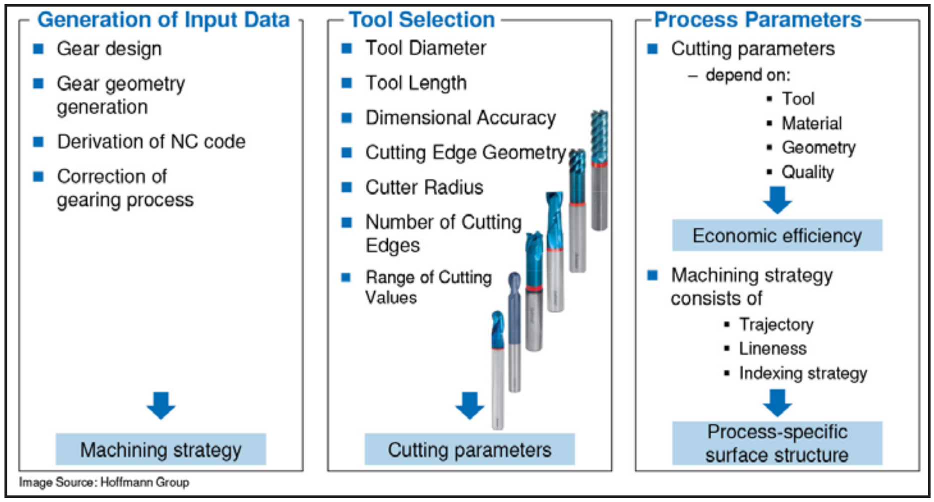

Figure 2 Process characterization of free form milling for gears.

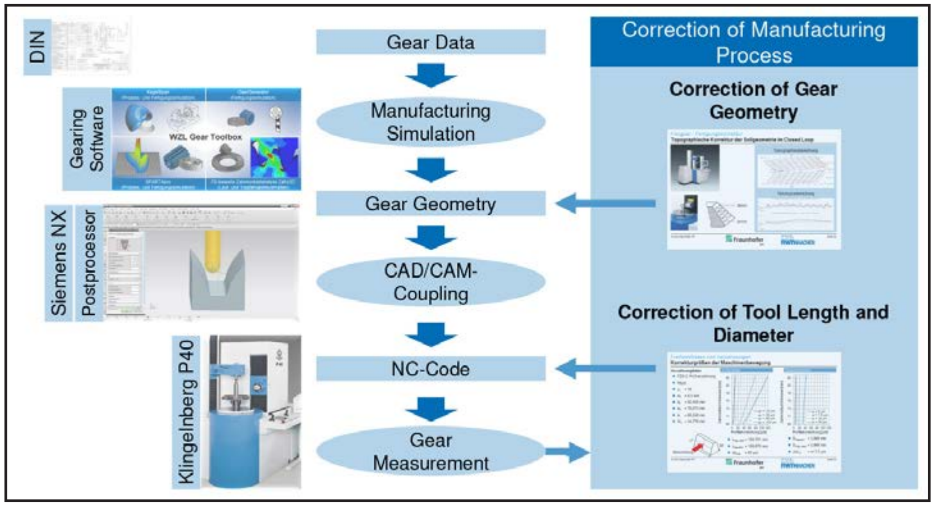

Figure 3 CAx process chain of generation of NC code.

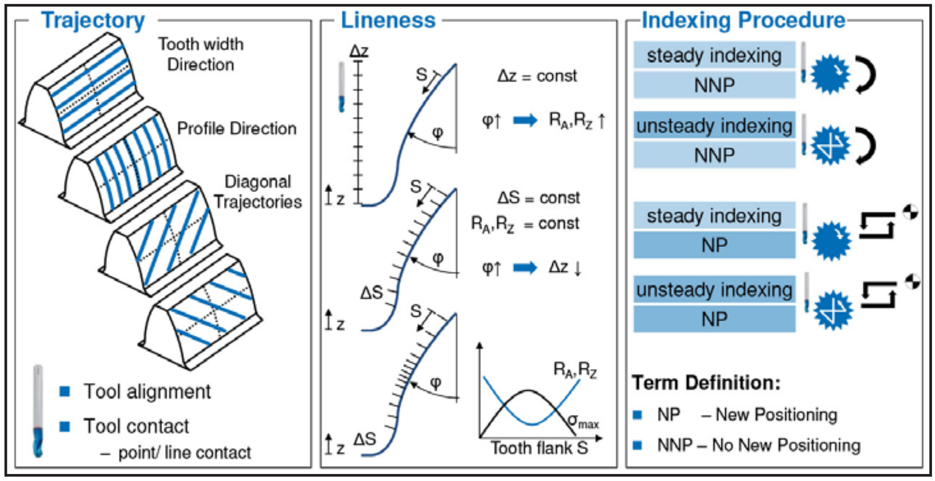

Figure 4 Machining strategy of free form milling of gears.

gears. Furthermore, the trajectory has a significant influence on processing effort and process kinematics (Fig. 4, left). The trajectory can be defined in direction of tooth width, profile direction or diagonal on tooth flank. Furthermore, common structures can be imitated (gear honing or gear finish hobbing) and new structures realized. From the manufacturing perspective, there are no technological restrictions. In terms of economical process design, the complexity of trajectories has to be taken into account, because complex trajectories require additional axes and tool movements.

Lineness. One, lineness defines the number of tool paths, which significantly influence machining time; two, lineness defines the schema, i.e. — how tool paths are located on the tooth flank. There are three possibilities that can be seen in the middle of Figure 4:

Tool feed can be equidistant for each tool path. That leads to a changing structure all over the tooth flank.

Define tool feed depending on gear geometry in order to keep the space between two paths on the gear flank constant. Surface structures at tip and tooth root are the same.

An independent definition of line spaces in tool feed and tooth profile direction. Here the structure can be defined freely and the flank surface can be realized basing on stress deviation for the whole flank. According to this, the effort for process configuration is very high in this case.

The space between tooth paths defines kinematic surface roughness (Refs. 12–13). The kinematic surface roughness can be described geometrically, so that the surface requirements can be taken into account during configuration of the milling process.

Indexing strategy. Centering of the gap for hard-machining can be realized by measuring equipment on the machine tool. The indexing strategy can be steady or unsteady.

During steady indexing the proximate gap is located next to the current one. The advantages are short movements of tool and part during machining. As a result, short machining times are attainable. Errors in part rotation and thermic influences are accumulated during

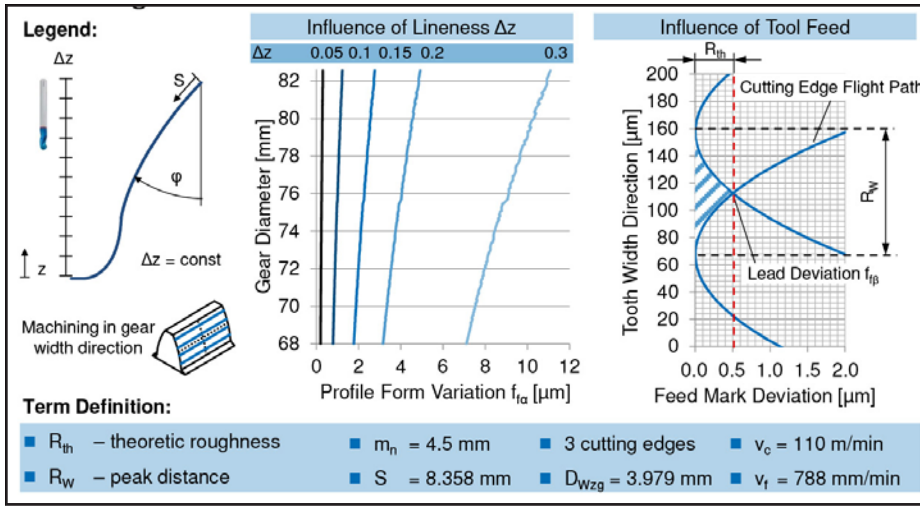

Figure 5 Influence of process parameters on kinematic surface roughness.

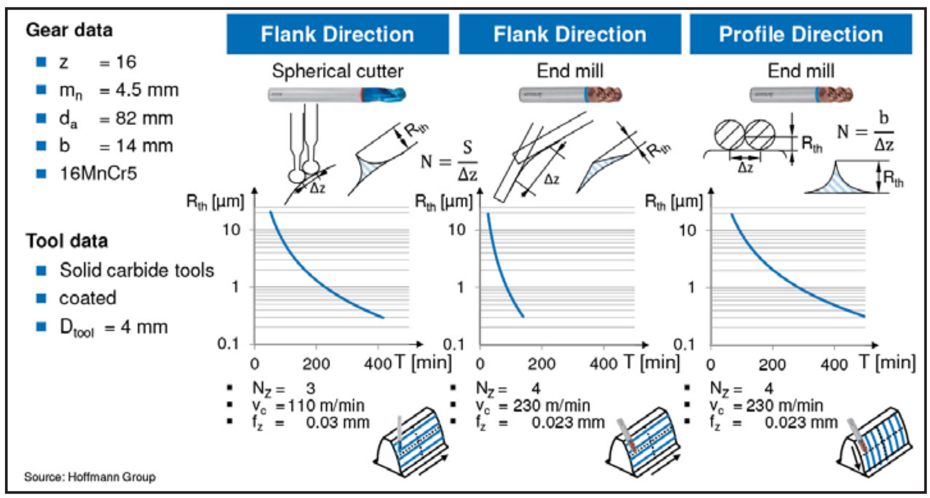

Figure 6 Machining time based on different milling strategies.

machining, so that the pitch deviation between first and last tooth are high.

During unsteady indexing, the gaps are machined in even distribution around the gear; errors are not accumulated in this case. The peak of pitch deviation can be avoided in this case. Machining time will be higher than with steady indexing, because more movements are necessary.

Process-specific surface structure. Lineness and trajectory directly influence the process-specific surface structure; the trajectory defines the orientation and the amount of lineness.

The free-form milling of gears has a high degree of freedom concerning different machinable surfaces, in comparison to conventional gear manufacturing. Similar to gear hobbing, the surface structure can be divided into feed marks (form tool blades) and generated cut marks (lineness). The theoretical roughness can be calculated — as well as determined — based on tool movement (Refs. 12–13). Dimensions of both deviations for one example gear are shown in Figure 5.

Profile deviation is increasing exponentially, with decreasing number of lines. Fifty lines lead to profile form deviation $f_{f\alpha} << 2\,\mu m$, which is quality class one. In this example, the trajectory is oriented in gear width direction so that feed marks should be visible as tooth flank form deviation $f_{f\beta}$. The diagram on the right-hand side shows the roughness R_{th} that occurred because of tool feed. For this purpose the flight path of the cutting blade is sketched in the diagram. Tool feed during one rotation of the tool is $f = 0.09$ mm, so that for this example theoretical roughness is $R_{th} = 0.50\,\mu m$ as a result of radial run-out of the tool.

In comparison to gear hobbing, the machining time for rough machining is much higher. This is related to two main aspects: the required surface roughness and the defined machining strategy.

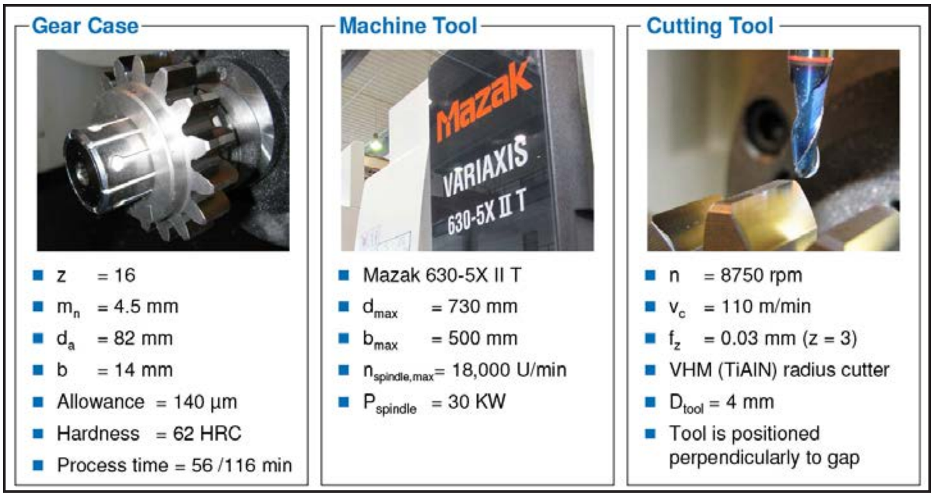

Figure 7 Gear case and machine tool.

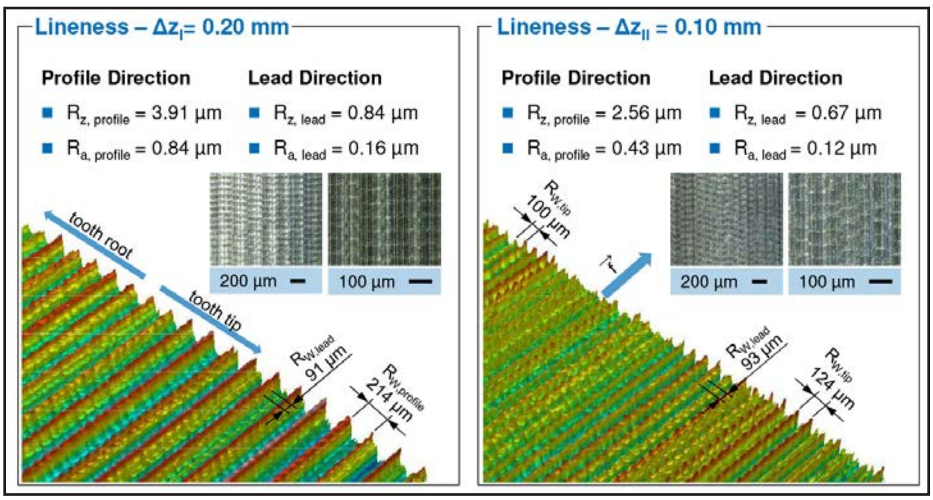

Figure 8 Analysis of process specific surface structure.

Figure 6 gives an overview of the influence of both aspects on machining time T per part.

The initial machining strategy on the left-hand side was arrived at with a radius cutter (Fig. 5); the tool is positioned perpendicularly to the tooth flank. The machined quality is directly related to deviations of tooth diameter and length. Surface roughness is directly defined by the penetration of tool radius. Quality class one ($R_{th} < 2\,\mu m$) requires a machining time of T = 160 min. The advantage of this strategy is that fewer axes are necessary for machining.

The second strategy in the middle of Figure 5 is using a shaft cutter. The tool is positioned tangential to the tooth flank. Note that deviation of tooth diameter is influencing tooth width — but not profile quality. The tool is cutting with the outer diameter so that a deviation of tool length has no influence on part quality. What is more, the tool can be shifted so that tool wear can be distributed equally over the entire length of the cutting blade. This strategy is much more efficient than the first one because fewer lines are necessary. Hence the machining time for $R_{th} < 2\,\mu m$ is T = 70 min.

The third machining strategy on the right-hand side of Figure 5 is using a trajectory in profile direction; tool and cutting parameters are equal to the second strategy. The tool is also positioned tangential to the tooth flank and is cutting with the outer diameter. In comparison to the other strategies, a high number of lines is required. In addition, complex movements of tool and part are necessary, which leads to a machining time of T = 200 min for $R_{th} < 2\,\mu m$.

Analyisis of Process Capability in Milling Trials

Process capability of free-form milling of gears with standard milling tools on universal cutting machines can be validated by hard-machining of parts after heat treatment. Hard-machining includes aspects of CAx process chain, as well as quality requirements of finished gears.

Gear geometry and machine tool. In order to analyze the process capability of the free-form milling of gears, a trial series with standard spur gears was carried out. Due to the smaller amount of influences, this simplification offers the opportunity for the basic research of fundamental process phenomena; the principles of process correction can be comprehended directly. Also, this gear type can be compared to various research projects with the same gear type.

For the milling trials the parts were soft-machined conventionally. Hard-machining tests were done after heat treatment (hardness 62 HRC). Thus the focus is on tooth flank quality. The tooth root was not hard-machined. Allowance for hard-machining was 140 µm to 150 µm. Radial and axial run-out were checked manually and less than 2 µm.

Experimental Set-Up and Overview

Cutting parameters were adopted from tool manufacturer data. Cutting velocity and tool feed were constant for all tests. Machining was done dry without cutting fluid.

The influence of lineness was analyzed; therefore two different feeds were compared. The first process had a feed of $\Delta_{zI} = 0.2$ mm (42 lines). The second process had a feed of $\Delta_{zII} = 0.1$ mm (84 lines). The trajectory was defined in tooth width direction. Tool feed was constant between two paths, so that tool positions were equidistant.

In the beginning of machining, the part was centered by measuring equipment of the machine. During indexing no additional centering step was applied. The indexing strategy was varied. Three different strategies were tested. Focus of the analysis was the process-specific surface structure of the flank and pitch deviation, as well as the tooth profile quality of the machined gears.

Surface analysis of gear flanks. Gear surface analysis was done by digital microscope as well as tactile measurement of 3D surface topology (4.8 mm × 4.8 mm); (Fig. 8).

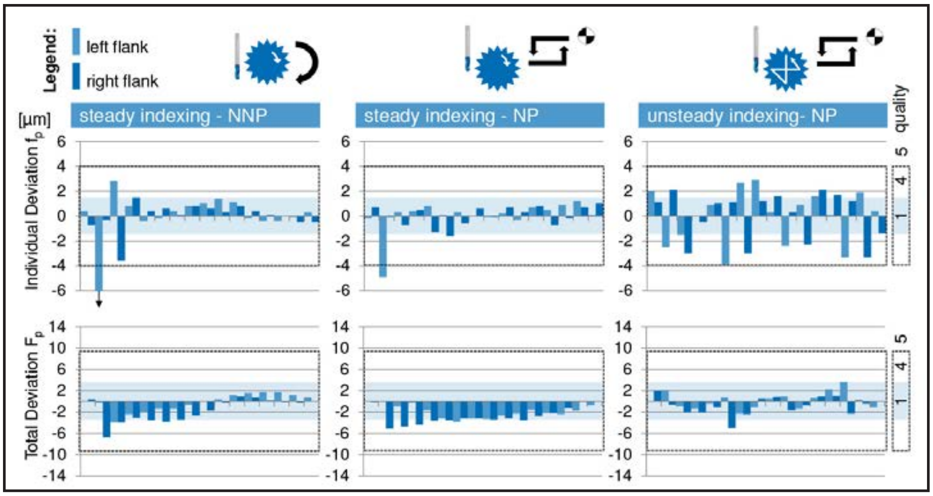

Figure 9 Pitch deviation depending on machining strategy.

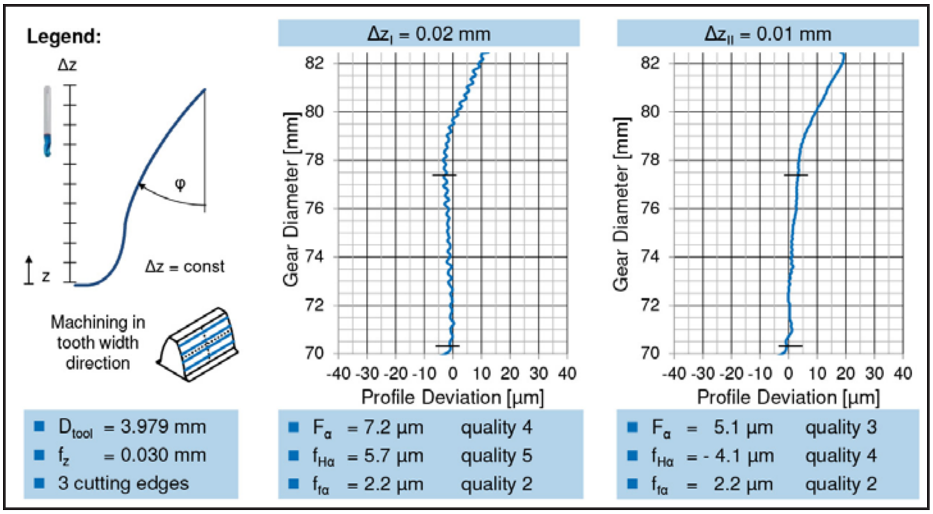

Figure 10 Profile deviation depending on lineness.

Based on these measurements the influence of lineness on surface structure can be described. Therefore gears were manufactured with two different line spaces, i.e. — $\Delta_{zI} = 0.2$ mm and $\Delta_{zII} = 0.1$ mm. It can clearly be seen that the surface structure significantly depends on the defined lineness. The line space is clearly visible in the measured topologies. The line space also changes over the tooth profile — which was expected — because of the equidistant tool feed ($\Delta z = const$). So the line space increases at the tip of the tooth.

Pitch deviation. Since free-form milling of gears is a discontinuous indexing process, every gap is machined separately and the focus must be on pitch deviation of the manufactured gear. Therefore different trials with three indexing strategies were compared. For every trial a whole gear was machined using one single strategy. Individual and total pitch variation (f_p and F_p) as well as pitch error f_u were compared (Fig. 9).

The first trial on the left-hand side was carried out with steady indexing and without new positioning of machine axes (NNP). Most gaps show a small, single pitch deviation. Only between the last and the first tooth is there a high single pitch deviation of $f_p = 7.0$ µm (quality class 6); the total pitch deviation F_p has quality class 2.

The second trial, shown in the middle, was also carried out with steady indexing but with new positioning of all machine axes for each gap (NP). The total pitch deviation is similar to the trial on the left-hand side (quality class 2). The single pitch deviation was reduced to $f_p = 4.8$ µm (quality class 5) — within the quality requirements for this gear.

The third trial (on the right-hand side) shows mainly higher individual pitch deviations. Nevertheless the highest pitch error ($f_{u\,max} = 6.6$ µm) leads to quality class 4. Also, the maximum individual pitch deviation is $f_{p\,max} = 3.9$ µm (quality class 4), which is an additional improvement in quality in comparison to the other indexing strategies. *And*, the total deviation F_p has a better quality.

Form deviation of gear tooth. The tooth flank form deviation $f_{f\beta}$ has quality class 1 for all parts. The deviation of tooth flank angle $f_{H\beta}$ has quality class 2. This can be caused by deviation of the fixture of the part. In total, the results are very sufficient.

The main focus is on the analysis of profile deviations $f_{H\alpha}$ and $f_{f\alpha}$. Lineness was varied from $\Delta_{zI} = 0.2$ mm to $\Delta_{zI} = 0.1$ mm; line space was equidistant. The results are shown in Figure 10.

The comparison of both results shows significant influence of lineness on profile form deviation $f_{f\alpha}$. For tool feed of $\Delta_{zI} = 0.2$ mm, maximum profile deviation is $f_{f\alpha} = 2.1$ to 2.6 µm. These values are very similar to the calculated values for kinematic surface roughness $R_{th} = 2.5$ µm.

For tool feed of $\Delta_{zI} = 0.1$ mm, the profile form is much smoother. Nevertheless the profile deviation is in the same range — $f_{f\alpha} = 1.2$ to 2.7 µm. This error cannot be based in kinematic surface roughness, which is $R_{th} = 0.63$ µm.

Summary and Outlook

Gear manufacturing with free-form milling has recently become more relevant for industrial use. The key reasons for that are high degrees of freedom, as usage of universal tool geometry and machine tool allows for the flexible machining of various gear types and sizes with one manufacturing system.

As "state-of-the-art" provides no sufficient description of this manufacturing process in any literature, terminology has been developed concerning the process characteristics of the free-form milling of gears. As such, machining strategy was fully defined in this paper. This definition includes the trajectory (path of tool movement during cutting process); lineness (number and distribution of trajectories); and the indexing strategy (machining order of gaps), as they are the three main components of the machining strategy. Additionally, process-specific surface characteristics were described and calculated, enabling immediate consideration of surface structure during process design for different machining strategies and tools.

Machining tests were conducted. Results show a direct link between process parameters (feed and lineness) and gear surface. Also, they validate the consideration of surface structure, as the correlation between test and calculation is sufficient. Gear geometry shows good results concerning pitch (quality 4) and tooth flank form deviation (quality 2). Furthermore, profile form variation is directly influenced by lineness.

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