Performance of Gears Manufactured by 5-Axis Milling

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Free form milling of gears becomes more and more important as a flexible machining process for gears. Reasons for that are high degrees of freedom as the usage of universal tool geometry and machine tools is possible. This allows flexible machining of various gear types and sizes with one manufacturing system. This paper deals with manufacturing, quality and performance of gears made by free form milling. The focus is set on specific process properties of the parts. The potential of free form milling is investigated in cutting tests of a common standard gear. The component properties are analyzed and flank load-carrying capacity of the gears is derived by running trials on back-to-back test benches. Hereby the characteristics of gears made by free form milling and capability in comparison with conventionally manufactured gears will be shown.

Motivation, Objective and Approach

Due to several advantages in matters of flexibility and degrees of freedom in gear and process design, 5-axis milling has established itself as an accepted manufacturing technology for the gear making industry (Refs. 1; 2; 11; 12; 3; and 26). Beyond the pure academic application in fundamental research, there are three main areas of application in the industry for this technology, i.e. — prototyping, single part production, and repair/spare parts; application areas for this technology are summarized (Fig. 1).

Because of the high flexibility, small batch sizes and various other gear types can be economically realized. Combining soft and hard machining on one single machine tool creates advantages over conventional process chains — even for manufacturing of very big gears and single part production. Furthermore, short delivery periods are one of the major aspects in the production of spare parts. Due to the usage of a universal machine tool and universal milling tools, delivery times for special hobbing tools can be eliminated and the duration of the production cycle for spare parts is reduced massively.

Five-axis gear milling finally provides the opportunity for additional degrees of freedom in gear and part design, in comparison to conventional gear making technologies. Now, the microgeometry of tooth flank and tooth root can be optimized freely. In addition, the minimal run-out of the tool and the accessibility to the cutting area can be used for constructional improvements to the entire gearbox and its arrangement of the gears.

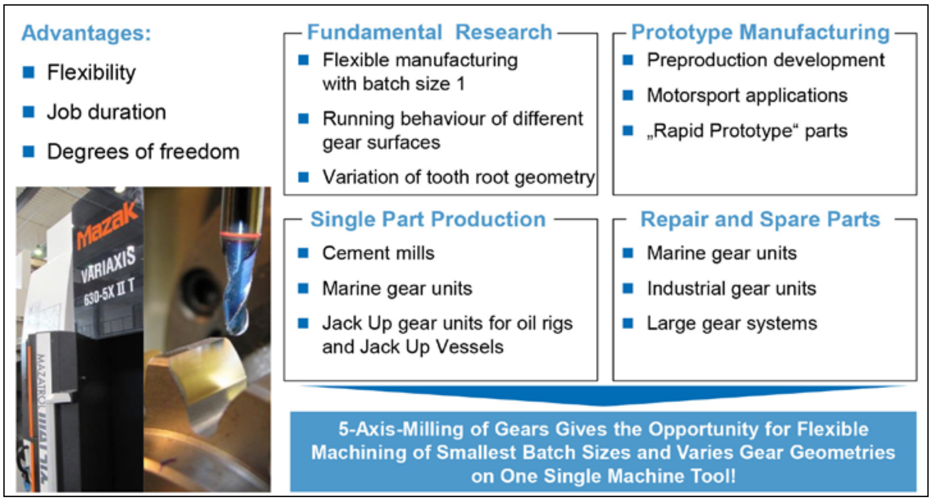

Figure 1 Area of application for free-form milling of gears.

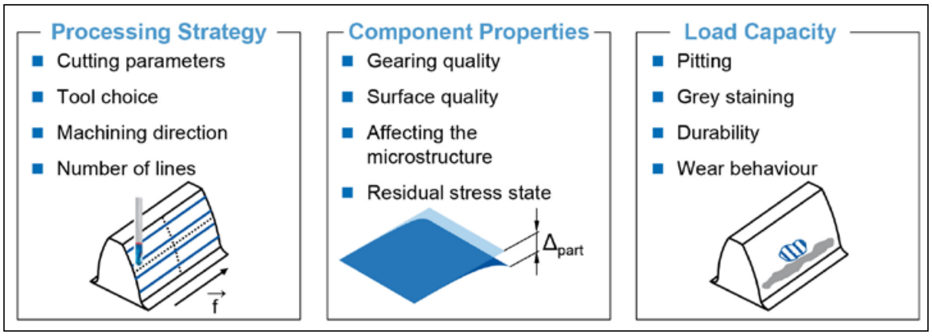

Figure 2 Objective and approach.

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

Note that as the technology is not as yet available (Refs. 12; 24; 22; 34; 11; 35), there is no scientific analysis available concerning the potential of this process regarding gear quality. In order to utilize the full potential of this technology the performance of the parts — in comparison with conventionally ground gears — must be analyzed.

This paper deals with the potential of 5-axis milling for gears, based upon years-long comprehensive and scientific work on the free form milling of gears. (Refs. 15–18; 19; 30–31). The objective of this paper and the approach concerning the related investigations are shown in Figure 2.

The process terminology and process characteristics — as machining strategy and process specific surface structure — are explained. The potential of gear manufacture with free form milling is investigated in cutting tests of a common standard gear type C; therefore the gear geometry and the surface were analyzed. Gear quality is compared to requirements of conventionally machined gears.

Process Definition — Terminology of Free Form Milling of Gears

According to DIN standard, manufacturing of gears on universal machine tools is located in the area of NC form milling (Ref. 4). The manufacturing process regarding machine tool and control unit is comparable to manufacture of molds and dies (due to similar materials, hardness and accuracies) and to the manufacture of impellers and turbo machinery components (due to similar geometries). Beyond this general definition of free form milling, process specific parameters for the manufacturing of gears have to be characterized. The process description includes the definition of process parameters, the tool selection and the generation of input data (Fig. 3).

A portion from the full description of the process characteristics of the free form milling of gears contains: *Tool selection, generation of input data* and, particularly, *machining strategy*; these three aspects will be discussed in the following. 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 machining and hard machining. Because of different requirements rough and fine cutting steps are met with different tools. For the machining of tooth root, a tool change can be necessary, too; standard milling tools are characterized by the parameters shown (Fig. 3, left).

For stability reasons a large as possible tool diameter is chosen; tool length is chosen as short as possible. Tool size, as well as blade radius, is restricted by the gear geometry.

Different types of milling tools are sorted into groups by their blade geometry. Possible tool geometries are full radius, torus and shaft cutter. 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 these contact conditions and for restrictions of tool selection.

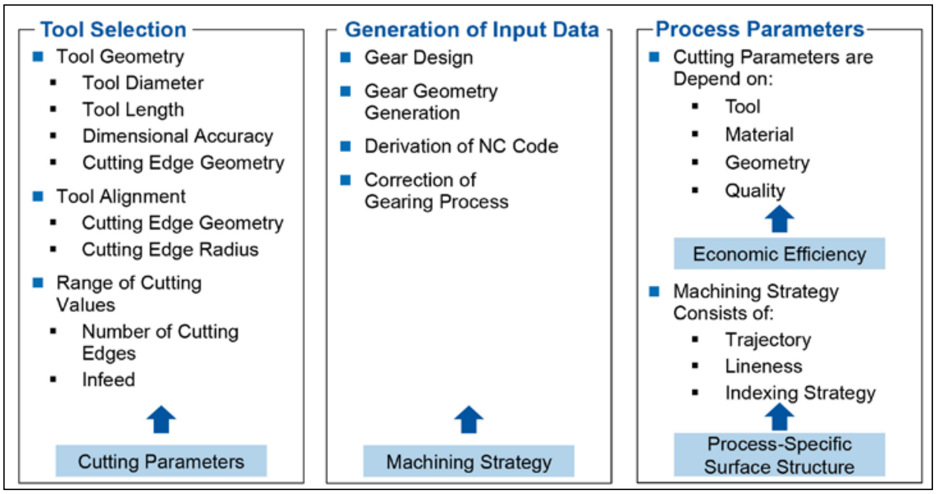

Figure 3 **Process characterization.**

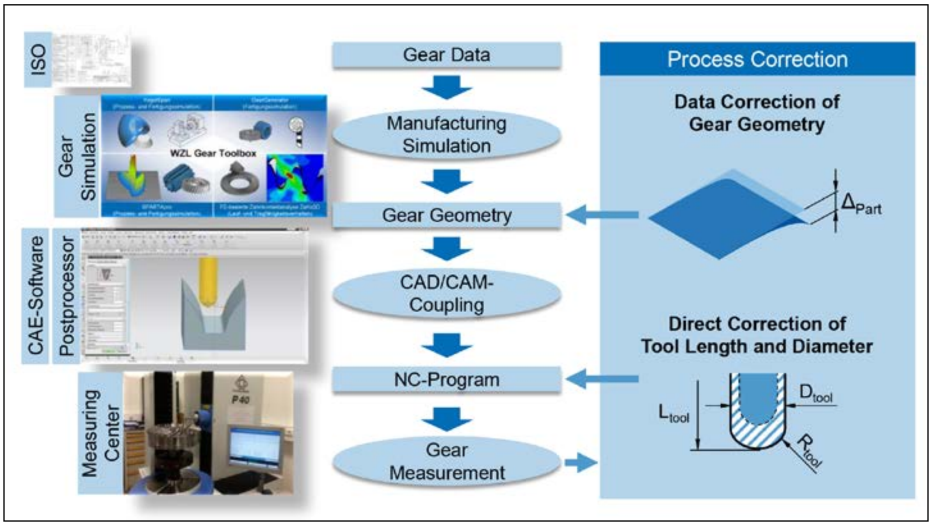

Figure 4 **CAx process chain.**

Generation of machine input data. In contrast to manufacturing of gears on conventional gear manufacturing machines, free form gear milling requires a defined geometry in the form of coordinates. Figure 4 shows the CAx process chain necessary for the generation of the NC code.

After gear design, the gear data is sent to the CAx process chain. In the first step the gear data is transferred into the gear geometry. The creation of gear geometry can be done analytically or by a manufacturing simulation, and includes a defined geometry of flanks and tooth root. In the next step the gear geometry is converted into NC code.

Deviation of geometry resulting from the manufacturing process can be offset 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 the compensation (Fig. 4, right).

Machining strategy. The machining strategy includes three major aspects of the definition of the manufacturing process, i.e. — the *lineness, trajectory* and *cutting strategy*; Figure 5 provides an overview of the machining strategy.

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

Trajectory. The definition of the trajectory is based on technological requirements for the running behavior of the gears. Furthermore, the trajectory has a significant influence on processing effort and process kinematics. Different trajectories are shown on the left hand side of Figure 5. 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 can be realized. From the manufacturing point of view, there are no technological restrictions. In terms of economical process design, the complexity of trajectories must be taken into account because complex trajectories require additional axes and movements of the tool.

Lineness. Lineness in part defines the number of tool paths that significantly influence machining time. Also, lineness defines the schema how tool paths are located on the tooth flank; there are three possibilities that can be seen in the middle of Figure 5.

First, tool feed can be equidistant for each tool path. That leads to a changing structure all over the tooth flank. The second possibility is to 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. The last shown possibility is 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 based upon stress deviation for the whole flank. Thus the effort for process configuration is, in this case, very intense.

The space between tooth paths defines the kinematic surface roughness (Ref. 13). The kinematic surface roughness can be described geometrically so that the surface requirements can be accounted for during configuration of the milling process.

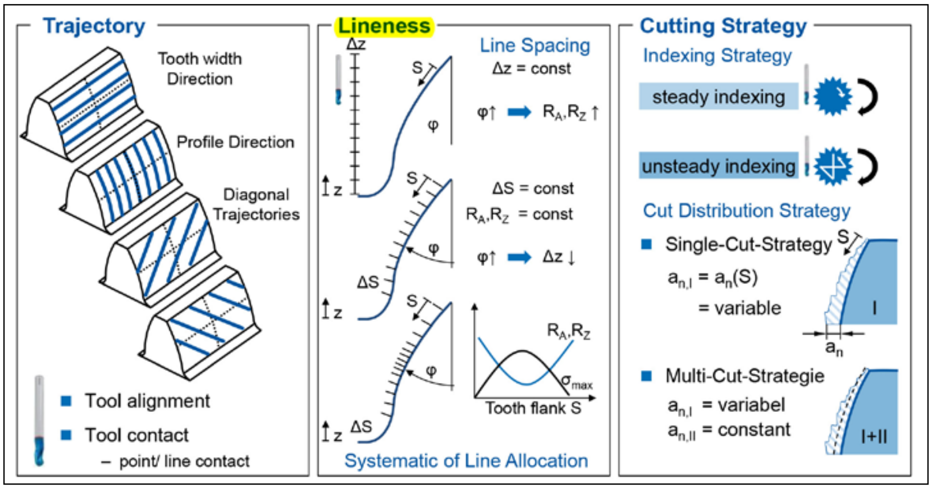

Figure 5 **Definition of manufacturing strategy for free-form milling of gears.**

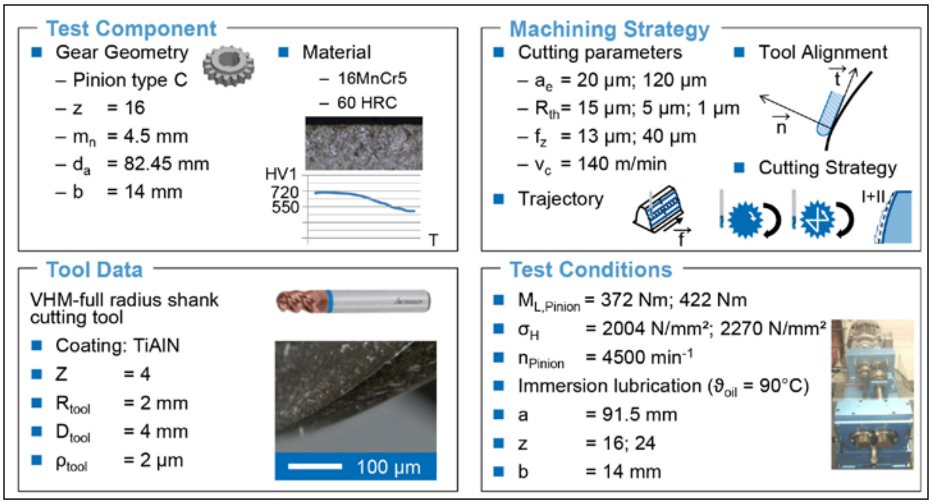

Figure 6 **Scope of investigations.**

Cutting strategy. The cutting strategy is divided into two categories — *indexing* and *cut distribution*. The 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 shorter machining times can be realized. Errors in part rotation and thermic influences are accumulated during machining so that the pitch deviation between first and last tooth is high. During unsteady indexing the gaps are machined/evenly distributed all over the gear. Errors are not accumulated in this case; the peak of pitch deviation can be avoided. Machining time will be higher than with steady indexing because more movements are necessary.

The distribution of cuts depends on the hard finishing allowance; single- or multi-cut strategies can be realized in order to finish the gear after heat treatment. The single-cut strategy leads to short manufacturing times and high chip volumes. Multi-cutting includes pre-finishing steps so that hardening distortions are equalized before the final cut is applied. In this case the chip volumes can become very small and the thermal influence on the part increases.

Scope of the Investigation and Experimental Setup

Using the given process definition for the free form milling of gears, fatigue tests were begun. The gear quality, further part properties, and the running behavior of the gears made by free form milling are analyzed; Figure 6 provides an overview of the experimental setup.

The used gear type is a standard test gear type C (Refs. 8; 21; 34). For analysis of the manufacturing technology and running behavior, only the pinion ($z_1 = 16$) was made by free form milling. The wheel ($z_2 = 24$) was conventionally profile ground.

Four different machining setups were chosen; (top, right) Figure 6 shows all used process parameters. The test gears were manufactured in single-cut strategy ($a_e = 20\mu m$) and multi-cut strategy ($a_e = 120\mu m$). Furthermore, the theoretic process-specific surface deviation was varied from $R_{th} = 1\mu m$ up to $R_{th} = 15\mu m$.

Defined test conditions are related to FVA No. 0/5 and shown (Fig. 6, bottom right) and (Ref. 9). Flank load carrying capacity for all variants was derived. In addition, conventionally ground gears were tested and a reference S/N-curve derived.

Integrity of Gears Machined by Free Form Milling

The first analysis aims for a comprehensive analysis of all gear properties. Therefore the gear quality, the process-specific surface structure, and the characteristics of the surface near (near surface) material structure are analyzed.

Gear quality. The gear quality of all four variants is shown (Fig. 7). The first three variants were made by a multi-cut strategy. The process-specific surface structure was varied by the lineness. The fourth part was realized by the same lineness as the third one, but hard finishing was done in a single-cut. The last of the shown parts is the reference gear, which is profile-ground.

All gears match the requirements of IT 5 concerning pitch and quality in lead direction. The quality in profile direction is pre-defined by the chosen lineness. Because of that the first part — with $R_{th} = 15\mu m$ — has a profile quality of IT 8, which is directly related to the lineness and the resulting profile form deviation $f_{f\alpha} = 15\mu m$. All in all, it is clearly visible that all variants have a sufficiently geometrical gear quality. The chosen manufacturing strategy affects the resulting gear geometry; thus the resulting gear quality becomes predictable and can be specified during manufacturing process design.

Process-specific surface structure. The gear quality measurements show a profile form deviation that is directly related to the chosen lineness; therefore the focus of the surface analysis initially is on the process-specific surface structure. The tactile 3-D measurement of the variant $R_{th} = 15\mu m$ is shown (Fig. 8). The surface-specific surface structure is divided into the amount of the deviation R_{th} and the spacing of the structure RW (Refs. 15–16; 19). Both parameters are driven by the tool alignment, tool geometry, and the chosen machining strategy (e.g., trajectory and lineness).

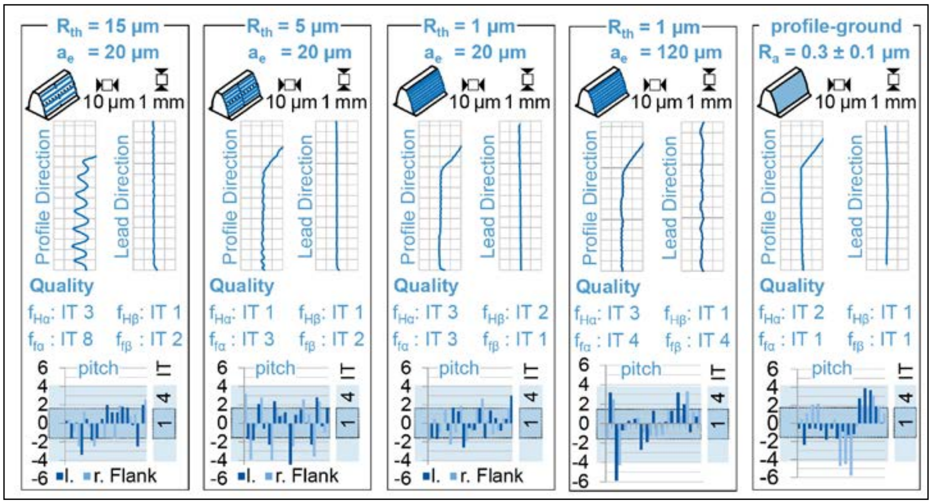

Figure 7 **Gear quality.**

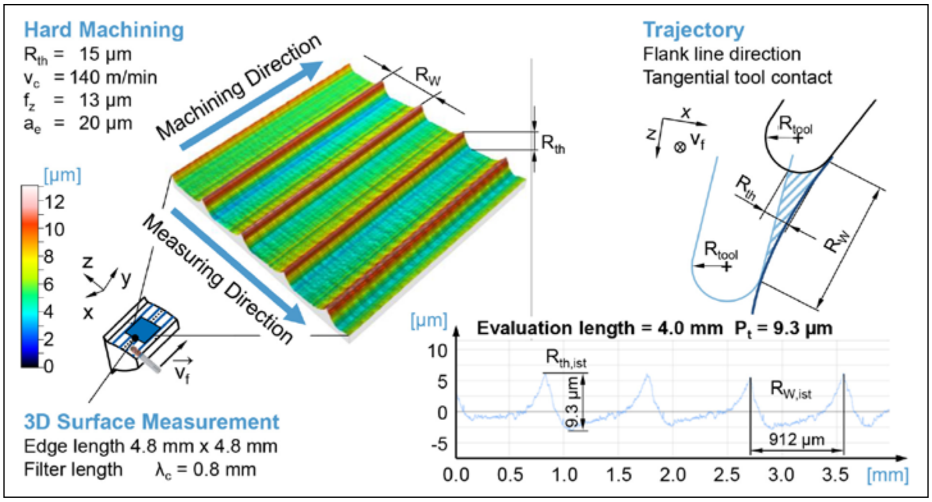

Figure 8 **Process-specific surface structure.**

The resulting surface structure meets the existing definition (Refs. 15–16; 29). The actual value of the deviation $R_{th,ist} = 9.3\mu m$ is smaller than $R_{th} = 15\mu m$ because the number of trajectories must be an integer and the deviation $R_{th} = 15\mu m$ may not be exceeded. In the shown case the difference between $R_{th,ist}$ and R_{th} can be high because the number of trajectories, $N = 10$, is small.

The microscopic geometry of the surface structure complies with the theoretical penetration between tool and part (Fig. 8). The change of the lineness must affect this structure directly. The results of the variation of the lineneness are shown (Fig. 9).

By increasing the number of lines, the deviation is reduced. The variant with $R_{th} = 1\mu m$ finally leads to a good surface quality that is equal to the reference. The variant with $R_{th} = 5\mu m$ sticks in the middle and compromises between high surface deviations (like the variant with $R_{th} = 15\mu m$) and high machining times (like the variant with $R_{th} = 1\mu m$). The change of the cut distribution from multi-cut strategy ($a_{e\ II} = 20\mu m$) to single-cut strategy ($a_e = 120\mu m$) leads to an increasing surface roughness. The difference is explained by the increase of chip volume and resulting increase of the cutting force that affects dynamic tool deflection and leads to a wavy surface structure in the machining direction.

Characteristics of surface-near area. The flank load capacity of gears is highly affected by the conditions of the surface-near area of the parts (Ref. 24); therefore negative effects of hard machining on the material structure must be avoided. Thus micrographs, residual stresses and the full width at half-maximum (FWHM) must be analyzed.

Material structure. There was no grinding burn or negatively affected

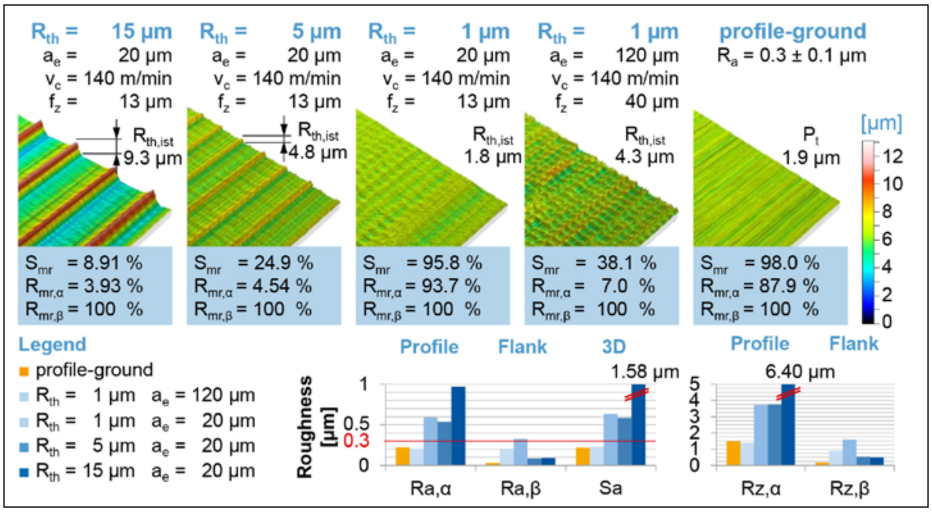

Figure 9 Surface quality.

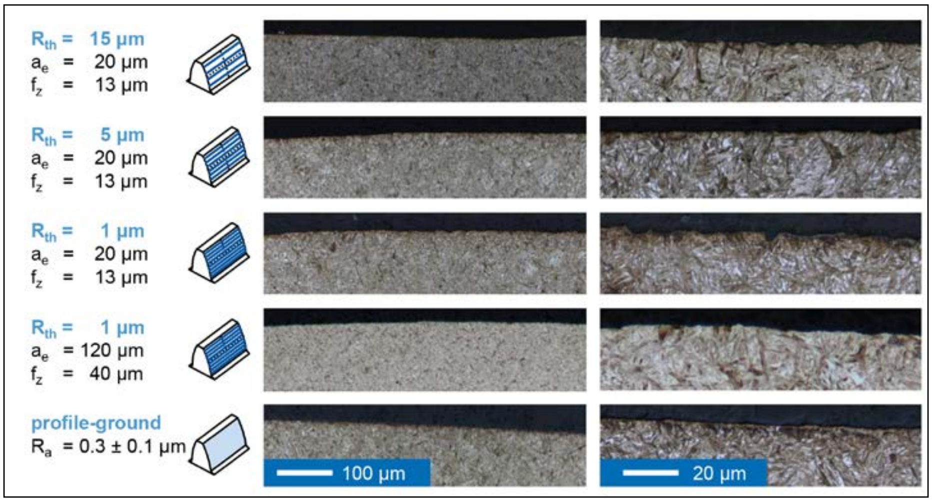

Figure 10 Material structure.

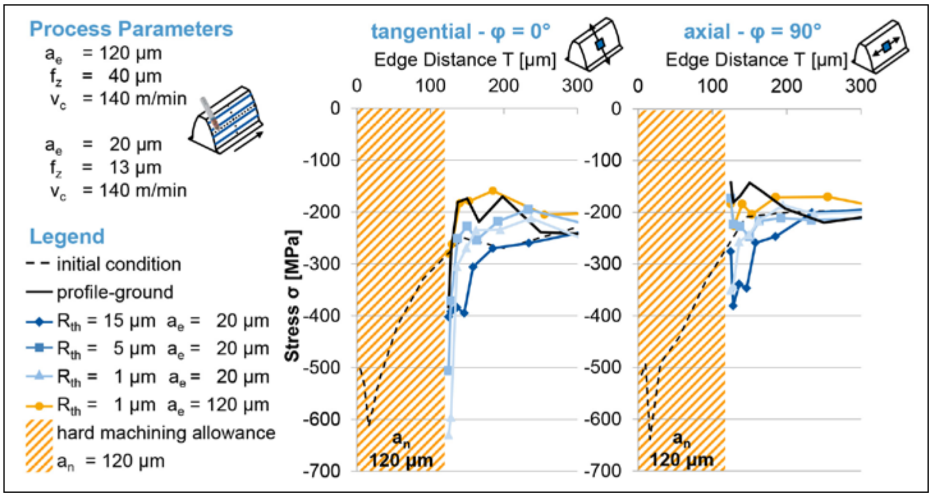

Figure 11 Depth profile of residual stresses.

material structure detected by nital etching of the hard machined parts. In order to prove even small influences, additional metallographic investigations were conducted; micrographs of all variants are shown (Fig. 10).

The material structure of both variants with $R_{th}=15$µm and 5µm has no visible influence on the microstructure due to the hard machining. In contrast, the variant with $R_{th}=1$µm and $a_e=20$µm (with multi-cut strategy) shows a slight annealing of the material at the outer surface, which correlates with the reduction of the chipping volume and much higher machining time. In this way the amount of thermal energy led into the part is increased. The variant with $R_{th}=1$µm and $a_e=120$µm (with single-cut strategy) also has no negatively influenced surface near area. This indicates that only the combination of higher machining time and small chip volumes lead to an exceeding of the critical level of thermal capacity of the material.

The profile grinding has a relatively small influence on the material structure of the reference part. The microstructure of the reference part is equal to material structures due to profile grinding known from literature (Refs. 7 and 27); thus no defect is detectable at the reference parts.

Depth profile of residual stresses. By measurement of the depth profile of residual stresses a closer look at the properties of the surface near area is possible. Influences of the 5-axis milling process and the chosen machining parameters on the properties can be quantified this way. Therefore the initial condition after heat treatment and the profile ground reference were analyzed as well. Figure 11 displays an overview of all measured depth profiles; the residual stresses of all parts were measured in tangential (profile) direction and in axial (lead) direction.

The direction of tool feed is in lead direction and equal for all machined parts. Hard machining parameters seem to have a relatively small influence on the depth profile in axial direction. Beneath an edge distance of $T=30$µm, all residual stress profiles are equal.

In tangential (profile) direction there are bigger effects on the residual stresses at the gear surface. The variant with minimal chip volume ($R_{th}=1$µm, $a_e=20$µm, $f_z=13$µm) leads to $\sigma_{tangential}=-630$ MPa directly at the surface. High chip volume (R_{th} = 1μm, a_e = 120μm, f_z = 40μm) is barely affecting the residual stresses.

Mechanical loads lead to an increase of compressive residual stresses, whereas thermal load reduces compressive residual stresses (Ref. 31). Because of this, grinding burn is usually detected by a local reduction of compressive residual stresses (Refs. 7; 27; 35; 26).

The small influence of microstructure (Fig. 10) was not detectable by analysis of the depth profile of the residual stress measurements (Fig. 11); even nital etching did not reveal any affected surface near area. This is why micro-residual stress also must be taken into account.

FWHM of residual stress measurement. Influences of the hard machining process on micro-residual stresses and homogeneity of material structure can be detected by analysis of the full width at half maximum (FWHM). Literature shows a correlation between reduction of part durability and a drop of FWHM by 10% (Refs. 1 and 32).

The depth profiles of FWHM of all 5-axis-milled variants are shown (Fig. 12). In addition, the profile ground reference is shown as a solid black line. The FWHM of the two variants with the smallest chip volumes (R_{th} = 1μm and 5μm, a_e = 20μm) are affected by the machining process at a depth down to T = 10μm. This is the same area where the annealing of the surface near area was detected in the micrographs (Fig. 10).

The variants with higher chip volumes are not affected in case of FWHM by the machining process. This can be confirmed by the analysis of the micrographs, which also show no negatively influenced material structure. This correlation between the reduction of FWHM and the resulting part durability must be confirmed by conducting flank load capacity tests.

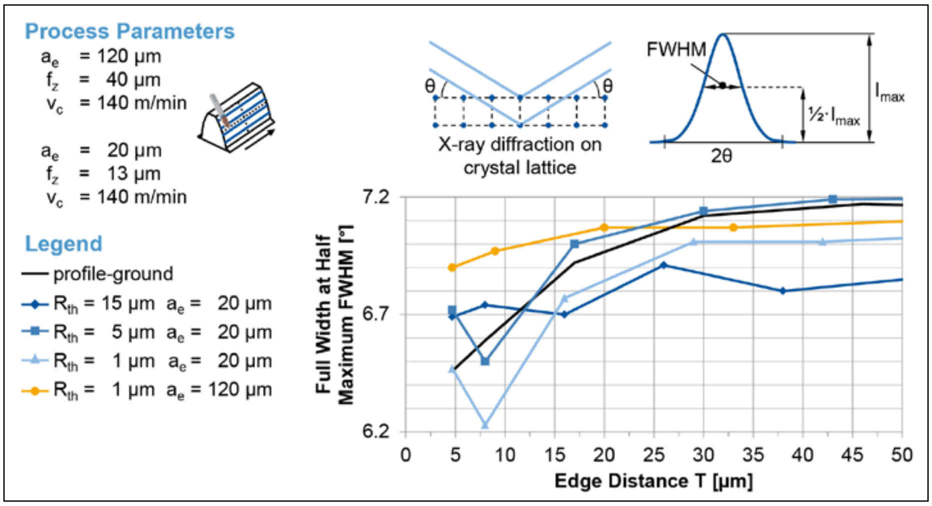

Figure 12 FWHM of residual stress measurement.

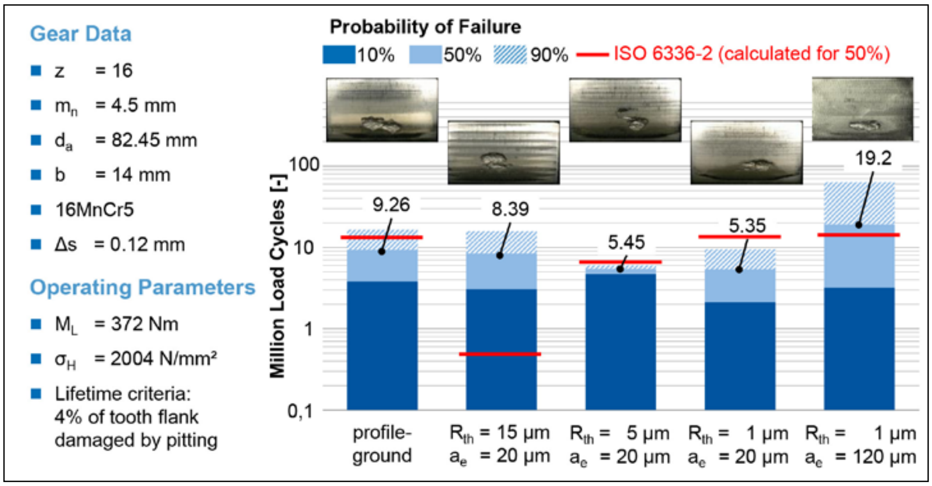

Figure 13 Tooth flank load capacity dependent upon processing strategy.

Flank Load Carrying Capacity of Gears Made by Free Form Milling

To prove the usability of 5-axis milling as a technology for industrial applications, the applicability of the ISO 6336 standard must be verified (Ref. 10). Concerning this, the effects of the process-specific characteristics of gears made by 5-axis-milling on the performance of the gears was validated in tests according to FVA Nr. 0/5 (Ref. 9). Therefore pinions of the standard test gear type C were used as the test part. The gear was conventionally profile ground. The tests were carried out on back-to-back test rigs according to DIN ISO 14635 (Ref. 5). Additionally, a Woehler curve for 50% probability of failure was derived from the profile ground gears as a reference for all tests. Based upon this reference, flank load carrying capacity can be calculated according to ISO 6336-2 for 50% probability of failure.

The tests were proceeded at M_L = 372 Nm load. Figure 13 shows the resulting performance of all variants for 10%, 50% and 90% probability of failure as a bar chart. According to ISO 6336-2, cycles-to-failure were calculated theoretically, based on the results of the Woehler curve, for the specific flank deviations $f_{f\alpha}$ caused by the process-specific surface structure of the specific variants.

It can be observed that the first 5-axis-milled variant (R_{th} = 15μm, a_e = 20μm) seems to massively exceed the expectation. In contrast, the third variant — machined with R_{th} = 1μm and a_e = 20μm — misses the expectation. The second variant (R_{th} = 5μm, a_e = 20μm) meets the calculated value, whereas the last variant actually exceeds the durability of the profile ground reference.

The differences in the durability of the gears cannot be based upon differences of surface structure; this means that a closer look at wear behavior of the parts is required. Therefore the occurrence of micropittings after 20 hours of testing and number of pitting defects on one single gear during the complete test were analyzed; results are shown (Fig. 14).

High process-specific surface deviations lead to bigger areas of micropitting. Thus, the variant R_{th} = 15μm shows a 50% area of micropitting on the flanks. At the variants R_{th} = 5μm and R_{th} = 1μm (both multi-cut-strategy), a nearly equal amount of micropitting occurs. This cannot be explained

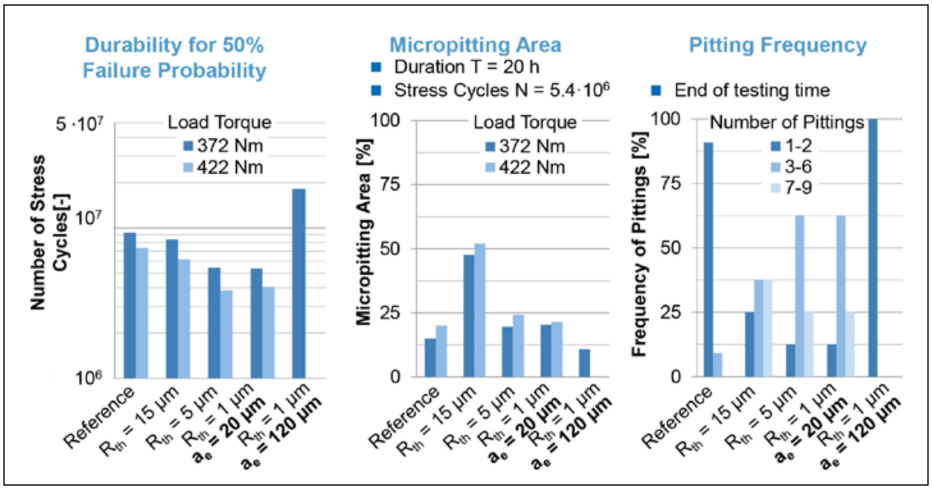

Figure 14 Wear behavior dependent upon processing strategy.

by the surface alone, as the surface quality of both variants is different. The variant $R_{th} = 1\mu m$ and $a_e = 120\mu m$ (single-cut strategy) has the best result concerning the micropitting area. As in the case of load cycles, micropitting behavior is even better than the reference.

In addition, pitting frequency at the end of each test run was analyzed. The distribution of the number of pittings for each variant is shown (Fig. 14, right). The reference usually has no more than one or two pittings on each gear. This failure characteristic is well known from literature for case hardened gears (Refs. 10; 24). All variants with higher process-specific surface structures (R_{th} 15µm and 5µm) have a much higher number of pittings. The variant $R_{th} = 1\mu m$ and $a_e = 20\mu m$ with the big area of micropitting, and the annealing of the material structure, leads to a high number of pittings as well.

In summary, failure behavior of gears made by free form milling depends directly on the chosen manufacturing parameters. The higher the chip volume, the better the gears performed in case of micropitting and pitting behavior (Fig. 14). As known from literature, good surface quality results in better running behavior. Too high process-specific surface structures affect micropitting and, finally, cause damage by pitting. The variant $R_{th} = 1\mu m$ and $a_e = 120\mu m$ (single-cut strategy) has the best result and shows the same behavior of failure as state-of-the-art gears. Hereby, the expectation of an ideal process strategy for free form milling of gears is verified (Ref. 30).

Summary and Outlook

The capabilities of five-axis milling of gears are becoming increasingly important, as this process is a flexible manufacturing technology for the machining of small batch sizes and single parts. And since there was no comprehensive knowledge available regarding the resulting function of 5-axis-milled parts (Refs. 21; 28), the aim of this paper was to describe the influence of 5-axis milling on the properties of the part and the resulting function of the gears in application.

The influence of the manufacturing strategy and chosen parameters on part integrity is important in predicting load-carrying capacity, and is decisive for industry application of 5-axis milling. Based on standard test gears, machining and running tests were carried out. From that R&D fundamental knowledge of the general process design for 5-axis milling of gears was derived (Ref. 30).

The machining strategy for free form milling of gears was defined based on existing definitions (Refs. 15; 18; 29). The process-specific surface structure was predicted, and from here on can be addressed during manufacturing process design. The surface near properties of the microstructure were influenced by the chosen manufacturing parameters. Number of trajectories, cutting strategy and tool feed can lead to unfavorable small cutting volumes; therefore an impairment of the function by tempering occurs. This impairment is small in comparison to grinding burn in conventional gear profile grinding, and so it is not possible to detect this effect by nital etching. The analysis of FWHM (full width at half-maximum) of the measurement of residual stresses was derived as an appropriate value for the quantification of the thermal impairment. The reduction of FWHM at depth $T = 10\mu m$ led to a negative effect on the function of the gears.

The performance of gears made by free form milling was proven and documented by this investigation. The tests showed a significant influence of the process-specific surface structure on the lifetime of the gears and the resulting wear behavior during application. It was shown that gears made by free form milling will provide the same performance as conventional, profile-ground gears — part integrity being equal. Large process-specific deviations lead to unconventional wear behavior that is not describable by existing criteria (damage of 4% of the flank by pitting, for example).

If the machining strategy leads to a gear and surface quality that is comparable to conventionally machined gears, free form-milled gears will have the same performance. Unfavorable choice of machining parameters leads to an impairment of the surface near microstructure and so to a lack of performance. In this way the positive effects of a good surface or gear quality can be reversed (Ref. 30).

Further investigation is needed in order to establish the transferability of outcomes of this research from standard test gears to actual application scenarios in industry. Especially, additional challenges concerning tool wear and realization of complex geometries — such as bevel gears — must be faced in order to utilize 5-axis milling as a process for hard machining of gears for industrial applications.

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