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# Hard Machining of Spur Gears with the InvoMilling™ Method

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**Abstract:** Recently, the 5-axis machining of gears has become increasingly important. This technology enables a flexible production of diverse gear types on a single universal machine with standard tools. In addition to the economic aspects, the focus is on the high quality standards that has to be achieved. This paper deals with hard machining for the finishing of spur gears with the 5-axis InvoMilling™ method developed by Sandvik Coromant. A comparison of the hard and soft machining of a module 5 gear is made. The achievable gear qualities in the profile and flank direction, the achievable surface roughness in the profile direction, the torque applied to the milling spindle during the machining process and the wear of different types of inserts are compared and evaluated. In addition, the hard machining with different insert materials/coatings is carried out.

**Keywords:** InvoMilling; hard machining; 5-axis machining; 5-axis-milling; spur gears; gear milling

## 1. Introduction

Gearings are widespread quality components in mechanical engineering. There are a large number of different gear shapes, each of them is based on a gear specific manufacturing process. These manufacturing processes are usually linked to special machines with special tools such as hobbing machines and the corresponding hob [1,2]. Therefore, the conventional gear manufacturing processes show very high productivity with concurrently low flexibility. On the other hand, agile gear production is becoming increasingly important due to the modern market requirements [3,4]. Developments in the field of 5-axis universal processing machines have enabled the production of high-quality parts such as gearings on universal processing machines [5]. One shortcoming is the ability to produce the various types of gearings true to the original geometry in a reasonable amount of time on universal processing machines [1]. Especially in the early stages of development, this leads to immense advantages in terms of flexibility and lead time reduction [6]. In addition, the combination of individual machining steps, e.g., turning of the blank, pre-toothing and deburring in the soft state on one machine increases the potential of these new methods.

With the development of the InvoMilling™ method for the 5-axis machining of spur gears, the base for rapid, flexible and conditionally economical machining for spur gears was laid. Through the InvoMilling™ package, which includes a complete solution, i.e., tools and software, different spur gears with different modules and micro/macro geometry can be produced with only one tool. This makes this technology very interesting for various applications where, in addition to the gear quality, the flexibility of the manufacturing process is of importance. These include the areas of research/development, prototype and production of single and small series [7]. Figure 1 shows a comparison of the standard freeform-milling and InvoMilling™ strategies for gear milling. The main differences, the feed and toolpath direction, can be seen.

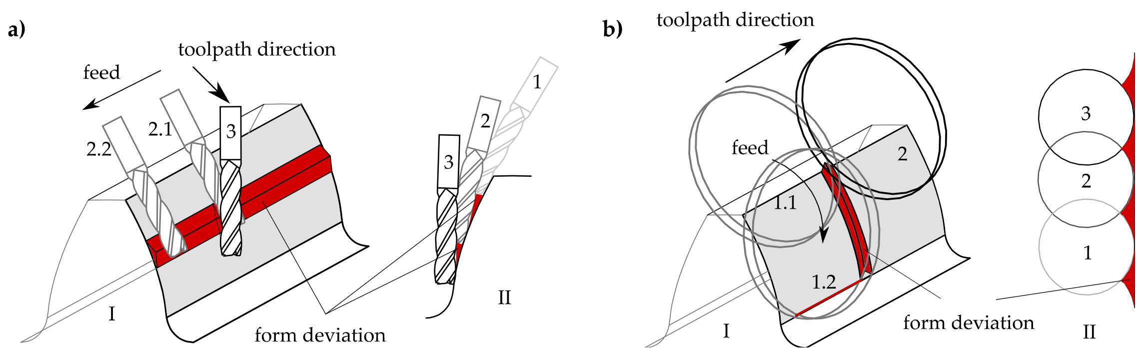



**Figure 1.** Comparison of the milling strategies standard freeform-milling (**a**) and InvoMilling™ (**b**) [8], Copyright © Thomas Glaser 2018.

The InvoMilling™ process is carried out with a standard disc cutter. The feed direction runs along the tooth profile from tip to root and the direction of the single toolpaths are along the face width of the gear.

Because of the complex stress on gear tooth, high quality demands are placed on their shape and their surface properties. In order to be able to fulfill these requirements, gears usually have to be heat treated after the pre-toothing in the soft state. Here, the case hardening of gear wheels dominates in gearbox construction [9,10]. During the heat treatment, the material values are brought specifically to the required properties, e.g., high surface hardness with a tough core at the same time. After the heat treatment, usually a finishing operation is carried out. Due to this fine machining manufacturing related dimensional and shape deviations in the form of flank line, profile line, concentricity and pitch deviations from preprocessing and heat treatment are compensated [11]. In addition, tooth flank modifications are often being introduced during the fine machining process according to the present state of the art. These modifications improve the noise and load capacity of gears and are intended to compensate the load induced deformations of the gear-shaft-bearing system. In order to be able to exploit the full potential of the InvoMilling™ method, more detailed investigations are necessary for the processing of hard finished gears. In the future, high quality and functional gears could be produced within a very short time. Through a combination of hard machining of the gear and hard turning of the gear body [12] after heat treatment, a new potential could be exploited.

## 2. Materials and Methods

The main goal is to examine the possibility of using the InvoMilling™ method as a hard finishing process for spur gears. The achievable tooth and surface qualities as well as the wear of different types of inserts will be analyzed. In addition, a direct comparison between soft and hard machining is carried out on a module 5 test gear. Here, the achievable gear and surface qualities, the occurring spindle moments and the tool wear will be compared and evaluated. Finally, it is assessed whether the InvoMilling™ method is a suitable hard finishing process for spur gears and which prerequisites may have to be fulfilled.

### *Test Execution*

One module five test gear is defined as test specimen (VZM5). Table 1 below gives a list of the most important gear data. Test material is 18CrNiMo 7-6 steel in different degrees of hardness.

**Table 1.** Gear data of the module five test gear.

| | VZM5 |
|---|---|
| Number of teeth | 52 |
| Normal module [mm] | 5 |
| Pressure angle [°] | 20 |
| Helix angle [°] | 15 |
| Face width [mm] | 40 |
| Helix direction | right handed |
| Profile shift factor | 0.1906 |
| Reference profile | DIN876 |
| Material | 18CrNiMo7-6 |
| Hardness/soft machining | 243 HV |
| Hardness/hard machining | 690 HV/58HRC |

The following tools of Sandvik Coromant (Sandviken, Sweden) with the listed inserts are used for the tests (Table 2).

**Table 2.** Used tool and insert types.

| | VZM5 | Material | Coating |
|---|---|---|---|
| Tool | CoroMill 162-090 | | |
| Insert 1030 | 176M40-N100608E-PM 1030 | Solid carbide | PVD TiAlN |
| Insert 1010 | 176M40-N100608E-PM 1010 | Solid carbide | PVD AlTiCrN |

The insert coatings show different qualities. The PVD (Physical Vapour Deposition) TiAlN coating provides good thermal and mechanical stability, and it is widely used for industrial application [13–15]. Due to the addition of chromium, the use of PVD AlTiCrN coating on the insert increases the thermal stability, mechanical strength chemical inertness and the hardness of the coating. This reduces the wear of the tool and leads to better results [13,16]. For economic reasons, the potential of both insert types will be checked. The shape of the two used insert types is identical and is shown in Figure 2.

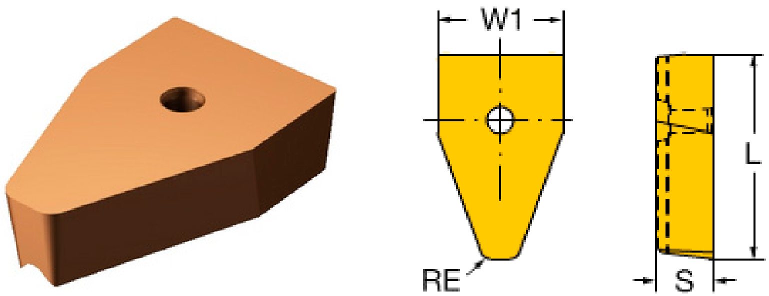



**Figure 2.** Geometry of the used inserts, with W1 = 9.7 mm, L = 10.4 mm, S = 5.5 mm, RE = 0.8 mm [17], Copyright © Sandvik Coromant.

For the test execution, the 5-axis machining center DMU65 with Siemens Sinumerik 840D control and HSK63 tool fitting is used. The clamping/mounting and alignment is carried out according to the same procedure in each experiment. The circular and axial run of the gear-specific device will be set to values <= 0.01 mm at the reference surfaces (a) and (b) (Figure 3).

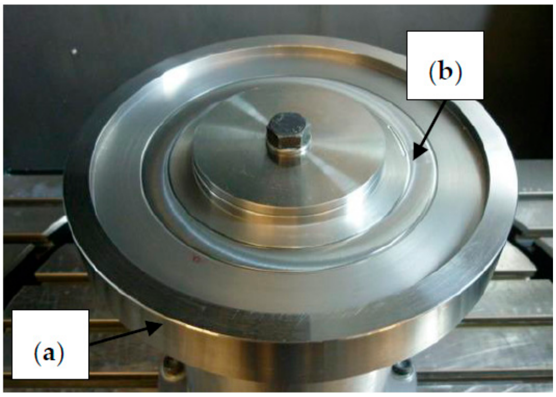



**Figure 3.** Test mounting of gear blank: (**a**) circular run reference surface; (**b**): axial run reference surface.

## 3. Test 1/Soft Machining

Prior to these studies, the influence of coolant on the achievable tooth quality, the surface roughness and the occurring spindle moments were investigated. It was found that, in the case of soft processing, the cooling lubricant should be used, since otherwise, the finished surface can be scratched by chips that have not been removed and thus a comparison is not possible in the following. No significant influence of the cooling on the occurring spindle moment was found. Thus, the soft machining is carried out with coolant and the hard machining without. In order to ensure comparable results, the blanks were also dismounted after roughing and mounted again for finishing during the soft machining. Thus, both soft and hard machining, are performed in two mounts.

The soft machining of the test gear with normal module 5 was carried out with standard inserts of type 176M40-N100608E-PM 1030 on three blanks. Table 3 shows the hardness of the individual blanks, the cutting parameters for finishing and the machining times (roughing, root, finishing and deburring) as well as the length of the cutting path of the InvoMilling™ machining.

**Table 3.** Individual hardness of test blanks, cutting parameters, machining time **T** and length of cutting path **M**.

| | **VP1.5.1** | **VP1.5.2** | **VP1.5.3** |
|---|---|---|---|
| Hardness | 230 HV | 243 HV | 243 HV |
| vc [m/min] | 350 | 350 | 350 |
| fz [mm/Z] | 0.045 | 0.045 | 0.045 |
| ap [mm] | 0.2 | 0.2 | 0.2 |
| T [min] | 100 | 100 | 100 |
| M [m] | 16.392 | 16.392 | 16.392 |

The achieved gear quality in profile and flank direction according to DIN 3962 [18] are listed in Table 4. Both the results for the left (**L**) and right (**R**) flank are shown.

Through the soft machining of three test gears with normal module 5 continuous gear qualities $\leq$6 in profile and $\leq$5 in flank direction could be achieved. These values lie in a very good range. In particular, the shape errors $ff\alpha$ and $ff\beta$, which are independent of misalignments or positioning errors, lie in a very good range with gear qualities $\leq$6. The surface texture resp. the surface roughness of the tooth in the profile direction is determined according to VDI/VDE 2612 [19]. The surface roughness values listed in Table 5 could be achieved. The roughness values listed below show the mean values of four measurements per gear wheel.

**Table 4.** Achieved gear quality according to DIN 3962 [18] of soft machining for test blanks VP1.5.1 to VP1.5.3.

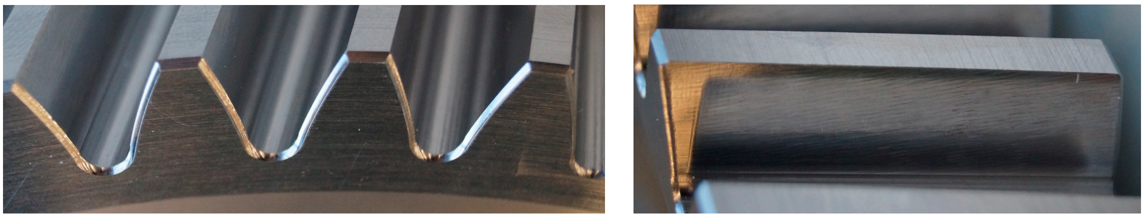
| | VP1.5.1 (L/R) | VP1.5.2 (L/R) | VP1.5.3 (L/R) |
|---|---|---|---|
| **Profile** | | | |
| Fα [Qual. DIN3962] | **6/6** | **6/6** | **6/5** |
| Fα [μm] | 9/10 | 11/11 | 10/8 |
| ffα [Qual. DIN3962] | **5/5** | **5/6** | **5/6** |
| ffα [μm] | 6/6 | 6/7 | 6/7 |
| fHα [Qual.DIN3962] | **6/6** | **7/7** | **6/5** |
| fHα [μm] | 6/6 | 8/-8 | 6/4 |
| **Flank** | | | |
| Fβ [Qual. DIN3962] | **5/4** | **4/5** | **5/5** |
| Fβ [μm] | 8/6 | 6/7 | 7/6 |
| ffβ [Qual. DIN3962] | **4/4** | **4/5** | **4/5** |
| ffβ [μm] | 5/4 | 5/6 | 5/5 |
| fHβ [Qual. DIN3962] | **6/5** | **5/5** | **5/4** |
| fHβ [μm] | 7/5 | 5/6 | 6/4 |

**Table 5.** Achieved surface roughness values on soft machining for test blanks VP1.5.1 to VP1.5.3.

| Profile Direction | VP1.5.1 | VP1.5.2 | VP1.5.3 |
|---|---|---|---|
| Ra [μm)], left | 0.2489 | 0.2464 | 0.2651 |
| Ra [μm], right | 0.2339 | 0.2336 | 0.2172 |
| Rz [μm], left | 1.0534 | 1.1625 | 1.0703 |
| Rz [μm], right | 1.0022 | 0.9041 | 0.7946 |

With average roughness values of $0.2172 \leq Ra \leq 0.2651$ μm and $0.7946 \leq Rz \leq 1.1625$ μm, the surfaces that could be achieved during the soft machining process are in a very good range.

Figure 4 shows a soft manufactured gear that has been milled with standard inserts of type 1030 with the InvoMilling™ method.



(**a**) (**b**)

**Figure 4.** Quality of the soft manufactured test gear: (**a**) transverse view on the gear profile; (**b**) lateral view on the gear flank.

The plot of the gear measurement of the manufactured gear is shown in Figure 5.

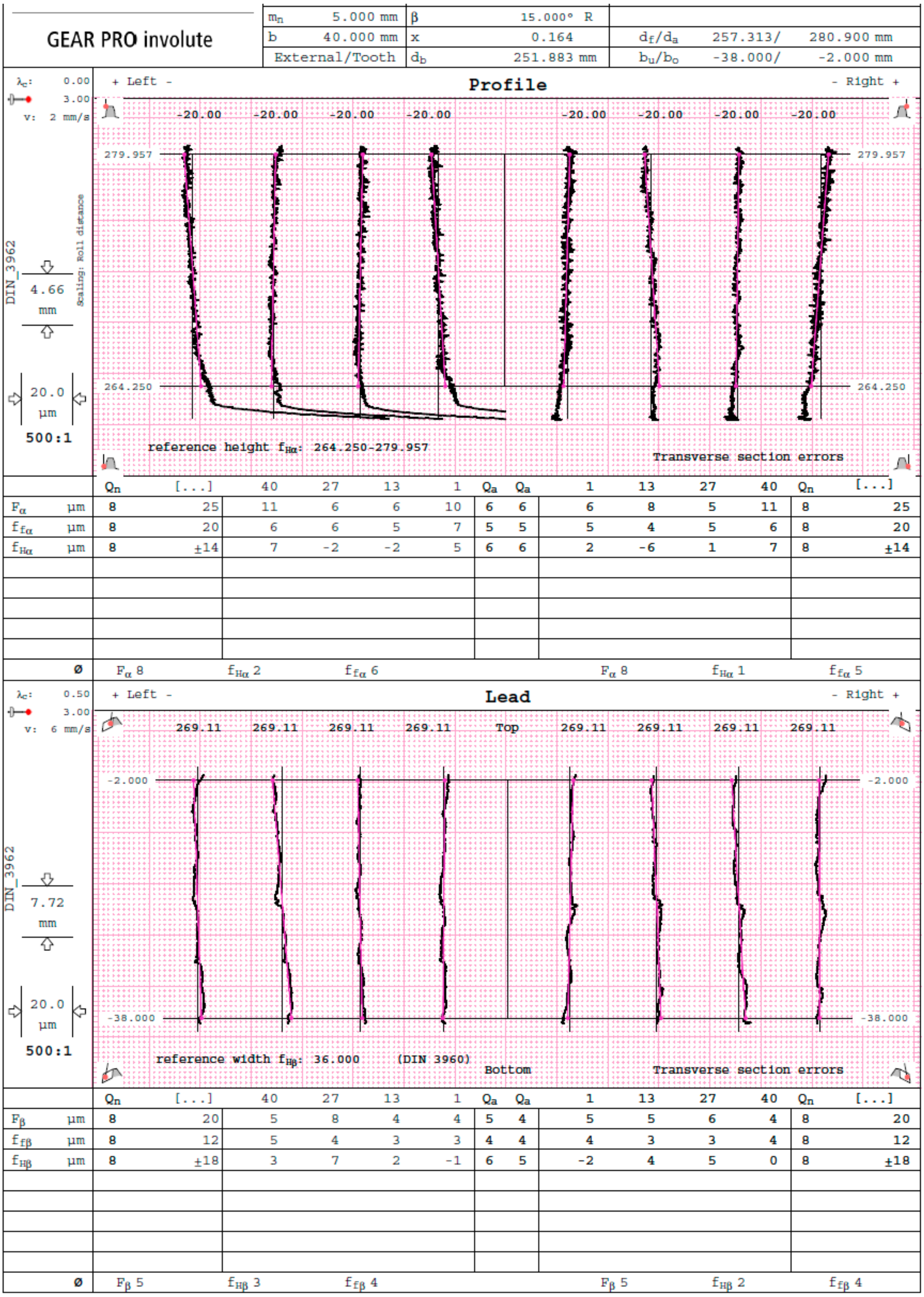



**Figure 5.** Gear measurement plot of manufactured soft gear, VP1.5.1.

## 4. Test 2/Hard Machining/1030 Inserts

In the following, the hard fine machining of two test gears (VP2.5.0 1030 and VP2.5.0 1010) was carried out. Various cutting parameters were tested. In addition, a direct comparison between the machining in the hard and soft state is made. The gear qualities, the surface roughness resp. surface texture, the occurring spindle moment and the insert resp. tool wear will be compared.

For hard machining, the same NC-programs were used as for soft machining. These ensure identical conditions. The blanks of the test gears were hardened with a hardness allowance of 0.25 mm. The following hardening depth and hardness values have been achieved:

- VZM5/hardening depth: 1 mm/hardness: 58 HRC+/−2.

The actual hardness values of the specimens were determined by the median over five measurements on different positions per blank and are listed in Table 6.

**Table 6.** Actual hardness values for both blanks of insert tests.

| | VP2.5.0 1030 | VP2.5.0 1010 |
|---|---|---|
| Pos. 1 [HRC] | 59.37 | 59.24 |
| Pos. 2 [HRC] | 59.14 | 53.11 |
| Pos. 3 [HRC] | 59.42 | 57.36 |
| Pos. 4 [HRC] | 59.52 | 58.76 |
| Pos. 5 [HRC] | 59.52 | 59.01 |
| **Hardness [HRC]** | **59.394** | **57.496** |

The required hardness values could be achieved on all test specimens. In addition, the following parameter combinations as shown in Table 7 were tested during hard machining test 1.

**Table 7.** Test parameters on hard machining test 1.

| Test | Gap | vc [m/min] | fz [mm/Z] | ap [mm] |
|---|---|---|---|---|
| 1 | 1, 2 | 110 | 0.05 | 0.1 |
| 2 | 3, 4 | 110 | 0.05 | 0.2 |
| 3 | 5, 6 | 67 | 0.05 | 0.2 |
| 4 | 7, 8 | 110 | 0.1 | 0.2 |
| 5 | 9, 10 | 80 | 0.1 | 0.2 |
| 6 | 11, 12 | 110 | 0.12 | 0.1 |
| 7 | 13, 14 | 67 | 0.05 | 0.1 |
| 8 | 15–52 | 110 | 0.1 | 0.2 |

The hard machining test is carried out without coolant. A comparison between the two insert grades 1030 and 1010 is carried out on the module 5 test gear.

In case of hard machining, the same test conditions are used as in the case of soft machining (test execution). The results concerning the gear quality and the surface roughness of the parameter tests 1–8 are shown in Table 8. For reason of clarity, the worst quality feature of the two flank sides is listed. The spindle torque is recorded with the parameter settings from test 8. For this test series, inserts of the type 176M40-N100608E-PM 1030 were used.

**Table 8.** Achieved gear qualities according to DIN3962 [18] for tests 1 to 8 of hard machining with standard inserts of type 1030.

| Test | Fα [Q/µm] | ffα [Q/µm] | fHα [Q/µm] | Fβ [Q/µm] | ffβ [Q/µm] | fHβ [Q/µm] |
|---|---|---|---|---|---|---|
| 1 | **6**/11 | **6**/7 | **6**/7 | **5**/8 | **7**/8 | **1**/−1 |
| 2 | **6**/10 | **6/7** | **6/**6 | **5**/8 | **7**/8 | **2**/2 |
| 3 | **6**/11 | **5/7** | **6**/7 | **6**/9 | **7**/9 | **1**/1 |
| 4 | **6**/11 | **6**/7 | **5**/5 | **6**/10 | **7**/8 | **5**/5 |
| 5 | **6**/10 | **5**/7 | **5**/4 | **7**/11 | **8**/10 | **5**/5 |
| 6 | **5/7** | **5/7** | **2/2** | **6/10** | **7/9** | **3/3** |
| 7 | **4/7** | **4/5** | **3/−3** | **6/10** | **8/9** | **1/2** |
| 8 | **6**/10 | **6**/8 | **5**/−**5** | **7**/13 | **8**/10 | **7**/10 |

Even in the hard state, gear qualities $\leq 6$ could be achieved in the profile direction. The gear quality in flank direction is with quality values $\leq 8$ a little worse than on soft machining. This can be clearly seen in the case of the flank shape error ffβ (soft $\leq 6$/hard $\leq 8$). Table 9 shows the roughness values obtained during the hard machining.

**Table 9.** Roughness values in profile direction of tests 1 to 7 of hard machining with standard inserts of type 1030.

| Test | Ra [μm] (L/R) | Rz [μm] (L/R) |
|---|---|---|
| **1** | 0.47/0.53 | 2.24/2.77 |
| **2** | 1.07/0.66 | 4.51/3.41 |
| **3** | 1.05/0.60 | 4.22/2.66 |
| **4** | 0.59/0.64 | 2.82/3.13 |
| **5** | 0.66/0.67 | 3.11/3.25 |
| **6** | 0.54/0.61 | 3.15/3.05 |
| **7** | 0.41/0.41 | 2.02/1.98 |

When machining with 1030 cutting inserts, a significant deterioration of the surface quality at hard machining compared to soft machining can be seen. Figure 6 shows this observation.

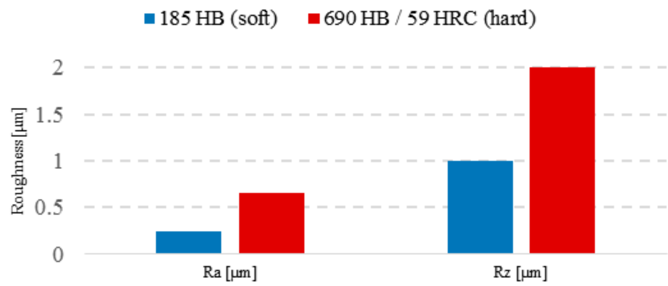



**Figure 6.** Comparison of mean surface roughness values of soft and hard machining with standard inserts of type 1030.

In hard conditions, the surface quality deteriorates by 150–200%. This deterioration in the surface quality can be attributed to the increased load on the cutting inserts resp. edge and the accompanying tool wear. The spindle torque occurring during machining were recorded with the same cutting parameter setting in the soft and hard state. After recording the torque, the signal was filtered with the filter settings listed in Table 10.

**Table 10.** Filter settings.

| | VZM5 |
|---|---|
| sampling rate | 250 Hz |
| type | Butterworth |
| order | 10 |
| cut-off frequency | 7 Hz |

The spindle torque profile shown in Figure 7 illustrates the curves of hard and soft machining. The following figure shows the recorded torque course during the finishing operation. The negative torque profile is the result of the mathematical rotation direction of the milling spindle. An increase in the maximum occurring torque during the hard machining can be seen, cf. Table 11.

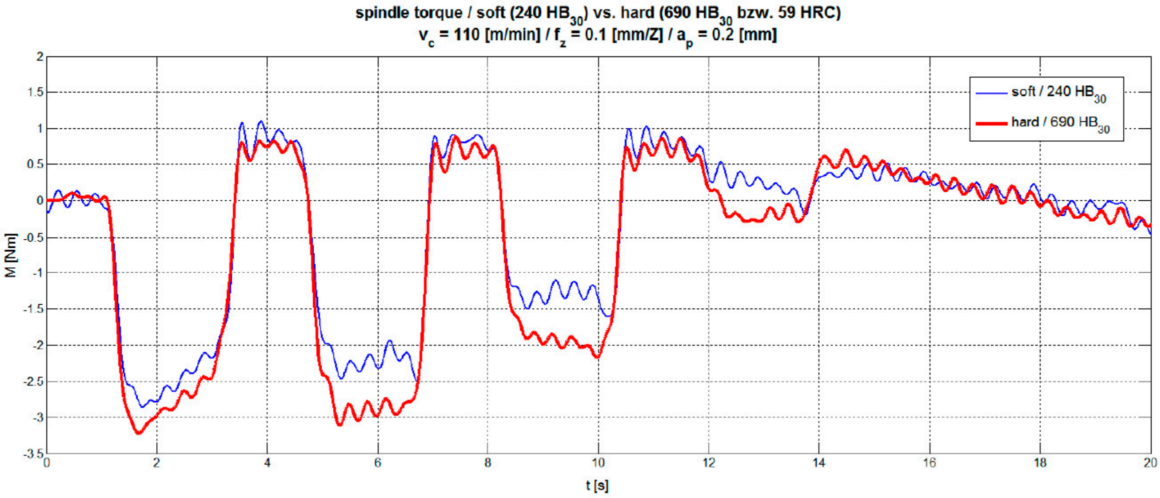



**Figure 7.** Course of spindle torque during finish operation on hard and soft machining with standard inserts of type 1030.

**Table 11.** Maximum torque on machine spindle during milling process in soft and hard state with standard inserts of type 1030.

| Measurement | Torque L [Nm], Soft | Torque R [Nm], Soft | Torque L [Nm], Hard | Torque R [Nm], Hard |
|---|---|---|---|---|
| 1 | −2.874 | −2.924 | −3.263 | −3.116 |
| 2 | −2.867 | −2.775 | X | −3.355 |

The average spindle torque for the two machining operations is shown in Table 12 with the percentage delta.

**Table 12.** Average spindle torque for soft and hard machining with standard inserts of type 1030 with percentage increase.

| | Soft 240 HB 30 | Hard 690 HB 30/59 HRC |
|---|---|---|
| \|∅ *Torque*\| [Nm] | 2.8604 | 3.2450 |
| ΔM [%] | | **+13.44** |

The increase of the spindle torque relative to 100% spindle load (74 Nm = 100% → data test machine [20]) is very small with an increase of 0.59%. This means that there are no damaging or critical torques or loads on the milling spindle when working with the InvoMilling™ operation in the hard state.

The occurring torque change in relation to the insert with a value of ΔM = 13.44% leads to a higher load on the cutting edge resp. insert. This stress increase is accompanied by an increased cutting insert resp. tool wear that adversely affects the surface roughness of the tooth flank and the service life of the tool. In order to be able to observe the tool wear, the hard and soft machining were carried out with a separate insert set. For experimental reasons, different tool path lengths per insert set were machined, cf. Table 13.

**Table 13.** Overview of tool path lengths.

| | Soft 240 HB 30 | Hard 690 HB 30/59 HRC |
|---|---|---|
| Tool path length [m] | 49.176 | 32.784 |

For the evaluation of the occurring tool wear, an analysis of the used cutting inserts is carried out with the aid of a light microscope on each tooth of the tool. The wear mark width as well as the number of outbreaks are measured and documented. Table 14 shows the results of the measurement of the individual cutting inserts.

**Table 14.** Tool wear for each insert after soft and hard machining tests.

| Insert | Wear Width [mm] Soft | Breakout Soft | Wear Width [mm] Hard | Breakout Hard |
|---|---|---|---|---|
| 1 | 0.1 | 0 | 0.08 | 0 |
| 2 | 0.05 | 0 | 0.16 | 3 |
| 3 | 0.08 | 0 | 0.08 | 0 |
| 4 | 0.09 | 0 | 0.12 | 1 |
| 5 | 0.06 | 0 | 0.09 | 0 |
| 6 | 0.07 | 0 | 0.12 | 1 |
| 7 | 0.09 | 0 | 0.13 | 3 |
| 8 | 0.06 | 0 | 0.08 | 1 |
| 9 | 0.14 | 2 | 0.11 | 0 |
| 10 | 0.09 | 0 | 0.1 | 1 |
| 11 | 0.05 | 0 | 0.14 | 3 |
| **Ø/SUM** | **0.08** | **2** | **0.11** | **13** |

Figure 8 shows a comparison of the wear mark width across the insert number of the tool.

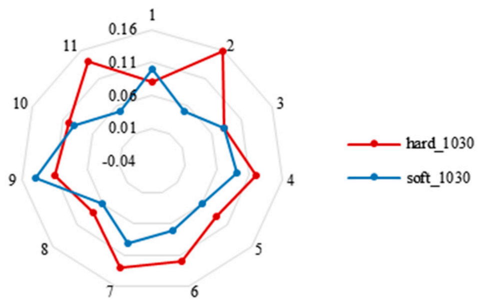



**Figure 8.** Comparison of tool wear [mm] over insert number after soft and hard machining tests.

Despite the shorter tool path length, there is a clear increase in the wear of the inserts from type 176M40-100608E-PM 1030. Specifically, the number of breakouts increases with this type of insert resp. coating and cutting material in the case of hard machining.

Figure 9 shows the microscope image of the most worn-out cutting edge resp. insert after soft (a) and hard (b) machining with 150-fold magnification. In the picture, the breakouts on the cutting edges are clearly visible.


(**a**)


(**b**)

**Figure 9.** Most worn out cutting edge: (**a**) cutting edge after soft machining tests; (**b**) cutting edge after hard machining.

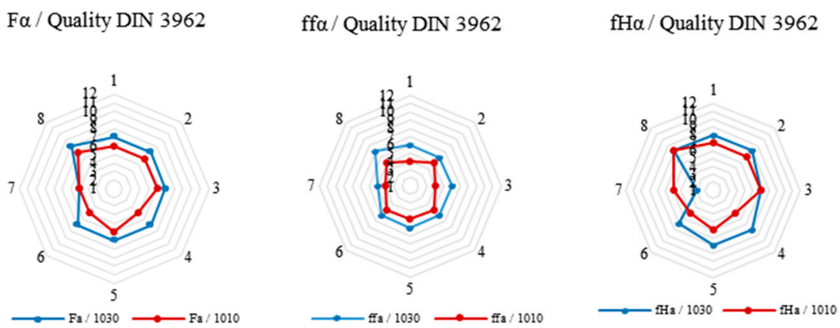
## 5. Test 3/Hard Machining/1010 Inserts

Due to the occurrence of tool wear on the 176M40-N100608E-PM 1030 inserts, the same parameter tests are carried out as described in Chapter 4 with inserts of type 176M40-N100608E-PM 1010. The results of this test series are summarized in Table 15.

**Table 15.** Achieved gear qualities according to DIN3962 [19] for tests 1 to 8 of hard machining with special inserts of type 1010.

| Test | Fα [Q/μm] | ffα [Q/μm] | fHα [Q/μm] | Fβ [Q/μm] | ffβ [Q/μm] | fHβ [Q/μm] |
|---|---|---|---|---|---|---|
| 1 | **6**/10 | **4**/4 | **7**/8 | **7**/12 | **7**/8 | **6**/−7 |
| 2 | **6**/10 | **5**/5 | **7**/8 | **7**/10 | **7**/7 | **5**/−5 |
| 3 | **6**/11 | **4**/4 | **7**/9 | **7**/12 | **7**/9 | **6**/−7 |
| 4 | **5**/8 | **5**/5 | **5**/5 | **6**/9 | **7**/8 | **3**/3 |
| 5 | **6**/9 | **5**/5 | **6**/6 | **7**/15 | **7**/7 | **7**/7 |
| 6 | **5**/8 | **5**/6 | **5**/−4 | **6**/10 | **8**/10 | **5**/5 |
| 7 | **5**/8 | **4**/5 | **6**/−6 | **7**/10 | **8**/10 | **5**/5 |
| 8 | **7**/12 | **5**/6 | **8**/10 | **7**/13 | **7**/8 | **7**/11 |

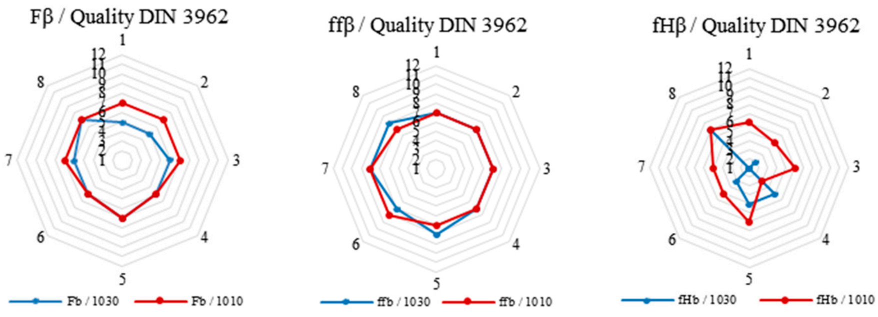
When using 1010 cutting inserts, a very good gear quality level in profile direction can be produced. The achievable gear qualities lie with one exception in the range of ≤6. In addition, it is found that the profile shape errors reach quality values ≤5. This suggests a lower cutting edge wear. The following figures show a comparison of the gear quality depending on the test number in relation to the used insert type for the hard machining. There is a clear improvement in the profile and the overall shape deviation resp. errors for the 1010 inserts, cf. Figure 10.




(**a**) (**b**) (**c**)

**Figure 10.** Comparison of gear quality in profile direction: (**a**) overall profile deviation, for 1030 and 1010 inserts; (**b**) profile form deviation, for 1030 and 1010 inserts; (**c**) profile angle deviations for 1030 and 1010 inserts.

The profile angle deviation is also better in the case of 1010 inserts. However, this is mainly dependent on the clamping resp. fixture and not on the insert type. The result is a continuous improvement of the achievable tooth quality in profile direction when using 176M40-N100608E-PM 1010 inserts. Improvements of up to two quality levels (test 4 and 6) are possible with the same cutting parameters. When looking at the flank line, there are clear deviations in the flank line angle deviation. This variation can be attributed primarily to the clamping and fixture situation. The flank line shape deviation, on the other hand, does not show any significant difference between the two types of inserts (Figure 11).




(**a**) (**b**) (**c**)

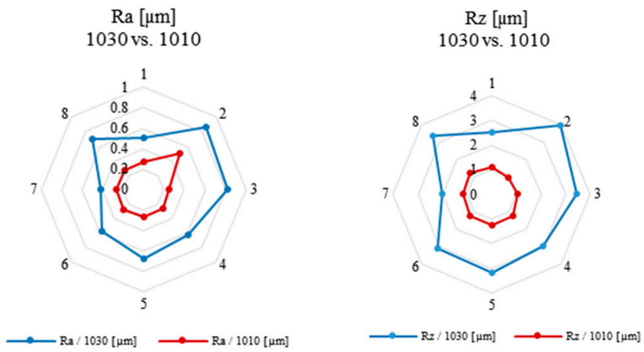
**Figure 11.** Comparison of gear quality in flank direction: (**a**) overall flank deviation, for 1030 and 1010 inserts; (**b**) flank form deviation, for 1030 and 1010 inserts; (**c**) flank angle deviations for 1030 and 1010 inserts.

The test series shows a deterioration of the tooth quality in the flank direction of up to two quality levels. These are due to the flank line angle deviation, which is largely influenced by the clamping resp. fixture. No significant influence of the used inserts could be observed. The observation of the lower insert wear is also clearly visible in the surface roughness. The achieved surface roughness values are listed in Table 16.

**Table 16.** Surface roughness values for hard machining with special inserts of type 1010.

| Profile | Ra [μm] (L/R) | Rz [μm] (L/R) |
|---|---|---|
| 1 | 0.31/0.23 | 1.25/0.95 |
| 2 | 0.21/0.28 | 0.87/1.10 |
| 3 | 0.27/0.22 | 1.17/0.95 |
| 4 | 0.26/0.27 | 1.27/1.16 |
| 5 | 0.30/0.23 | 1.41/1.06 |
| 6 | 0.29/0.26 | 1.21/1.22 |
| 7 | 0.26/0.26 | 1.15/1.20 |
| 8 | 0.28/026 | 1.41/1.28 |

Very good surface roughness values of 0.21 < Ra < 0.31 μm and 0.87 < Rz <1.4 μm could be achieved. In the case of hard machining with InvoMilling™ and with inserts of type 176M40-N100608E-PM 1010, comparable surface roughness values compared to grinding operations (0.2 < Ra < 0.8) [21] can be achieved. An improvement of the surface roughness in the hard state of 50–60% can be achieved with a suitable cutting insert type. Figure 12 shows a comparison of the achieved roughness values between the two insert types during hard machining over the test number.




(**a**) (**b**)

**Figure 12.** Comparison of achieved surface roughness values after hard machining tests: (**a**) roughness average, Ra; (**b**) roughness depth, Rz.

The observation of the spindle torque shows no significant dependencies on the type of the insert. The course of the spindle torque during hard machining is plotted for insert type 1030 and 1010 in Figure 13. The values obtained are at the same torque level as in Chapter 4.

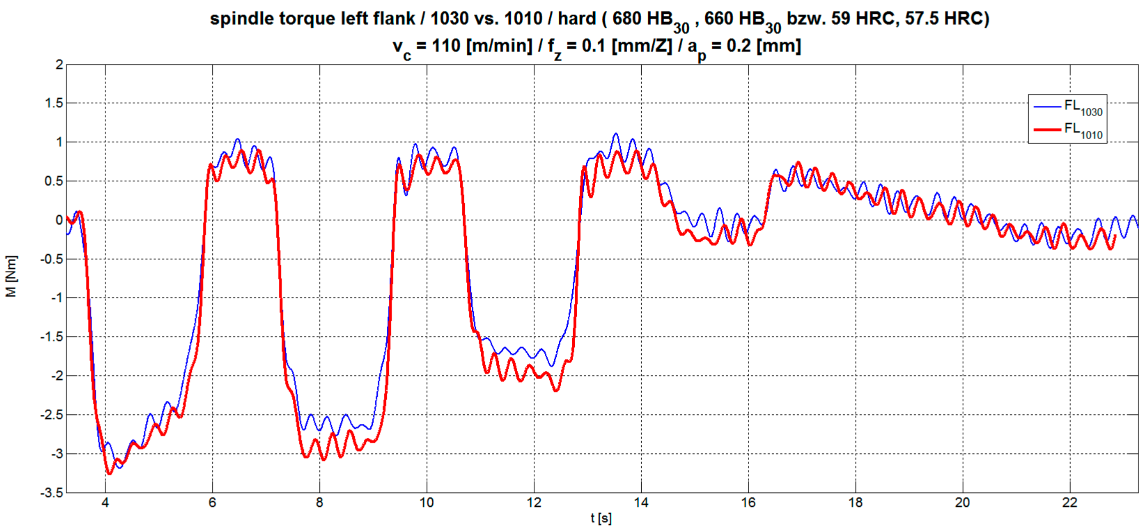



**Figure 13.** Course of spindle torque during finish operation on hard with standard inserts of type 1030 and special inserts of type 1010.

The observation of the tool wear shows very little or no wear phenomena on the cutting edge of the insert of type 176M40-N100608E-PM 1010. The observed wear mark width is listed over the insert number in Table 17.

**Table 17.** Tool wear for each insert after hard machining tests with special inserts of type 1010.

| Insert | Wear Width [mm] | Breakout |
|---|---|---|
| 1 | 0.03 | 0 |
| 2 | 0 | 0 |
| 3 | 0 | 0 |
| 4 | 0.04 | 0 |
| 5 | 0.04 | 0 |
| 6 | 0 | 0 |
| 7 | 0 | 0 |
| 8 | 0 | 0 |
| 9 | 0.02 | 0 |
| 10 | 0 | 0 |
| 11 | 0 | 0 |
| **Ø/SUM** | **0.0325** | **0** |

Figure 14 shows a comparison of the wear on the two types of cutting inserts. With each insert set, a tool path with the length of 32.784 m has been machined.

The wear of the inserts is very small in the hard state. Figure 15 shows a new insert of type 176M40-N100608E-PM 1010 before and after use on hard machining. There are no breakouts and very slight signs of wear can be seen.

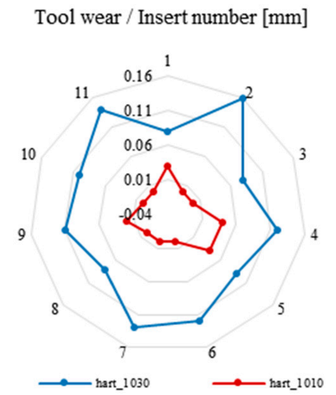
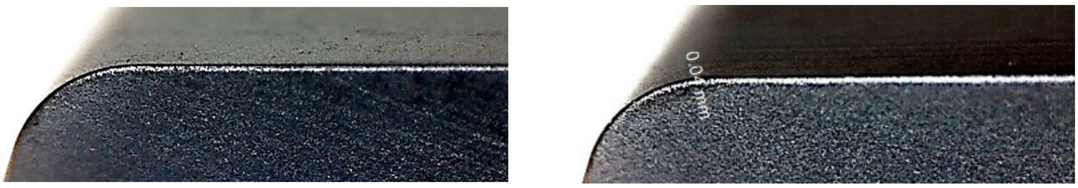



**Figure 14.** Comparison of tool wear after hard machining of 32.784 m with inserts of type 1030 and 1010.




(**a**) (**b**)

**Figure 15.** Tool wear of the special inserts of type 1010: (**a**) unused insert; (**b**) used insert after hard machining tests.

## 6. Summary

The results of the tests show that the InvoMilling™ method is a suitable process for the finishing of gears in the hard state. Depending on the insert type, good to very good results can be achieved with regard to the machined gear quality. The quality ranges of hard machining tests are summarized in Table 18.

**Table 18.** Summary of gear qualities achieved of the hard machining tests, for inserts of type 1030 and 1010.

| | **Fα [Q]** | **ffα [Q]** | **fHα [Q]** | **Fβ [Q]** | **ffβ [Q]** | **fHβ [Q]** |
|---|---|---|---|---|---|---|
| VZM5 1030 | 4–6 | 4–6 | 3–6 | 5–7 | 7–8 | 1–7 |
| VZM5 1010 | 5–7 | 4–5 | 5–8 | 6–7 | 7–8 | 3–7 |

The shape errors in profile direction can be used for the evaluation of the hard machining process because they are insensitive to positioning and alignment errors. These values show qualities $\leq 6$ and thus very good results. Table 19 summarizes the surface roughness of the individual hard machining tests.

**Table 19.** Summary of surface roughness values of the hard machining tests, for inserts of type 1030 and 1010.

| | **Ra [µm]** | **Rz [µm]** |
|---|---|---|
| VZM5 1030 | 0.41–1.07 | 1.98–4.51 |
| VZM5 1010 | 0.21–0.31 | 0.87–1.40 |

The achievable roughness values for the insert type 1010 lie in the area of ground gears. Due to the increased tool wear, the insert of type 1030 deliver highly scattering and poorer values. This insert type can't be recommended for hard finishing of gears. The spindle torques which occur during hard machining are summarized in Table 20.

**Table 20.** Summary of occurring spindle torque of the hard machining tests, for inserts of type 1030 and 1010.

| | Ø Spindle Torque [Nm] | Ø Spindle Load [%] |
|---|---|---|
| VZM5 1030 | 3.2450 | 4.38 |
| VZM5 1010 | 3.2240 | 4.35 |

No critical loads occur on the machine spindle. The resulting spindle torques at the hard finishing with InvoMilling™ can be neglected.

However, the stress on the cutting edge increases more clearly in the case of hard machining by the applied torques. Here, the inserts of type 1010 show the best service life and thus provide the best overall results. Table 21 gives a comparison of the wear width and the number of breakouts for boath insert types. This insert type should be used for the hard machining of gears with the InvoMilling™ method.

**Table 21.** Summary of tool wear after the hard machining tests, for inserts of type 1030 and 1010.

| | Ø Wear Width [mm] | Breakout |
|---|---|---|
| VZM5 1030 | 0.11 | 13 |
| VZM5 1010 | 0.032 | 0 |

Figure 16 shows the quality of the hard machined test gear. Inserts of type 1010 were used on this gear.

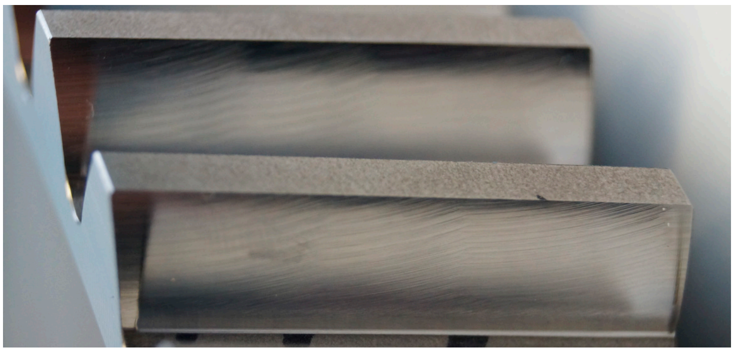


**Figure 16.** Quality of the hard machined test gear (with inserts of type 1010), lateral view on the gear flank.

The plot of the gear measurement of the manufactured gear is shown in Figure 17.

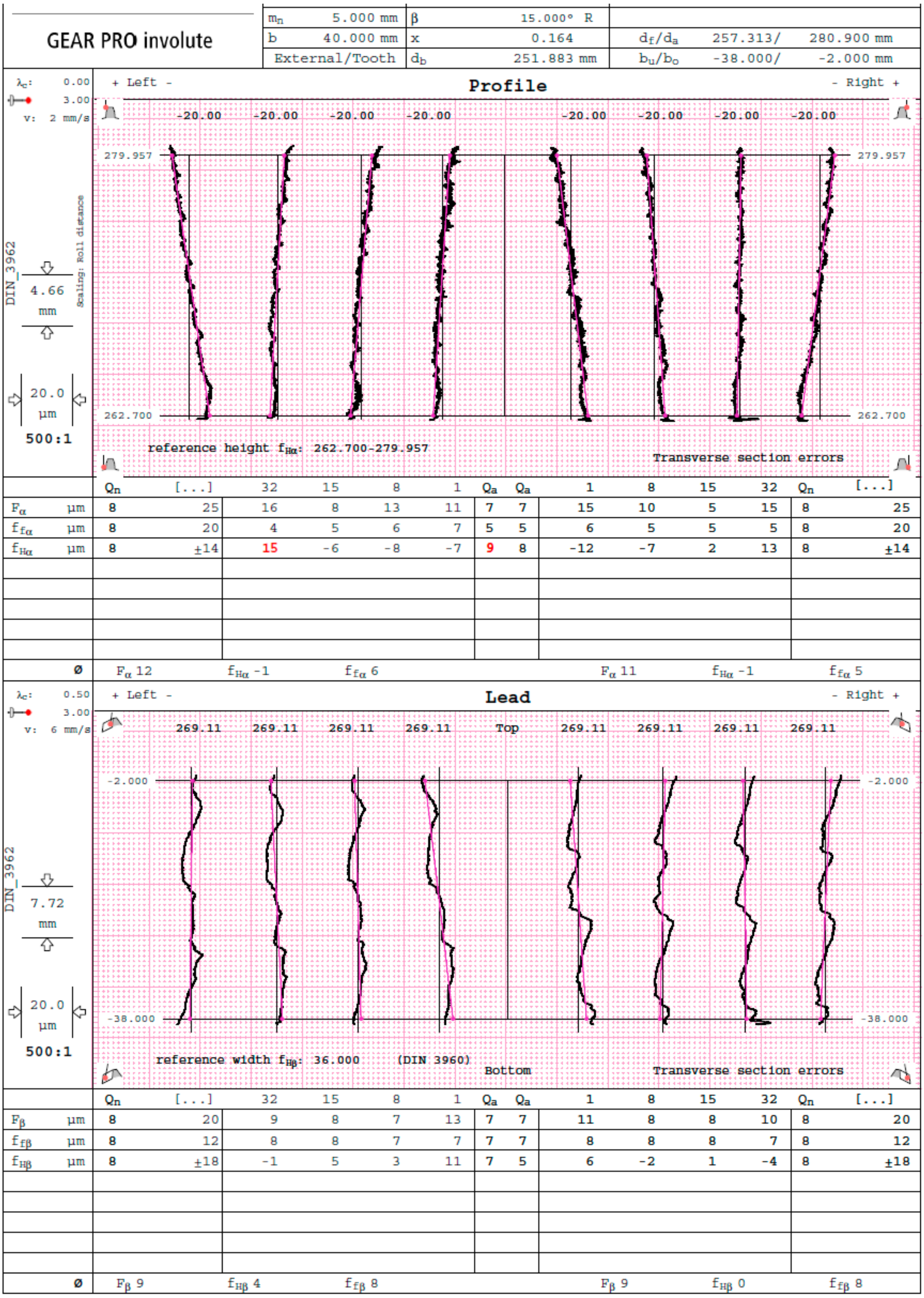



**Figure 17.** Measurement plot of one manufactured hard gear, with inserts of type 1010.

## 7. Conclusions

The results of the test series show that the InvoMilling™ method is a suitable method for the hard finishing of spur gears. With suitable cutting parameters and cutting materials resp. inserts, very good gear qualities and surface roughness values can be produced. Special attention must be paid to the clamping and the fixture, since clamping and alignment errors directly affect the gear quality characteristics' profile and flank line angular deviation errors and thus affect the profile and flank line total deviation. These errors are not attributable to the actual InvoMilling™ method but have a significant effect on the overall gear quality.

The loads on the milling spindle are only very small and therefore do not show any critical values during hard machining. The load on the cutting edges, on the other hand, is significantly higher during hard machining (VZM5 + ca. 13%). This leads to a drastic reduction of the service life of inserts of unsuitable cutting materials along with this effect, the surface quality also deteriorates.

For economical and qualitative reasons the inserts of type 176M40-N100608E-PM 1010 with PVD AlTiCrN coating should be used for the hard fine machining of spur gears with the InvoMilling™ method. Because of the attributes of AlTiCrN coating this insert type shows less wear and thus a longer service life. In the following tests should be carried out with this insert. Thus the hard-finishing with the InvoMilling™ method offers the advantage that all processing steps can be carried out on one universal machine. Due to the flexibility of this method, the time to the finished functional gear prototype can be drastically reduced. In this case, not only the pure processing time, but the entire time from incoming orders to the finished gear must be considered.

The cutting parameters used in this series of tests provide a good basis for the hard machining of spur gears. In order to optimize the gear quality, the surface roughness as well as the processing times, these cutting values should be adapted and improved in the following.

A closer look should also be given to the surface characteristics or roughness profiles. Milling shows a surface with a periodic roughness profile (machining with geometrically determined edge), and, in case of grinding (machining with geometrically undefined cutting edge), a random roughness pattern occurs. This regular roughness or surface profile could have a negative influence on the sound or noise behavior of the milled gearing. More detailed investigations should follow in the future.

In addition, the InvoMilling™ method can not only be used for the hard finishing of the gear, but for an equalizing cut before the grinding or finishing operation. Through this leveling, the oxide layer formed during the hardening process can be removed and subsequently the grinding power could be increased while reducing risk of overheating while grinding.

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