Software-Based Process Design in Gear Finish Hobbing

ANALYSIS AND OPTIMIZATION OF GREEN GEAR FINISH HOBBING BY PENETRATION CALCULATION COMBINED WITH CUTTING TRIALS

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Management Summary

In this paper, the potential for geometrical cutting simulations—via penetration calculation to analyze and predict tool wear as well as to prolong tool life—is shown by means of gear finish hobbing. Typical profile angle deviations that occur with increasing tool wear are discussed. Finally, an approach is presented here to attain improved profile accuracy over the whole tool life of the finishing hob.

Introduction

For efficient gear manufacturing, green finishing processes have to be applied, rather than a cost-intensive hard finishing operation, whenever they are capable to reach the necessary geometrical accuracy of the tooth system. Therefore the machining process and its technological influences must be well known. For green finishing of gears, machining with a geometrically defined cutting edge is common. This includes gear shaving and the growing market of gear finish hobbing.

Compared to gear shaving, finish hobbing offers ecological as well as economical advantages (Ref. 1). Hobbing is the only process that enables a dry gear finishing operation, which, in turn, allows a coolant-free process chain of gear manufacturing. Economical advantages refer to a shorter value creation chain. With finish gear hobbing, no separate finishing machine tool is needed. At the same time, setup and transportation time can be saved, as washing after wet machining is not needed.

In rough and finish machining of running gears by hobbing, a separate

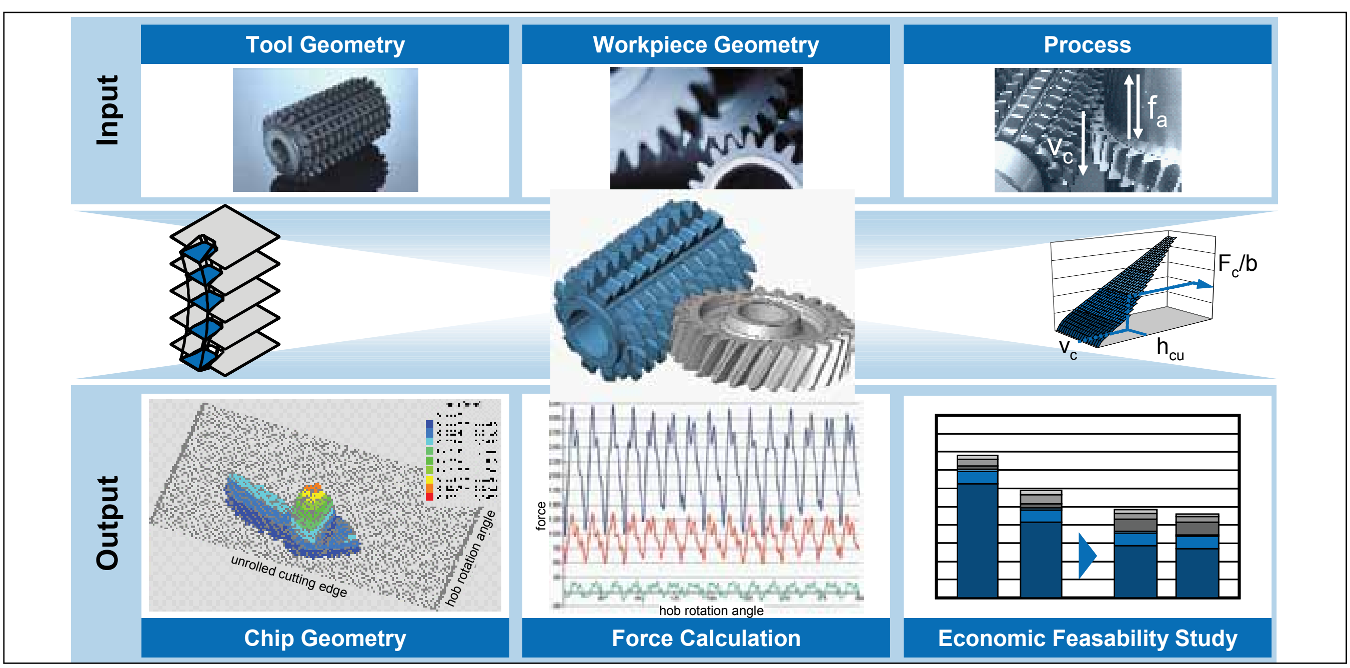

Figure 1—Functions of the software *SPARTApro*.

roughing-and-finishing pass is worthwhile (Ref. 2). During roughing, most of the material has to be removed, which leads to high forces and corresponding deviations. In this operation, only relatively low cutting speeds are applied. In finishing, restrictions exist regarding surface quality, feed marks and generated cut deviations due to the quality requirements of the part. Since only a small stock is machined, cutting speeds can be increased significantly (Refs. 3–5).

This paper addresses the question of how the roughing pass can be adapted to optimize gear finish hobbing regarding tool life and gear quality. For this purpose, theoretical analyses—as well as machining trials—are described.

Potentials of Software Support in Gear Hobbing

Hobbing is a very effective method for the green manufacture of external cylindrical gears. However, its productivity is influenced by numerous, mostly non-linear interacting factors. The tool costs per piece are likewise determined by the geometrical tool design. The parameters for a given machining operation have to be designed in order to meet the operational requirements of machining time and costs. Due to the complexity of the interrelations, this is a challenging task. Therefore the software tool *SPARTApro* has been developed at WZL to assist in designing and optimizing gear hobbing processes (Fig. 1).

The software can be used for three major applications:

1. ***Analysis of the chip geometries for a concrete process design***. *SPARTApro* provides all undeformed chip geometries that occur during the machining process by a process simulation based on penetration calculation. Characteristic process values like the maximum, undeformed chip thickness or the local chip volume for every point of the cutting edge are determined by this data. Based on this information, wear phenomena that occur in industrial applications can be analyzed. An experience-based estimation of the performance of a planned process design can be aided by the simulation results.

2. ***Estimation of cutting forces***. The progress of the cutting forces for the single generating positions (hob teeth) and of the resulting forces for the tool and the workpiece coordinate system can be determined based on empiric cutting force models, referring to Bouzakis (Ref. 6) and Gutmann, (Ref. 7). For the design of machine tools, cutting tools and workholding for high-performance cutting, knowledge of the static and dynamic process forces, as well as of the necessary spindle torque, are very important.

3. ***Economical or technological optimization of the tool geometry***. *SPARTApro* is able to consider a great number of possible tool variants with different design parameters—like the diameter and number of starts and gashes. For these tool variants, a process design is determined that meets defined requirements, such as maximum chip thickness and resulting feed marks. Based on analytic formulas regarding machining times, costs and further figures are calculated for all variants so that the operator can search for the tool geometry—e.g., with the lowest cycle time.

For the analysis of gear finish hobbing, the chip-forming software part has been used.

Sample Gear and Process Design

The investigations shown in this paper have been carried out by means of a gear that is representative for the automotive sector (Fig. 2). The material is a case-hardened steel 16MnCr5 with a tensile strength of about R_m = 565 N/mm². The finishing process will be analyzed by theoretical examinations as well as by cutting trials. For the cutting trials, a fly-cutting test is applied. This test is common for investigations in hob tool life since the fly-cutter creates nearly the same chip geometries as a real hob. Thus the load on the fly-cutter is the same as on a tooth in the middle of a shifted hob.

The hob that is simulated in the theoretical investigations, as well as by the fly-cutters, is designed with a separate roughing and finishing area (Fig. 2). This design allows roughing and finishing with the same tooth pro-

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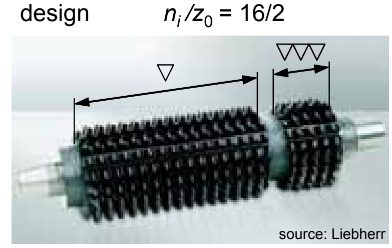
Workpiece:
module m_n = 2.56 mm
number of teeth z_2 = 39
pressure angle α_{n2} = 17.5°
helix angle β_2 = 23 °
diameter d_{a2} = 116.2 mm
face width b = 30 mm
tooth height = 8.1 mm
no modifications

Material:
16MnCr5N
hardness = 168 HV
tensile strength R_m = 565 N/mm²

Flank Topography:
feed marks δ_x < 1.1 µm
gen. cut dev. δ_y < 0.8 µm

Simulated Hob:
carbide HW K10F
(Al,Cr)N-coating
separate roughing and finishing area
diameter d_{a0} = 80 mm
design n_i/z_0 = 16/2



Stock Geometry:

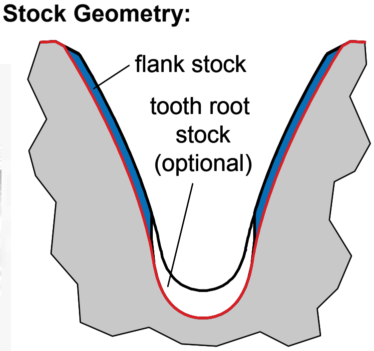


Figure 2—Workpiece, tool and stock geometry for finishing.

file, as well as roughing with a specially adopted profile and finishing only the flanks of the gear. Since the highest chip volume in finishing will be reached at the tip of the tool, avoiding the engagement of the tip during finishing may lead to an enhanced performance of the tool. The finishing part of the hob is designed with $n_i = 16$ gashes and $z_2 = 2$ starts, so that a surface with generated cut deviations of $\delta_y = 0.8$ µm can be achieved.

Theoretical Analysis

To analyze the load on the tool, a geometrical simulation of the chip geometries has been carried out with the software *SPARTApro*. Figure 3 shows some of the results for the finishing pass—with and without tooth root machining. A conventional cutting process is analyzed with a radial infeed in finishing of $h_2 = 0.2$ mm and an axial feed of $f_a = 1.0$ mm. The graphs display characteristic values for a tooth of a shifted hob. This means that the given graphs represent the chip geometries of all occurring generating positions. The values are plotted versus the unrolled cutting edge of the tooth, meaning that the middle of the graph represents the tip center of the tool. The horizontal axis represents the distance along the cutting edge from the tip center.

When the tooth root is machined, the maximum chip thickness appears for the tool tip with about $h_{cu,\,max} = 50$ µm, while the maximum chip thickness for the flanks is below $h_{cu,\,max} = 20$ µm. Due to the stock distribution left from the roughing process, the maximum cutting length along the cutting edge is nearly constant, with about $l_{cu,\,max} = 5.0$ mm. The number of cuts gives an idea of how often one single point of the tooth has to be engaged to finish one gear. For the transitions between the tip radius and the flanks, a maximum value of about $n_s = 10{,}000$ cuts can be found, which is about 30% more than the maximum value for the flanks. The graph of the specific chip volume shows peaks at the same positions of the tool. In general, the tooth tip has to cut a lot more material than the flanks. And so the highest mechanical and thermal load will be found at the tooth tip when it is engaged. When the tooth tip is not engaged, and only the tooth flanks are machined, this load maximum can be avoided.

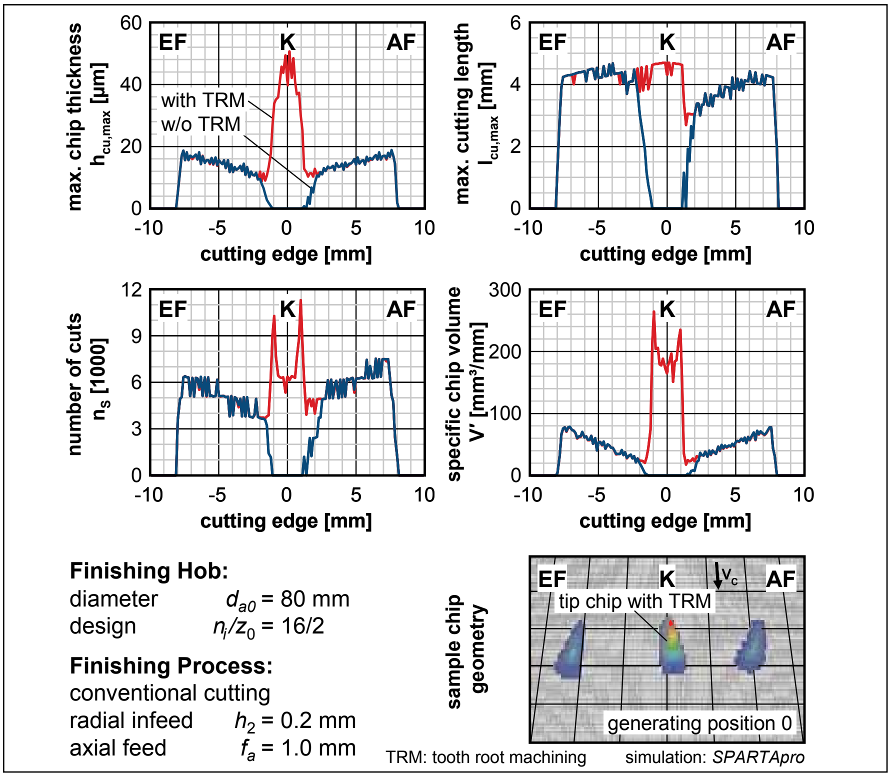


Figure 3—Characteristics of gear finish hobbing with and without tooth root machining.

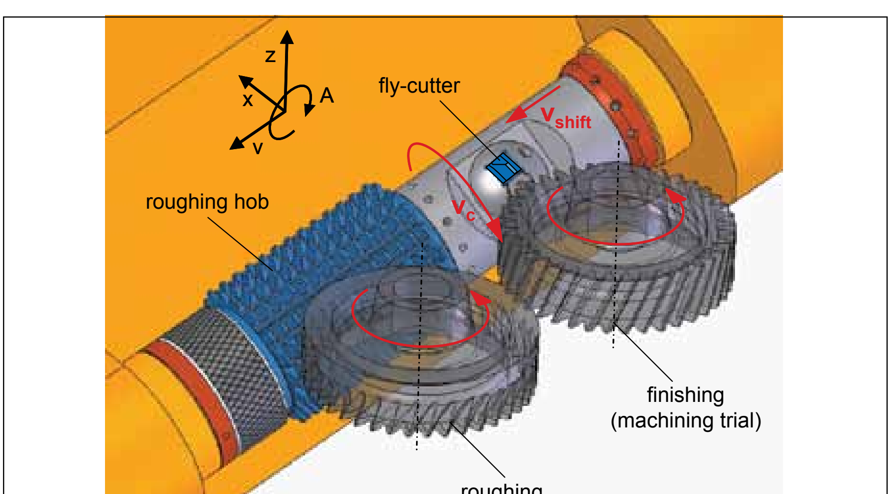


Figure 4—Experimental setup.

Cutting Trials

Cutting trials have been carried out with the parameters applied for the theoretical analysis. For the trials, the experimental setup shown in Figure 4 has been applied. A hob is used for roughing the gear while the finishing process is carried out with a fly-cutter mounted on the same shaft. This fly-cutter is shifted during the machining operation so that the created chips are similar to those created by a hob. The advantages of machining trials with a fly-cutter compared to a hob are fewer needed workpieces and the opportunity of wear analysis by an optical microscope or SEM, due to the good accessibility of the cutting edge.

Due to the low chip volume in the finishing process, the cutting trials have been carried out at a relatively high cutting speed of $v_c = 1{,}000$ m/min.

When the tooth root is machined, a tool life of about L = 27 m is reached before tool wear starts to increase progressively (Fig. 5). Since the tool life of a fly-cutter is in general about three times higher than the tool life per tooth of a real hob, this would mean about L_{hob} = 9 m per tooth. The SEM images of the tool (different scale in horizontal and vertical axis) show that the transition areas between the flanks and the tip radius show the greatest flank wear width. The rest of the cutting edge shows only initial wear and is in very good condition. This demonstrates that the tool life of the fly-cutter can be increased by more than 200% when the tooth root has already been finished in the roughing pass. The corresponding SEM images show a very smooth distribution of the flank wear for this trial, with a maximum flank wear width of about VB_{max} = 0.12 mm.

When the wear images are compared to the graphs in Figure 3, the correlation between the local wear—and especially the specific chip volume—stand out. This applies as well to the maximum wear at the transition zones of the first tool, as also seen in the increasing flank wear width from tip to root of the second tool with higher tool life.

Since gear finish hobbing is a green finishing process, the requirements for the resulting gear quality are higher than for a standard hobbing process. Figure 6 shows the profile and flank geometry of gears at the beginning and end of tool life for the tool with only flank machining. At the beginning of tool life, both profile and flanks are very straight, and good accuracy is reached. However, the accuracy highly depends on the tool and process design so that it can actually be improved by, for example, a higher number of gashes.

The profile of the gear's left flanks at the end of tool life shows a profile angle deviation, while the profile of the right flanks is straight. This can be traced back to two different factors. The first factor is a slight inclination of the fly-cutter due to its clamping. This causes a slight profile angle deviation, and consequently both flanks have to be parallel in the graph. The second factor is a change of the cutter profile, due to wear. The local wear causes an offset of the cutting edge, which is proportional to the flank wear width. The increasing wear from the tip to the root (Fig. 5) leads to an increased thickness of the workpiece tooth—from the root to its tip.

To sum up, there is a fundamental tendency of increasing profile angle deviations with increasing tool life that has been pointed out to be dependent on the local chip forming characteristics shown in Figure 3. This leads to exploring whether the deviations can be avoided by adjusting defined chip forming characteristics.

Improved Stock Distribution to Avoid Profile Angle Deviations

As shown above, the wear of the tooth flanks and the specific chip volume correlate very well. Therefore the first approach to avoiding profile angle deviations is adjusting the specific chip volume on the tooth flanks to a constant value. To do this, modifications in the stock distribution along the gear profile are necessary. These modifications must be reached by a specially adopted profile of the roughing hob.

Geometrical simulations have been carried out with *SPARTApro* in order to find this profile. The result is a tool profile with an adjustment of the pressure angle, as well as a slight crowning. The stock geometry generated by this tool leads to the characteristics shown in Figure 7 when compared to the original figures. Indeed, the distribution of the specific chip volume is much more even along the engaged cutting edge. Therefore the goal of theoretical process optimization to improve profile accuracy in gear finish hobbing has been met.

The outstanding question is if the wear behavior of the tools will change, as assumed.

Conclusion

This paper has shown that there is a wide field of applications for software support in gear hobbing, particularly regarding cost-effective hob design, cutting force determination and the analysis of tool wear causation. The software *SPARTApro* has been used to

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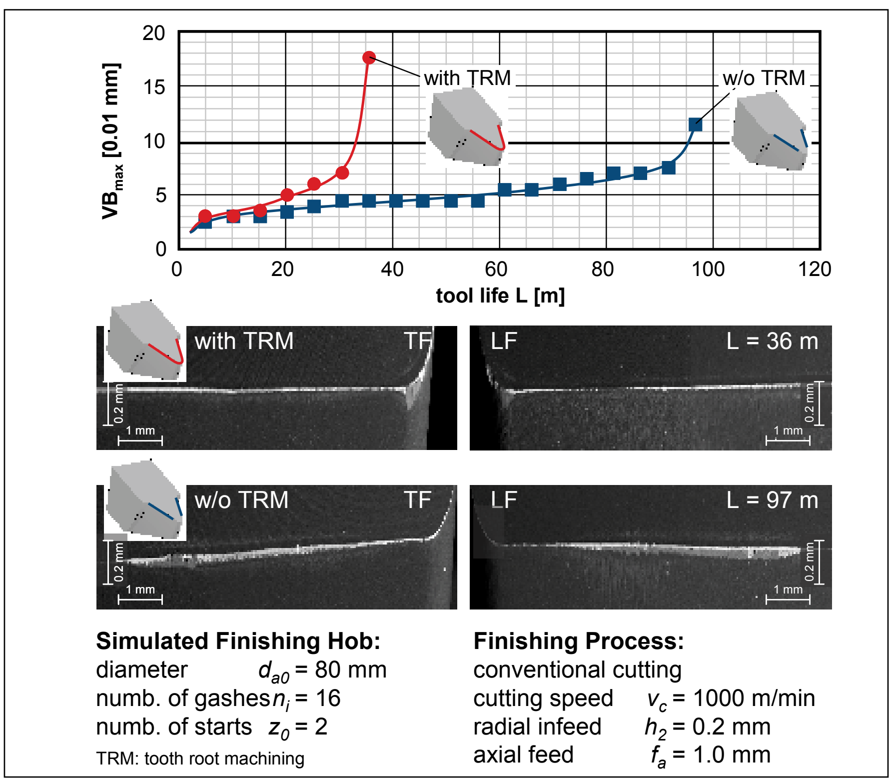

Figure 5—Gear finish hobbing with and without tooth root machining: performance.

simulate the undeformed chip geometries of a gear finish hobbing process, and to identify critical areas of the cutting edge. In combination with cutting trials, the geometrical simulation has shown that the greatest local load on the tool can be avoided when the tooth root is not machined in the finishing pass. This can be used either to increase tool life by about 200% or to boost productivity by increasing cutting speed.

However, typical profile angle deviations arise with the progression of tool life. They can be traced back to the distribution of tool wear along the flanks due to other local cutting conditions. To avoid these profile deviations, the influence of the roughing tool profile on local cutting conditions has been analyzed theoretically. Profile modifications have been found that promise a very smooth distribution of the specific chip volume.

Further cutting trials are needed to prove whether this modified roughing tool profile leads to improved wear behavior of the finishing tool and, in the end, to enhanced profile accuracy.

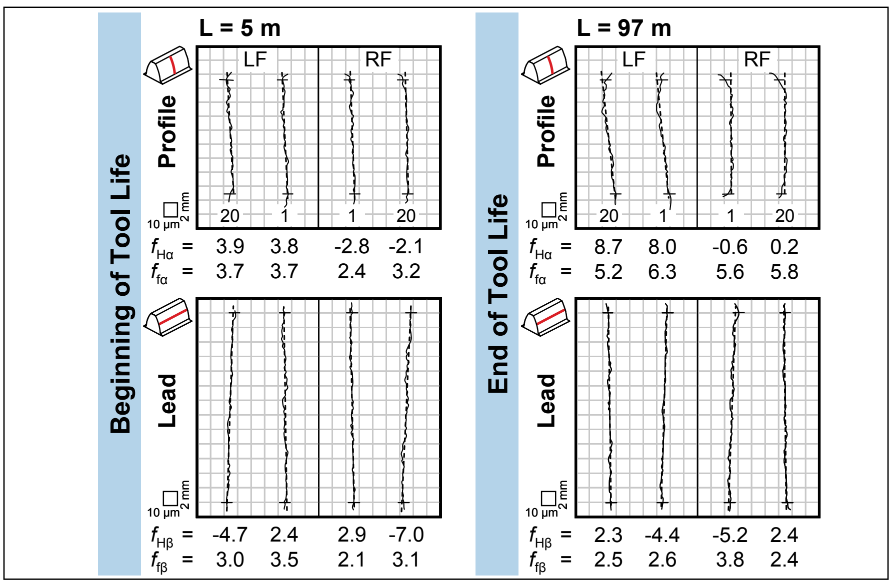

Figure 6—Gear finish hobbing without tooth root machining: workpiece accuracy.

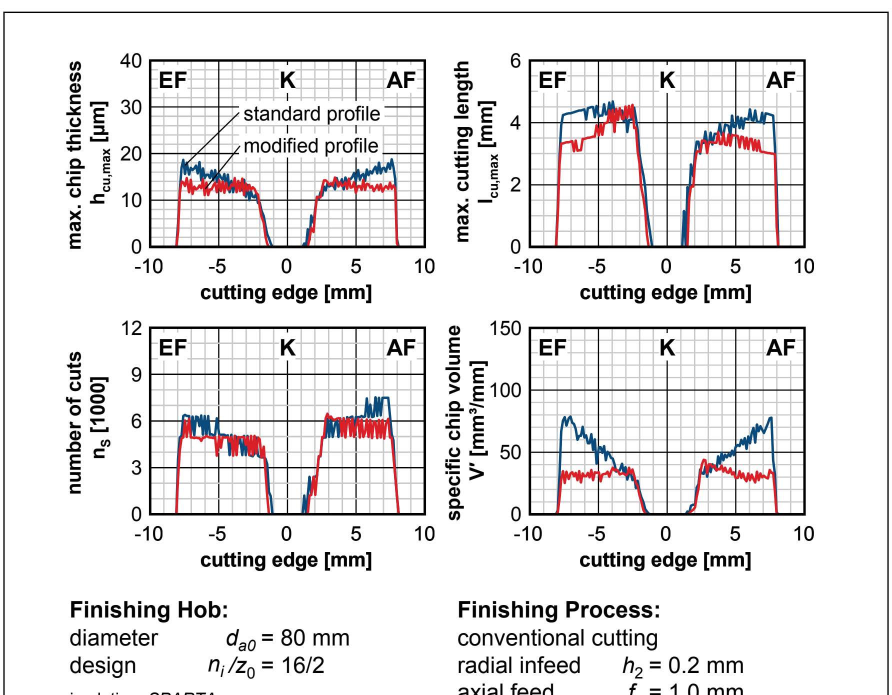

Figure 7—Characteristics of gear finish hobbing with modified stock geometry.

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