An Innovative Way of Designing Gear Hobbing Processes

F. Klocke, C. Gorgels, R. Schalaster and A. Stuckenberg

Management Survey

In today's manufacturing environment, shorter and more efficient product development has become the norm. It is therefore important to consider every detail of the development process, with a particular emphasis on design. For green machining of gears, the most productive and important process is hobbing. In order to analyze process design for this paper, a manufacturing simulation was developed capable of calculating chip geometries and process forces based on different models. As an important tool for manufacturing technology engineers, an economic feasibility analysis is implemented as well. The aim of this paper is to show how an efficient process design—as well as an efficient process—can be designed.

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Introduction and Objective

In order to shorten production time, it is wise to use simulation tools at every step of product development. Simulation tools can help avoid iterative steps based on trials and minimize development time—as well as costs. Along with existing WZL software packages (Refs. 1–2), a software simulation tool for gear hobbing has been in development for several years—i.e., *PARTApro.* Gear hobbing is one of the major manufacturing processes in the industry; indeed, nearly every soft-machined gear made is hobbed.

It therefore makes sense that—especially for a manufacturing technology with such high importance—a manufacturing simulation is needed for the reasons mentioned above, and due to the complexity of the process design. The complexity results from numerous, mostly non-linear, interacting factors. The tool costs-per-piece are also determined by the geometrical tool design. The parameters for a given machining operation require a specific design in order to meet operational requirements (machining time and costs). What's more, a manufacturing simulation is needed to enable easy and fast process design. The approach includes a penetration calculation in order to identify the chip geometries. But knowing only the chip geometry is insufficient for manufacturing simulations; of equal importance are characteristics and/or other values with a technological or economic background relative to a specific process.

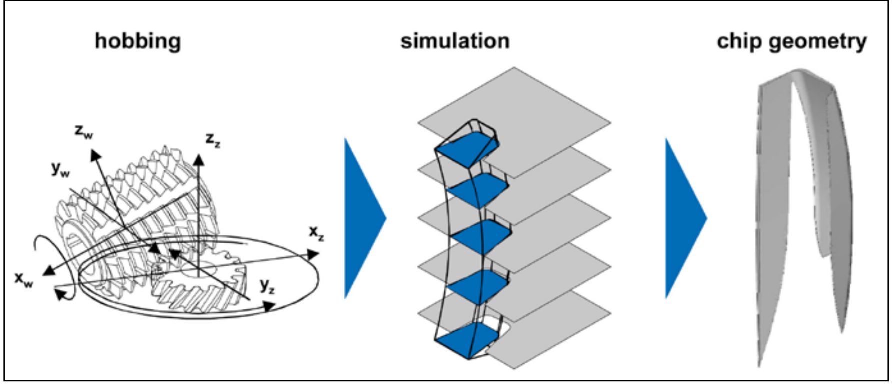


Figure 1—General approach for Penetration Calculation I.

Basics of a Manufacturing Simulation

Manufacturing simulations make the characteristics of complex processes more visible. The complexity of the hobbing process, for example, is demonstrated by the existence of the various chips created for every generating position caused by the complex kinematics. In gear hobbing, hob and workpiece move in a linked revolution ratio. The most common kinematic approach in hobbing is to start machining below the workpiece with the correct in-feed to reach the tooth height and feed the tool along the axis of the workpiece until the entire width of the workpiece is machined. Additional opportunities exist concerning the kinematics.

The kinematics are represented in the software. By a mathematical, geometric calculation the penetration between tool and workpiece over the complete manufacturing process is calculated

(Fig. 1). The resolution is limited by the number of layers along the workpiece width (199), the number of angle steps for a single chip (200) and the medium dot distance on the workpiece and tool profile. This distance has a relative limitation of 0.05 times module.

With the input data hob, workpiece and process kinematics, the chip geometries can be evaluated by modeling and creating non-deformed chips. Figure 2 (right) shows an exemplary chip geometry; the chip width is displayed on both the axis unrolled cutting edge and the cutting length on the axis cutting direction. The chip thickness is displayed vertically to the picture and distinguished by different colors; the dark areas have a low chip thickness, the light areas at the top have a high chip thickness.

Tool Design with Manufacturing Software

Along with technological investigation requiring concrete chip geometries, determination of economic value is of equal importance to the process designer. Therefore, examples of how manufacturing software assists in that determination are shown. To be determined in this case is which cutting material and tool design fit best for an existing, exemplary process. In determining which cutting material is preferable, one must consider not only productivity and tool life, but tool costs as well. Generally, the tool costs for PM-HSS hobs are lower than for carbide tools; tool costs consist of three parts:

1. Purchase cost—especially for hobbing tools
2. Re-coating cost
3. Re-sharpening cost

The costs for re-coating typical, various cutting materials are quite similar, but the purchase and re-sharpening costs are higher for the more robust carbide tools. That is why in analyzing which is the best tool, determining total cost of ownership is crucial. For machining a 16MnCr5N steel, for example, a profitability analysis is shown (Fig. 3). Starting with investigated parameters in an analogy process for gear hobbing, the process is opti-

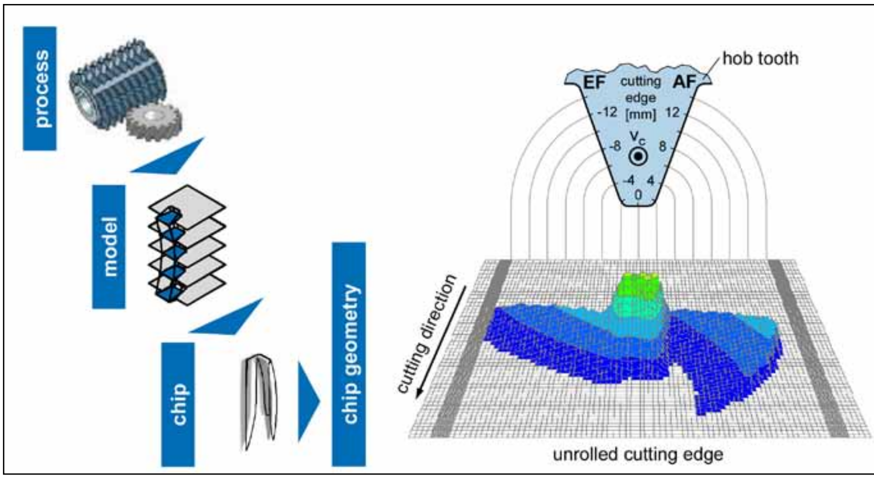
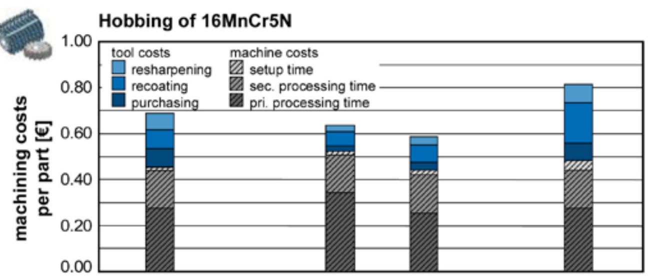


Figure 2—General approach for Penetration Calculation II.

Tool:
PM-HSS: HS 10-2-5-8
carbide: HF K30F
coating: (Al,Cr)N
m_n = 2.5 mm
α_{n0} = 20°
d_{a0} = 50 - 100 mm
z_0 = 1 - 5
n_i = 10 - 25

Workpiece:
material: 16MnCr5N
R_m = 565 N/mm²
z_2 = 48
b = 25 mm
β_2 = 24.62°; right

Machining:
(only for tool optimization)
$h_{cu,max,hof}$ = const.
δ_x < 20 µm



cutting mat.	cemented carbide	PM-HSS	PM-HSS	PM-HSS
coolant	-	-	-	-
v_c / $h_{cu,max,hof}$	450/0.16	240/0.20	240/0.24	300/0.20
f_a [mm]	2.1	3.2	4.3	3.2
d_{a0} [mm]	80	80	80	80
z_0 / n_i	2/15	2/15	2/15	2/15
L [m]	11.0	11.0	8.6	3.9

Figure 3—Process design of existing process for 16MnCr5N.

Tool:
PM-HSS: HS 10-2-5-8
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(only for tool optimization)
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δ_x < 20 µm

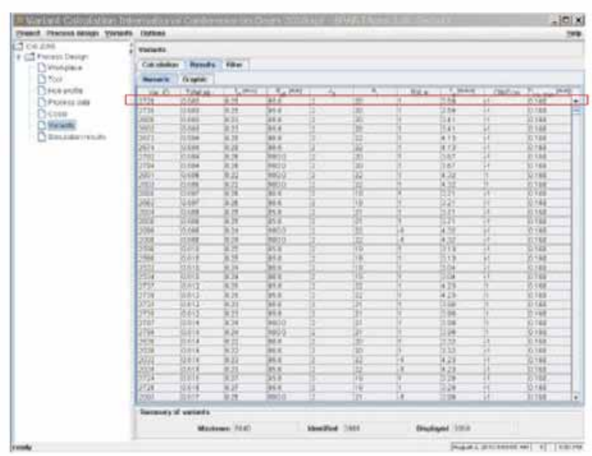

Figure 4—Variant calculation to optimize tool and process design.

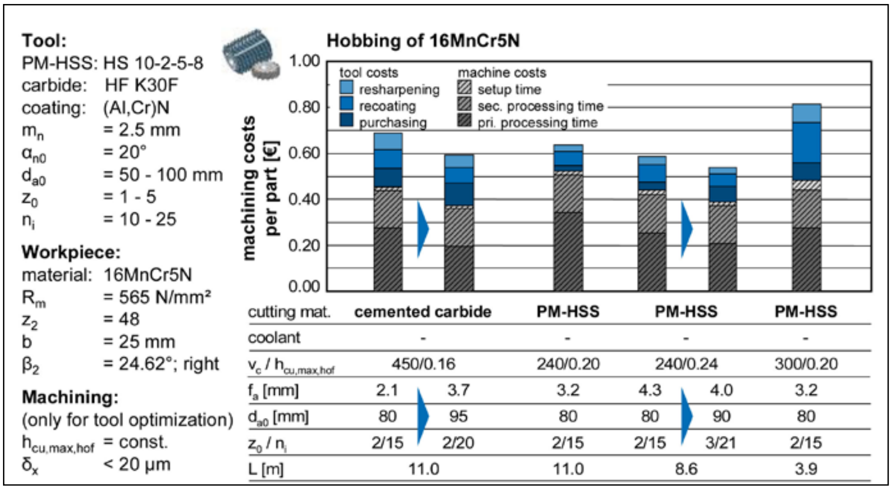

Figure 5—Profitability analysis of machining case-hardening steel 16MnCr5N.

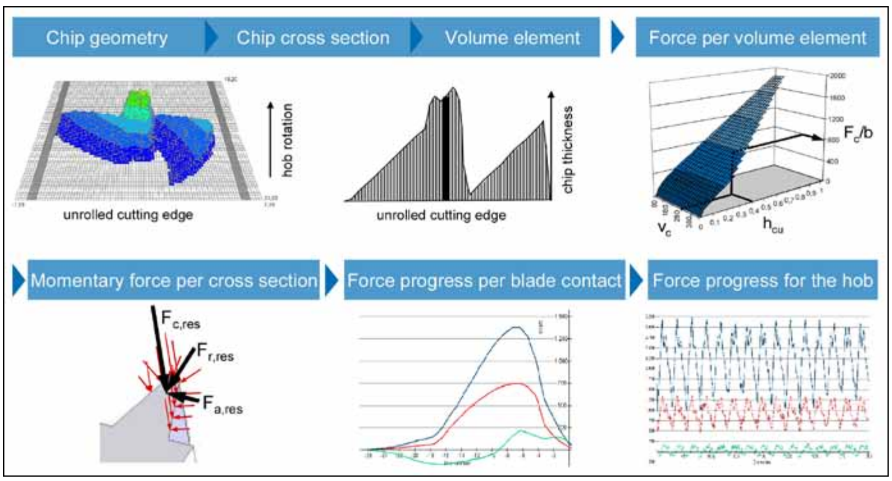

Figure 6—Approach for calculation of cutting forces in gear hobbing (Gutmann, Ref. 3).

mized with software. Based on trial parameters, the first determination of cost-per-part is made.

Initially, the cost-per-part for PM-HSS at medium cutting speed (Fig. 3) is lower than for machining with carbide. Only the PM-HSS process with very high cutting speeds is not competitive. With the results for the tool life based on trials, a calculation of different tool and process variants is made with the target of an axial feed with feed marks of δ_x<20 µm and a constant maximum chip thickness for each set of cutting parameters. The tool outside diameter and number of starts and gashes are varied. With these default values, the software calculates every possible tool design capable of achieving these requirements (Fig. 4).

The result in this case is a combined total of 7,040 variants. Due to the given limitations, 3,968 variants are determined and shown. In the different columns, different values are presented. In Figure 4, the variant ID for the identification (Var ID); the cost-per-part (total); the primary processing time (t_h); the tool outside diameter (d_{a0}); the number of starts (z_0); the number of gashes (n_i); the gradient direction of the spiral (*Ri*/*Le*); the axial feed (f_a); the manufacturing direction—climb or conventional cutting—(*Clb*/*Con*); and the maximum chip thickness ($h_{cu,max}$) are visible. Next to these values different other values are selectable. Every column can be sorted in descending or ascending order. In this way the opportunity presents itself to look for a variant with, for example, the lowest processing time or the lowest cost. The data for the tool and resharpening costs—plus the cost for the machine tool-per-hour—are input data and must be supplied by the user.

The result of the tool and process optimization shown (Fig. 3) is presented (Fig. 5). For the cemented carbide tool variant, the variant chart is shown (Fig. 4). After this variant calculation the machining cost-per-part for gear hobbing could be decreased about 15%. It seems to be that the cemented carbide is now competitive with the PM-HSS tool. But, optimization of the PM-HSS tool (Fig. 5) leads again due to lower machining costs. In this case the analysis of the process could show which tool material and design fits best.

Process Force Calculation Based on a Manufacturing Simulation

Next to the economic values of a process, knowledge of the forces in gear hobbing is important regarding tool, machine tool and workpiece clamping dimensioning. So the tool and machine tool manufacturer—as well as the production plant owner—have keen interest in that topic.

The need for a process force calculation is industry-driven and implemented in the manufacturing software. The calculation is based on a cutting force model for gear hobbing provided by Gutmann (Ref. 3).

The approach of cutting force calculation with *SPARTApro* is illustrated (Fig. 6); the basis of the approach is the dependence of cutting forces on the chip thickness and the cutting speed (Ref. 3).

Earlier in this paper it was explained that the software calculates all appearing chip geometries via penetration calculation. The single-chip geometries are split in cross-section elements. The result is a graph over the unrolled cutting edge for discrete hob rotation angle steps. This graph is divided again in discrete volume elements with a defined chip thickness. For each volume element, the force is calculated with the aid of a cutting force characteristic diagram. A characteristic diagram considers chip thickness—h_{cu}—and cutting speed—v_c. The data basis for the force calculation—and thus for the characteristic diagram—is generated based on turning trials. In this quasi-static trial the cutting forces in each spatial direction are measured. The measurements are carried out for different cutting speeds, chip thicknesses (realized by the feed) and materials.

After the force values for each volume element of a single-hob-rotation-angle-step along the cutting edge are determined, the resulting forces in the cutting speed direction—i.e., in both radial and axial directions—are calculated. This procedure is required for every discrete hob-rotation-step and blade. Results of these calculations are shown in Figure 6, as in the "force-progress-per-blade-contact" over the hob rotation angle, for example. The sum-of-force progress for each blade is in turn the "force progress for the hob."

With the trials data in hand, this method of force calculation is verified; the trials involved hobbing operations on an industrial hobbing machine tool. A dynamometer is mounted between hobbing tool and main bearing of the tool-holder axis; with the dynamometer, the torque and forces in every spatial direction can be measured. In Figure 7, a comparison between calculated and measured spindle torque over a single hob rotation is presented. The medium values for both graphs are quite similar. The main difference between them is the amplitude—i.e., it is much higher for the measured torque, due to the higher dynamic influence of an actual process, as compared to the static summation provided in the calculation algorithm. Therefore, although the software cannot simulate the dynamic behavior of a real-time hobbing process, it does in fact generate good results regarding the medium values. Visible in both graphs is the effect of a two-start hobbing tool ($n_i = 2$). This results in a wavelike envelope and a second, lower peak next to each of the 17 main peaks. The 17 main peaks result from the number of gashes ($Z_0 = 17$).

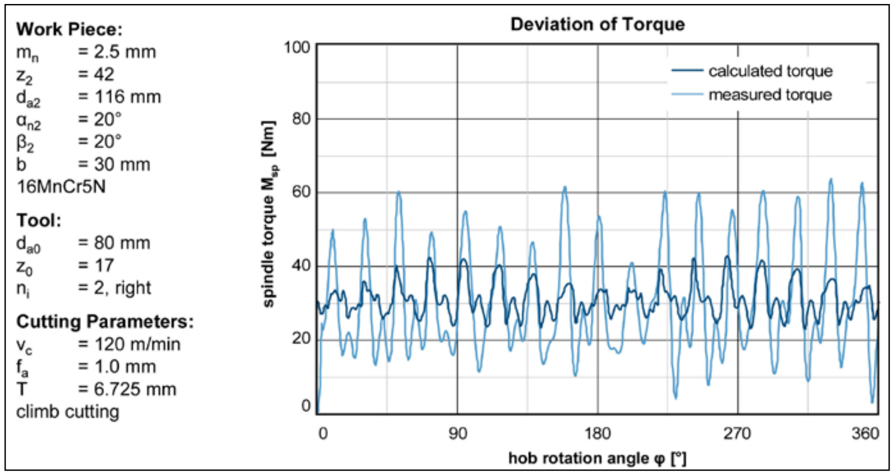

Figure 7—Comparison of calculated and measured torque: process example.

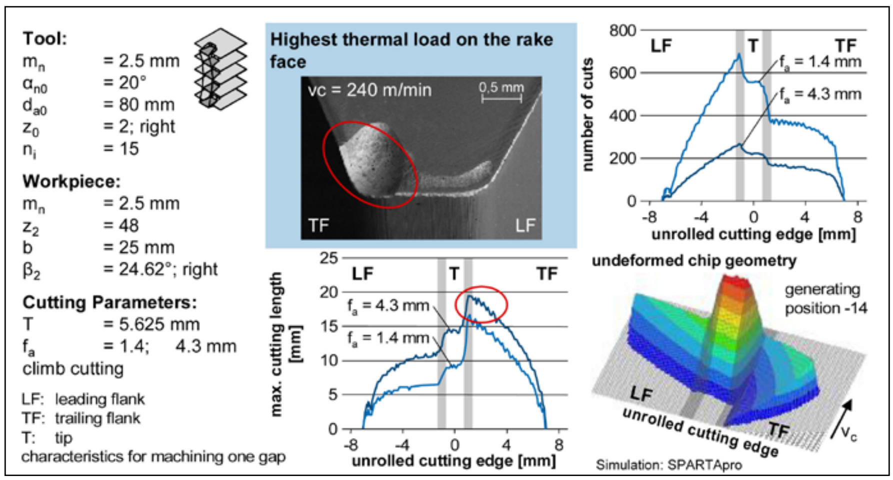

Figure 8—Chip-forming characteristics calculated by *SPARTApro*.

Further Benefit of Gear Hobbing Analysis

It has been demonstrated that manufacturing simulation provides economic analysis and force calculation capabilities. Nevertheless, it cannot replace the experienced engineer. With that in mind, following are two applications demonstrating the value-added benefit of manufacturing simulation when combined with process knowledge.

1. ***Optimization of wear behavior.*** This first example shows the primary advantage in use of the software. Two of the most desired goals of the manufacturing process are 1) low tool wear and 2) long tool life. The reality is that a combination of reasonable cutting parameters and medium tool life are most typical in industrial production. Especially in processes with complex kinematics and the attendant, various single-chip geometries, it is difficult to estimate the correct cutting parameters. In Figure 8 the chip-forming characteristics and an SEM photograph of a PM-HSS tool are shown. Results for the wear behavior are based on a hobbing trial with a single blade; note the high crater wear at the transition between the tip and trailing flank; note as well that the chip-forming characteristic for the maximum cutting length and the number of cuts over the unrolled cutting edge for varying axial feeds are presented. There are two peaks of particular interest: 1) the characteristic number of cuts, the peak at the transition from tip to leading flank; and 2) the characteristic maximum cutting length—the peak at the transition from tip to trailing flank. With a detailed view of the wear at the cutting edge, wear caused by thermal load is examined. The maximum cutting length characteristic correlates well with the wear occurrence. The result is that a decrease of the cutting length peak leads to optimized wear behavior, which can be achieved via another tool design; e.g., lower outside diameter, higher number of gashes. The general result is that no single, special characteristic can be taken to analyze a process. But together with the knowledge of wear behavior and the occurrence of wear, analysis can begin, in turn lead-

Figure 9—Surface defects.

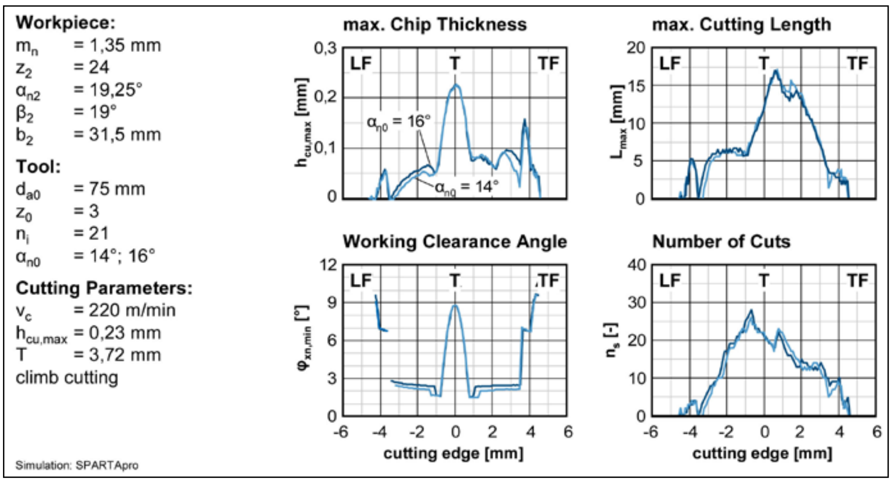

Figure 10—Changing of the chip geometry characteristics by modification of the pressure angle.

ing to a faster process optimization by reducing the number of trials.

2. *Software simulation to avoid surface defects.* The second example for the advanced use of manufacturing simulation is the topic of surface defects on spur gears. For specific gears the appearance of surface defects is observed (Fig. 9). Surface defects are smeared areas, scratches or welded-on chips. These defects are not acceptable for various reasons and therefore the parts are scrapped.

One reason for this is that surface defects—especially welded-on chips—cause a local raised stock. This decreases stability in subsequent manufacturing processes like gear shaving, grinding or honing.

A second reason is the minimization of local stock by pitting or similar occurrences of surface defects. Welded-on chips can rip out material by breaking out of the flank, and scratches can be so deep that the stock is reduced significantly. This reduction or increase in stock must be avoided when following manufacturing steps with a low stock, as in, for example, gear shaving. At minimum, such surface defects are a visual impairment; worst-case is that surface defects decrease process reliability.

One approach to avoiding such mistakes in tool and process design is manufacturing simulation. Figure 10 shows the result of a theoretical process analysis of the chip-forming characteristics of two different tool designs based on an industrial process. The examined gear reveals a surface defect characterized by smeared areas on the flank. The displayed chip-forming characteristics are the maximum chip thickness, cutting length, working clearance angle and number of cuts; each characteristic is plotted over the unrolled cutting edge.

The difference in tool design variation is the varied pressure angle, i.e.—$\alpha_{n0} = 14°$ and 16°. The initial tool design reflects pressure angle of $\alpha_{n0} = 14°$. After the occurrence of smeared areas on the flank with the starting pressure angle, a pressure angle correction is made. Production continues with a pressure angle of $\alpha_{n0} = 16°$, resulting in sufficient gear quality regarding surface defects.

By analyzing chip-forming characteristics, first approaches for optimization can begin. In the case at hand, chip thickness increases slightly at the leading flank with a higher pressure angle. Likewise, the cutting length and number of cuts increase somewhat in that area. The most significant change between the two tool designs is the higher-working clearance angle at both the leading and trailing flank. The working clearance angle—especially in that area—is higher where the part of the tooth gap with smeared areas is generated. The increase of the minimum working clearance angle is $\Delta\phi_{xn,min} \approx 0{,}3°$.

Based on this knowledge, the smeared areas can be attributed to crushed chips built up at the flank. A too-low clearance angle—combined with a higher temperature caused by higher friction at the chip-building zone—may lead to smeared areas at the flank. In final analysis, the space between clearance and workpiece flank is insufficient and so contact with chips on the workpiece flank may in fact be unavoidable.

For now, theoretical process analysis can only provide approaches addressing surface defects. But with a variation in the tool design characteristic, a change in chip-forming values can be shown that will assist in further research.

Summary and Conclusion

In this paper, the ability to attain through simulation cheaper, faster process development for gear hobbing is demonstrated. As such, the operating mode of manufacturing simulation software for gear hobbing is explained.

Following that was a discussion of tool design, process force calculation and usage of chip-forming characteristics. Using the tool optimization feature of the software showed that—with *existing* processes—tool and process optimization are possible, although the process can be more productive.

The method for force calculation was presented in detail, after which the calculated values were compared with measured values for the spindle torque; the comparison showed good correlation. The main deviation is caused by not accounting for the dynamic behavior of a real hobbing process within the calculation model.

To conclude, two examples of the main function of a manufacturing simulation were given.

In the first example, the tool wear behavior was compared with chip-forming characteristics. It could be shown that the software supports the engineer by designing gear hobbing processes that address both wear behavior and productivity.

In the second example, surface defects were examined. Also shown and demonstrated in this example were the existing support opportunities available for the process designer in response to challenges in the design process.

References

1. Brecher, C., C. Gorgels and T. Röthlingshofer. "Manufacturing Simulation of Beveloid Gears for Use in General Tooth Contact Analysis Software," *Production Engineering Research and Development 3,* 2009, pp. 103–109.
2. Weck, M., C. Brecher, F. Klocke and U. Rütjes. "Analysis of a Bevel Gear Cutting Process by Manufacturing Simulation," *Production Engineering–Research and Development XII,* 2005, pp. 107–110.
3. Gutmann, P. "Shear Force Computation with Hobs," Dissertation, RWTH Aachen, 1988.

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