New Potentials in Carbide Hobbing

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Abstract

To meet the future goals of higher productivity and lower production costs, the cutting speeds and feeds in modern gear hobbing applications have to increase further. In several cases, coated carbide tools have replaced the commonly used high speed steel (HSS) tools. Because this leads to production processes working on the upper limit of their performance capabilities, the tolerances for deviations from the optimum process settings are getting smaller. To deal with this situation, especially in carbide hobbing, all factors that have an influence on the hobbing process—like the workpiece geometry, the process parameters and especially the tool design—have to be taken into account if a high level of process performance is desired.

This essay will present a case study based on two industrial gearings. The investigations include the influence of coating, substrate, layout and edge preparation on tool performance.

In detail, fundamental baseline trials using "fly-cutter hobbing" will be presented. Besides several coating and substrate combinations, different tool layouts have also been tested. To verify the results, real hobbing trials under industrial production conditions have been carried out as well. Finally, the potential of modern simulation and calculation programs to optimize hobbing processes will be shown.

The report aims to give new impulses to the tool design of carbide hobs and to an optimized process setting.

Nomenclature

ρ_s	cutting edge roundness (µm)
l_{zn}	total resharpening stock (mm)
$\gamma_{0\,max}$	maximum hob lead angle (°)
$\delta_{x\,max}$	maximum scallop depth (µm)
t_h	machining time (min.)
φ_{as}	tip clearance angle (°)
ST	semi-topping
P	protuberance

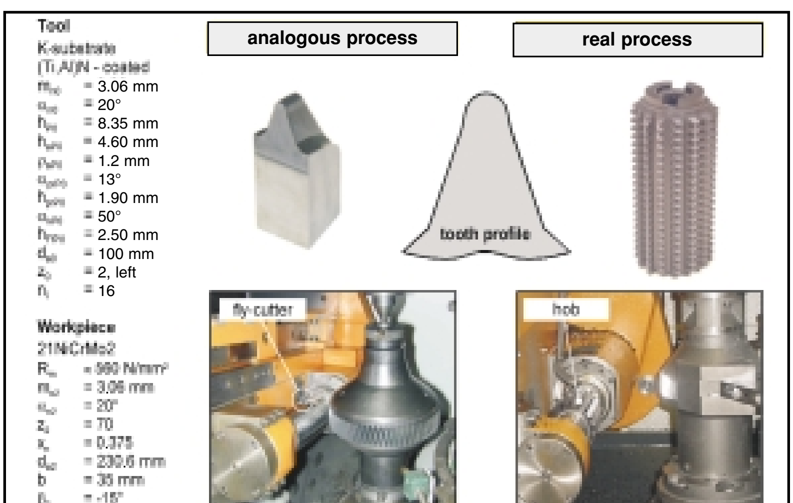

Figure 1—Analogous and real hobbing processes.

Introduction

To be competitive on the global market, gear manufacturers would like to increase their productivity and reduce their production costs. Therefore, cutting speeds and feed rates have increased significantly over the last years. Additionally, new substrate materials like carbide have been established in many hobbing applications to meet these demands.

Since the price for carbide tools is usually two to three times higher than the price of an HSS tool (Refs. 1–3), the cycle times have to be much smaller to realize economically efficient manufacturing processes. Furthermore, the consequently higher cutting parameters—in combination with the usually desired dry cutting conditions—increase the necessity of an optimized setting for the hobbing process (Ref. 4).

To assure a high level of productivity and reliable process performance, a total understanding of the gear cutting process and its complex structures becomes more and more important. Especially for carbide hobbing applications, all factors that have an influence on the process—like the machine, the workpiece geometry, the process strategy and particularly the tool design (Ref. 5)—have to be taken into account if a high level of optimization is desired.

In order to achieve widespread use of carbide hobs for dry gear cutting and to compete with the more commonly used HSS tools (Ref. 6), some further potentials for the optimization of the performance of the carbide hobs have to be used. Besides the continuous improvement of sintering and grinding technology, new developments in the fields of coatings and substrate materials, edge preparation (Ref. 7), decoating (Ref. 8) and simulation software (Ref. 9) might offer new possibilities.

In this paper, the potential of a modern tool design concerning coating, substrate, edge preparation and tool layout for carbide tools in dry hobbing applications will be presented. Additionally, the uses of new software tools for tool layout and process analysis will be shown.

An Analogous Process

To do more work and be cost effective, fundamental investigations have been carried out using an analogous process, "fly-cutter hobbing," to simulate the gear hobbing process. In this analogous process, the hob is replaced by just one tooth (see Fig. 1).

The figure shows the comparison of the tools and the set-ups for the analogous and the real hobbing trials. The interior of the machine with the fly-cutter collet and the workpiece clamping system for the analogous process can be seen on the left side. The hob and the machine setting for the real hobbing process are shown on the right. To assure the best possible comparability between the two kinds of trials, the design and the profile of the fly-cutter tooth and the hob teeth are identical.

To simulate the wear behavior of a shifted hob, the fly cutter is moved continuously through all generating positions of the corresponding hob. After each pass, the axial position of the fly cutter is increased by the amount of the axial feed of the simulated hobbing process. With this strategy, it is possible to create the same chip geometries as in real hobbing and to generate an identical gear.

Since the real hob is reduced to just one tooth, the tool costs are much lower and a smaller number of workpieces is needed to create the desired wear on the fly cutter. Furthermore, the analogous tools are easier to handle, and therefore a more detailed analysis of the wear phenomena is possible.

To prove the applicability of the tendencies discovered in the analogous trials, real hobbing trials under industrial production conditions have been carried out.

In this report, the investigations are based on two industrial gearings. The first one is a gear from a car gearbox, with a module of m_n = 2.5 mm, 38 teeth and a face width of 14 mm. The second one is a gear from a truck gearbox with a module of m_n = 3.06 mm, 70 teeth and a face width of 35 mm.

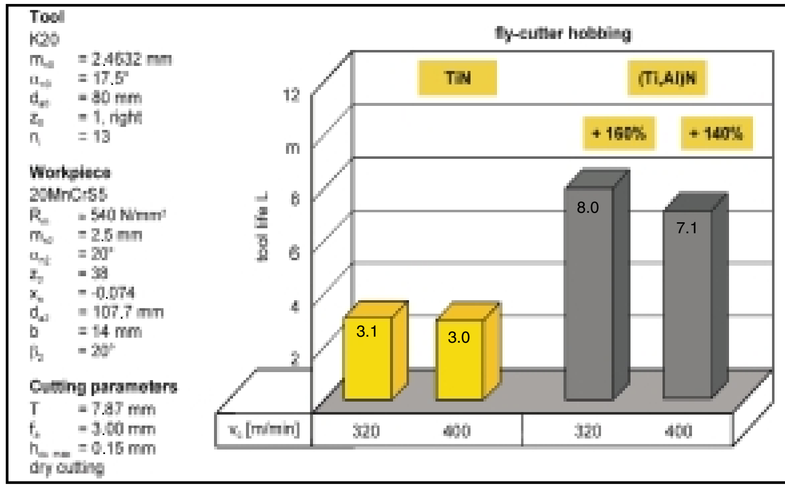

Figure 2—Advantages of (Ti,Al)N coatings in dry hobbing.

Optimization of the Coating System

Since dry cutting requires more tool performance than wet cutting concerning mechanical, thermal and chemical wear resistance, the choice of a suitable coating system is an important factor. Furthermore, the coating system, together with a suitable edge preparation, could be the component of the tool that is the easiest to change if all steps carried out previously, e.g. the grinding, are best adapted.

The TiN coating is still commonly used because of its relatively low price compared to its performance, especially in wet cutting operations. Figure 2 shows that these performance abilities will very quickly reach their limit if a dry cutting operation is desired.

During the investigations shown in the figure, the tool life of the TiN-coated tools was only about L = 3 meters. (A hob's tool life is often measured in meters per shifted hob tooth. The length is the total length of workpiece teeth cut by a hob tooth. In the analogous process, the fly-cutter hob has only one hob tooth, so its life is measured as simply 3 meters, for example.)

With the (Ti, Al)N-coated tools, up to L = 8 meters of tool life could be achieved. This means an improvement of the tool performance by a factor of 2–2.5. The reason for this significant difference is, on the one hand, the higher hardness of the (Ti,Al)N coating. While the TiN coating has a hardness of about 2,700 HV, the hardness of the (Ti,Al)N coating is about 3,600 HV (Ref. 10).

On the other hand, the higher thermal wear resistance is the most dominant factor. The maximum application temperature for the (Ti,Al)N coating is about 850°C, whereas this temperature for the TiN coating is only 450°C (Ref. 10). Therefore, the absence of the cooling lubricant in dry cutting leads to temperatures which the TiN

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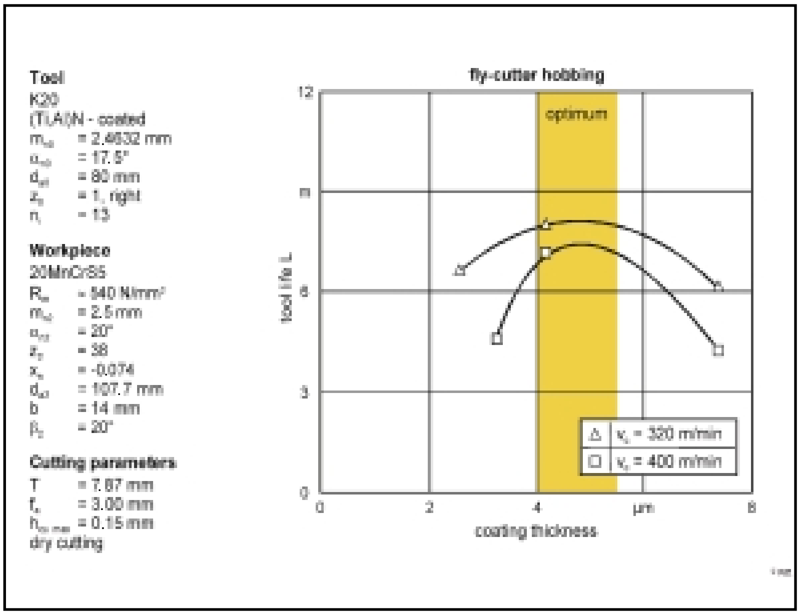

Figure 3—Tool life depending on the coating thickness.

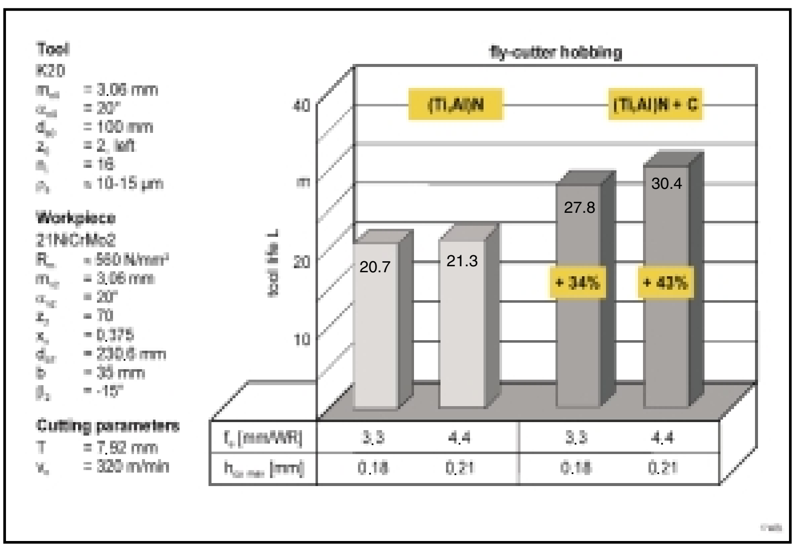

Figure 4—Influence of a lubricious top layer on the tool life.

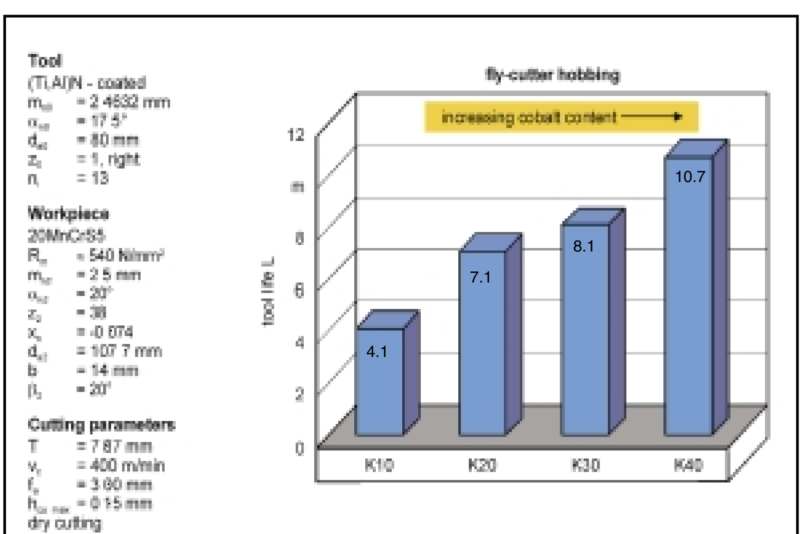

Figure 5—Tool life depending on the choice of the substrate.

coating is not able to resist. Here, (Ti,Al)N-based coating systems are the best solution.

Besides the type of coating, the coating thickness is of high importance. Figure 3 shows that optimum values for the coating thickness have been identified at 4–5 µm for carbide tools.

If a coating thickness of 5.5–6 µm is exceeded, the tool life decreases significantly. This can be explained by the fact that, on the one hand, a higher coating thickness will increase the abrasive wear resistance as well as the thermal isolation of the substrate. But, on the other hand, too much coating thickness will lead to a chipping of the coating because of increasing internal stresses.

Because of these results, this (Ti,Al)N-monolayer coating with a coating thickness of about 4 µm has been chosen as the standard coating system for all the following analogous and real hobbing trials.

As was stated before, it can also be seen that an increase of the cutting speed makes the tool life more sensitive to deviations from the optimum coating thickness. While the difference in the tool life for both cutting speeds is quite small in the area of the optimum thickness, the tool performance at higher or lower coating thicknesses is much worse.

To investigate the potential of coating combinations, a coating system based on the standard (Ti,Al)N-monolayer coating in combination with an additional lubricious top layer of amorphous carbon was tested. The hardness of the top layer is only about 800 HV (Ref. 10) and its thickness was about 1 µm. Because of the low hardness, the idea of this top layer is to reduce the friction and consequently the forces at the cutting edge (Ref. 11). Thus, the initial wear should be minimized and the progress of wear of the tool should be reduced. Both should lead to higher tool life.

Figure 4 shows a comparison between the tool life for the standard (Ti,Al)N coating and the coating with the additional top layer.

For the two different cutting parameters in both cases, the lubricious top layer leads to increases in the tool life of more than 30% and more than 40%. Therefore, the investigations prove that the hard/soft concept for coating systems can improve the tool performance not only in conventional cutting applications (Ref. 11) but also in hobbing applications.

As a conclusion, TiN coatings should be substituted with (Ti,Al)N-based coatings in dry hobbing applications. Because of the higher thermal stability of the (Ti,Al)N coating, much higher tool life can be achieved. The optimum area for the coating thickness is about 4–5 µm. To further improve the tool performance, lubricious top layers, e.g. made of amorphous carbon, offer additional benefits.

Choice of Substrate

Besides the choice of a suitable coating system, the substrate material is of special importance. The substrate must combine a high resistance against abrasive wear and a sufficient toughness to match the loads in interrupted cutting processes.

Therefore, Figure 5 shows a comparison of the tool life for different carbide substrate materials under constant cutting conditions. These investigations focused on WC/Co substrates (K-grades) because they are the most commonly used carbide materials today. The cobalt content differs between 6% (K10) and 12% (K40). The increasing Co content thereby corresponds with a decreasing hardness and an increasing toughness of the substrate.

The figure shows that with increasing cobalt content, higher tool life can be achieved. The tool life for the K40 is more than 2.5 times the value for the K10. Therefore, the toughness of the substrate seems to be more important than the hardness in this application. It also can be concluded that "softer" carbide materials are able to match the demands in dry hobbing applications. Furthermore, the higher toughness should help to improve the process reliability concerning cutting edge chipping.

Edge Preparation

Besides the continuous improvement of the coating systems and the carbide substrates, the tool preparation, especially the cutting edge treatment, might offer new benefits. Although the positive influences on the tool performance are well known from conventional cutting processes, like turning and milling, this technology is not very commonly used for gear hobs.

An adequate edge roundness is supposed to lead to improved tool life behavior and to offer better process reliability. Although there are some recommendations for an optimum edge radius for hobbing tools (Refs. 12–17), this technology is not very commonly used. This may be related to the uncertainty about the optimum radius values, the manufacturing of the rounding and the tool performance during hobbing.

Starting with the improvement of the cutting edge preparation, some trials were carried out to optimize the cutting edge roundness of fly cutters. An optimal edge roundness should reduce the initial wear of the fly cutters and should lead to a better tool life. To create the desired cutting edge roundness, the tools have been blasted with aluminum oxide.

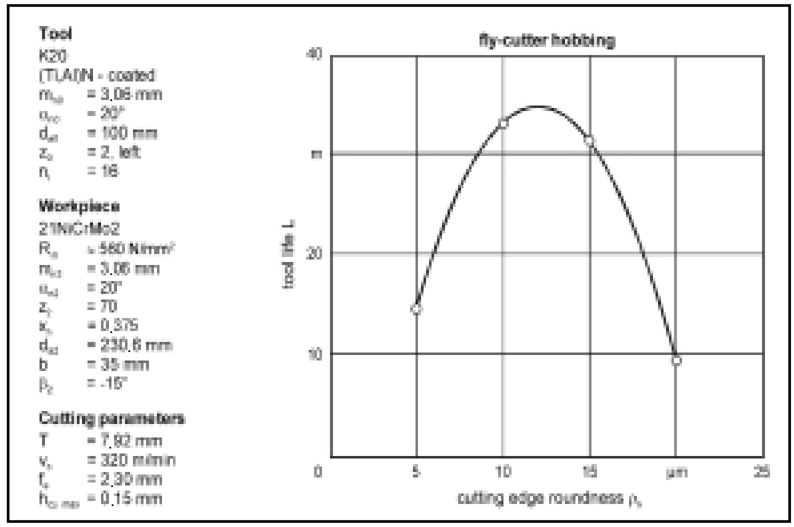

Figure 6—Tool life depending on the cutting edge roundness.

In some basic trials, the influence of different cutting edge radii on the tool life was investigated. Therefore, various edge radii in the range between 5 and 20 µm have been tested. All values for the radii are related to a measurement before coating. During these trials, the cutting speed and the axial feed with respect to the maximum head chip thickness have been kept constant.

The tool life depending on the cutting edge roundness is shown in Figure 6. It can be seen that the tool life can be improved significantly by an adequate rounding of the cutting edge.

For the investigated cutting conditions, the optimal cutting edge radius is in the range of $\rho_s \approx$ 10–15 µm. The increase in tool life compared to the almost untreated tool ($\rho_s \approx 5$ µm) can be more than 120%. Therefore, there is a large potential benefit in the edge treatment for this application.

If the cutting edge radius exceeds values of $\rho_s \approx 15$ µm, the tool life decreases drastically. It is assumed that the decrease of the tool life is related to the rise of the cutting forces that will increase the stresses in the substrate and the coating. The cutting edge is no longer sharp enough to cut the high number of relatively small chips that typically occur in hobbing processes.

Too small of a cutting edge radius leads to very sharp cutting edges that have to withstand much higher stresses during cutting than rounded ones (Ref. 18). In this case, the coating or the substrate can be overloaded and a chipping of the cutting edge occurs. For the fly cutters with an optimized

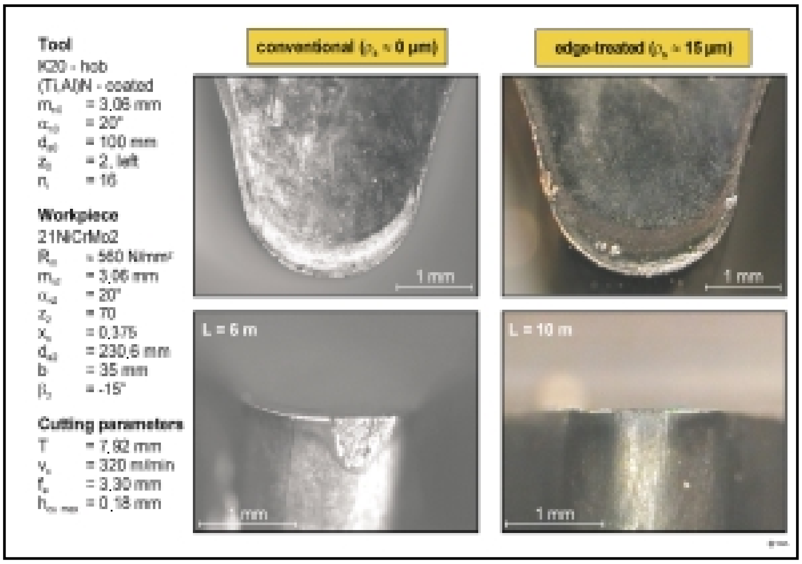

Figure 7—Wear behavior depending on the edge treatment.

edge preparation, the protective effect of the coating is greater for the substrate than it is if the cutting edge radius were too small (Ref. 19).

As a conclusion, an adequate cutting edge roundness will increase the tool life by protecting the cutting edge and coating against chipping. Through an optimized edge radius, the usually sharp cutting edge does not crack any more during the first cuts. Therefore, the coating fulfills its protective function on the cutting edge for a longer time. Additionally, the edge becomes more resistant to chipping. Since the coating protects the substrate material against abrasive and adhesive wear, this edge treatment should lead to better tool performance.

Based on these results, verification tests through real hobbing trials have been carried out under industrial production conditions on the same gearing. The test hobs have been used untreated (conventional) and prepared with a specific cutting edge roundness in the area of $\rho_s \approx 15$ µm (see Fig. 7).

In the first real hobbing trials, the hobs without a special edge treatment were used. The cutting edge roundness was in the area of $\rho_s \approx 0$–3 µm before coating. After 6 meters of tool life, chipping of the cutting edge on the tip of only some of the hob teeth could be found (see Fig. 7's left photographs). The chipping happened unexpectedly because after 5 meters, there was only initial wear. It is well known that for carbide hobs, the substrate tends to chip when it is overloaded because of lower toughness and less ductility compared with HSS (Ref. 20). Therefore, the process reliability which is very necessary for mass production was not achieved.

Based on the good results from the analogous trials, the next trials were carried out with edge treated hobs. Under the same cutting conditions as in the first real hobbing trials, the tool performance was significantly better. No chipping of the coating with respect to the substrate occurred at the tip of the hob teeth, and the tool life was much better, as shown in Figure 7's right photographs.

The trial was stopped after 10 meters of tool life because the maximum wear width exceeded $VB_{max} = 0.15$ mm. At that time, there was only a little wear on the tip, and a characteristic wear in the protuberance of the leading flank could be seen on all teeth in the shifting area. So not only the tool life, but also the process reliability was significantly improved. In this case (higher cutting parameters), the edge preparation has led to an improvement in tool life of about 60%. The differences in tool life between the analogous and the real hobbing trials can be explained by the ideal laboratory conditions and the lower dynamic effects because of the lower cutting forces in the analogous process.

As a conclusion, during the real hobbing trials, the transferability of the results from the analogous process to the real process concerning the wear phenomenon was quite good. Although the tool life in real hobbing was only about 30–40% of the tool life in the fly-cutter hobbing tests, the tendencies were comparable and the tool performance was still at a very high level.

Software Support

Besides the choice of an adequate coating system, substrate material or edge preparation, the tool design is one of the most important criteria to assure both satisfactory tool life and sufficient cost effectiveness. The tool design has to take into account the cycle time, the machining costs and the tool costs.

Especially in gear hobbing, the tool design is very difficult because of the high number of parameters. On the one hand, the workpiece geometry and the technical data of the machine are fixed conditions. On the other hand, the technological parameters—like cutting speed and axial feed with respect to maximum head chip thickness—have to be chosen correctly. Finally, maximum scallop depth or maximum cycle time are boundary conditions that have to be fulfilled by a proper tool design. Taking into account that the hob itself has a high number of degrees of freedom, e.g. outside diameter, number of gashes, number of threads, usable length, etc., the optimum hob design becomes a multi-dimensional problem.

Since this problem usually cannot be solved by hand, adequate software programs have to support the tool designer. This was the motivation for WZL to create its own software tool, *Hobbit*. The program is able to calculate by boundary iteration the optimum hob design out of a matrix of thousands of possible tool designs. Thus, the user only has to enter his boundary conditions concerning machine and workpiece data as well as desired cutting speeds and chip thickness. Then, the program calculates all possible tool designs that match the declared circumstances and assesses them.

To illustrate the potential of such software systems, Figure 8 shows two calculations for an improved hob design. The first case is an HSS tool, the second one a carbide hob. Analogous trials have been carried out with both tool systems, so that the specified cutting parameters will result in approximately equal tool life for the two basic tool designs, which are shaded in gray. As shown in the figure, both hobs are not optimal designs for their cycle time.

Therefore, certain boundary conditions were declared which are documented on Figure 8's left side. Afterwards, the calculation was done, and the best results are presented in the chart on the right side of Figure 8. It can be seen that in both cases, the main times could be decreased significantly. On top of each chart, the fastest tool designs are shown. Furthermore, the best designs with relatively small outside diameter (lower tool cost) and the best designs with a higher number of starts are presented.

Figure 8 expresses two statements very clearly. The first is that, because of their totally different cutting parameters, HSS and carbide tools for the same gear must have a different geometry. While the HSS hob is usually used at medium cutting speeds and high chip thickness, the carbide hob is used at high cutting speeds and lower chip thickness. Therefore, the tool layout has to be different.

The second statement is that, although the carbide tool will be run at very high cutting speeds, the HSS tool will almost reach the same cycle time because of the higher achievable chip thickness. Since the carbide hob usually has to be faster than the HSS hob to be cost efficient, new developments have to provide new benefits to realize improved cutting speeds and also higher allowable chip thickness.

As a conclusion, software tools, like *Hobbit*, have to allow users to find the best tool design for their boundary conditions out of a huge number of possible layouts. Furthermore, the user is able to get quantitative information about which tool concept (HSS or carbide) might be the best for his application.

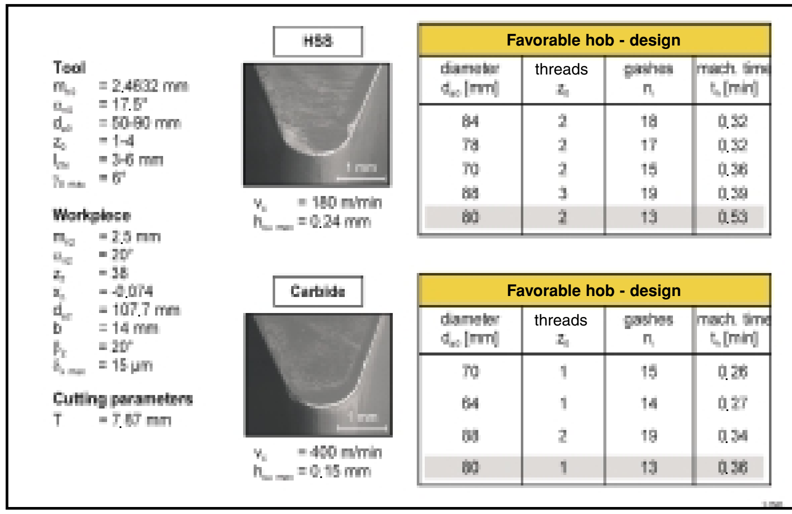

Figure 8—Example for a machining time-optimized hob.

Even if an optimized tool design has been identified, the hobbing process still is very complex and hard to understand. Because of the complicated generating kinematics in combination with a complex tool geometry, the chip geometries in hobbing processes are not easy to calculate. Since the chip geometry correlates with the loads during cutting and the wear of the tool, it is helpful to know the existing contact conditions. Therefore, WZL has developed another software program, named *Sparta*, which is able not only to simulate the hobbing process and calculate the chip geometries but also to calculate characteristic process values to quantify the process.

Starting with the different chip geometries, the program illustrates the complex shape of the undeformed chips, as can be seen in Figure 9. Here, a three-flank chip geometry typical for hobbing processes is shown.

The X-axis shows the position on the cutting edge, and the Y-axis represents the cutting direction. The chip thickness is illustrated by the height (Z-axis) of the diagram. It can be seen very clearly that every point of the cutting edge has to withstand a different type of load. This makes the hobbing process so difficult to optimize because one coating/substrate system has to match all these different demands.

However, several characteristic values—e.g. the distribution of the chip thickness or the contact length, the effective clearance angles, the chip volumes or the dynamic contact conditions

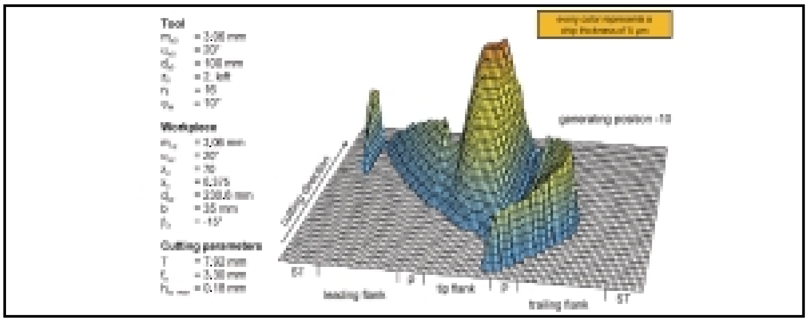

Figure 9—3-D illustration of a simulated chip's geometry.

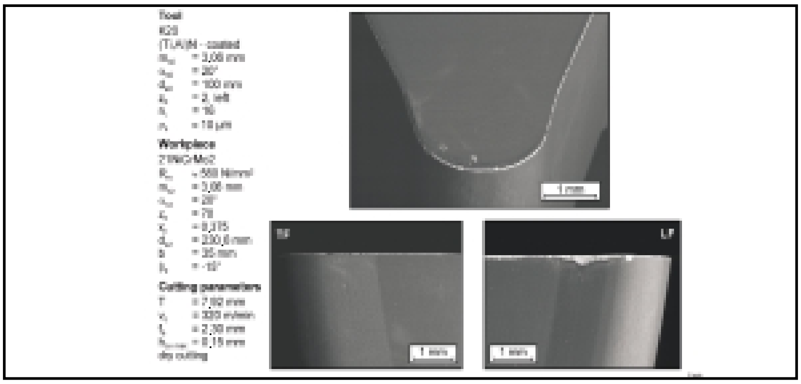

Figure 10—Typical wear on a fly cutter.

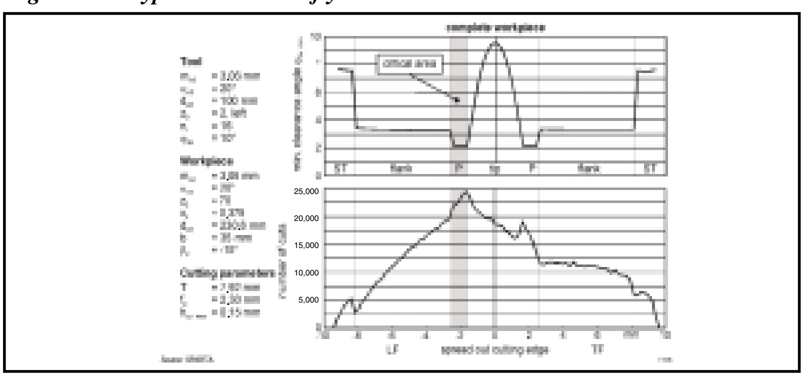

Figure 11—Analysis of two important parameters in hobbing.

between hob and workpiece—can be calculated out of these data for the chip geometries.

These characteristic values can help the user get a deeper insight into his process than just judging it by the maximum head chip thickness. This additional information can be used, on the one hand, to support a better process setting or tool design and, on the other hand, to analyze processes and tools which have not performed satisfactorily.

To give a practical example, Figure 10 shows the typical wear of a fly cutter for the considered gearing.

While the wear on the trailing flank is very small, the wear on the leading flank in the area of the protuberance is critical and sets the limit for the tool life. Since analysis of the chip geometries did not lead to concrete ideas about this phenomenon, additional calculations concerning the characteristic values have been carried out.

Two of those values are shown in Figure 11 along the cutting edge to give first hints to explain the observed wear.

Figure 11's upper part shows the minimal effective clearance angles, while its lower part shows the number of cuts. In this context, the number of cuts means the number of chips during the cutting of a whole workpiece in which the considered cutting edge section is involved. On the left side of each diagram, the leading flank is shown and the wear critical area of the protuberance is marked in gray.

It can be seen that wear was relatively small in the area of the protuberances with effective clearance angles about 2°. This is related to the lower pressure angle of only 13° compared to the pressure angle of 20° on the flanks. These low clearance angles lead to a bigger contact zone between the workpiece and the tool in this area. The bigger zone consequently results in higher friction and thus higher temperatures and abrasive wear.

Furthermore, the number of cuts is significantly higher on the leading flank than on the trailing flank, especially in the area of the protuberance. Therefore, the corresponding cutting edge section has to penetrate the workpiece more often. The combination of these two effects explains the wear phenomenon.

Improvements might be possible by increasing the effective clearance angles at this point, for example, by choosing a bigger tip clearance angle or, if possible, a profile modification with a higher pressure angle in the protuberance.

As a conclusion, both software systems can help the user in better designing, analyzing and understanding the challenging hobbing process. Such programs will give valuable support to create technologically and economically efficient processes, especially in the field of dry hobbing with coated carbide tools because of the smaller windows for optimal process settings.

Conclusions

There are still large potentials in the field of dry hobbing with coated carbide tools. This includes the further optimization of the coating system, the substrate material, defined edge preparation and tool design. The process reliability of the carbide hobs should especially be a key aspect because these tools are usually applied in mass production.

In this paper, the investigations were based on different (Ti,Al)N-based coating systems because TiN coatings are not suitable in dry hobbing applications. Concerning tool life, the coating thickness should not exceed 4–5 µm. Lubricious top layers, e.g. amorphous carbon, can lead to an increase in tool life by 30–40%.

The trials on different carbide materials proved that the requirements of a dry hobbing process with regard to substrate are concerned primarily with toughness, not hardness. Therefore, substrates with higher cobalt content showed better tool life.

Furthermore, investigations to determine a suitable range for cutting edge rounding and its potential concerning the tool life of carbide hobs were performed. The results show that a cutting edge roundness of $\rho_s \approx$ 10–15 µm improves the wear behavior of the carbide tools in fly-cutter hobbing significantly. The results from the analogous process were verified by real process trials carried out under conditions of industrial production. Although the tool life was much smaller in real hobbing, the better tool life and higher process reliability could be achieved.

Finally, software tools, like *Hobbit* and *Sparta*, have been presented to point out their ability to support the user in his efforts to determine optimal tool designs and process settings as well as to achieve a better process understanding. Additionally, the software tool *Sparta* should also help to analyze and give hints to improve insufficient tool or process performances. Especially in the field of dry hobbing with carbide tools, because of the smaller windows of the optimal process settings, such programs will give valuable support to create technologically and economically efficient processes.

Only with an optimized tool design with regard to substrate, coating and layout, one will have the chance to run carbide hobs with very high speeds and feeds.

Therefore, it can be summarized that carbide hobbing is still a challenge. But there are also new benefits to using the high potential of this substrate material, especially since HSS materials seem to have reached their performance limits.

Systematic research activities in combination with a consequent software development will be necessary to support the end user in his efforts to meet future demands.

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