Reducing Production Costs in Cylindrical Gear Hobbing and Shaping

Prof. Dr.-Ing. Fritz Klocke and Dipl.-Ing. Claus Kobialka

Introduction

Increased productivity in roughing operations for gear cutting depends mainly on lower production costs in the hobbing process. In addition, certain gears can be manufactured by shaping, which also needs to be taken into account in the search for a more cost-effective form of production.

One way of increasing the productivity of the hobbing process is to raise cutting speed. Another potential strategy for reducing costs and thus increasing productivity is to eliminate the use of cooling lubricants. High-speed hobbing is now understood almost exclusively as dry machining with carbide tools at cutting speeds in excess of 300 m/min (Ref. 2). Together with the introduction of such new technology, productivity can also be enhanced through the use of innovative high speed steel cutting tools.

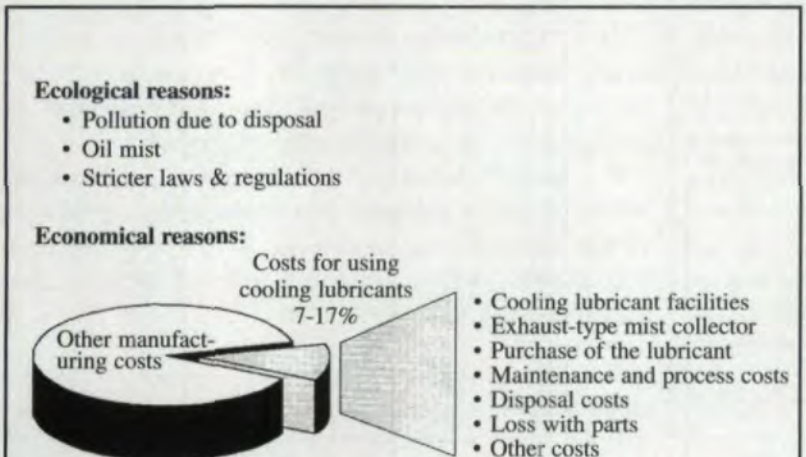

Fig. 1—Reasons for eliminating cooling lubricants (Ref. 7).

The potential of each of these rationalization measures (use of HSS and carbide tools) is discussed below for the case of hobbing. This information is supplemented by an indication of the technological limits and process reliability of specific applications. Finally, because certain gear cutting applications require the use of shaping, a lubricant-free option for manufacturing internal gears is indicated.

In order to make a comprehensive and reliable assessment of the required productivity, the report first analyzes wear-relevant mechanisms in hobbing and shaping operations. Various tool materials and coatings are investigated at differing cutting parameters in relation to the special stresses encountered in machining at high specific removal rates and differing machining conditions. The objective is to demonstrate both the performance potential and the current limits for existing tool systems. Finally, the tool lives determined in the tests are assessed.

State of the Art

Economic and technological significance of cooling lubricants. Modern cooling lubricant systems make a decisive contribution to the high level of performance of numerous production processes by performing their main tasks of cooling and lubricating the contact point and by transporting chips away from it. Despite their great technological importance, they have been the target of increasing criticism in recent years, stimulated by rising operational and disposal costs due to stricter environmental regulations.

Consideration of these problems has made many users aware of the costs involved in the use of cooling lubricants. A recognition that part-related costs for the cooling lubricant system may be several times higher than tool costs has led to a reevaluation of cooling lubricant use in many companies. The logical consequence is a demand for solutions which reduce or eliminate the use of cooling lubricants and hence the associated costs (Fig. 1, Ref. 1).

Especially in terms of economic criteria, purchase costs for the cooling lubricant must be seen in association with investment costs for a cooling lubricant unit. Cooling lubricants also need maintenance and disposal (Refs. 2-6). Losses on parts and chips, vaporization and evaporation likewise contribute to lubricant consumption. Overall, costs to the company associated with the use of cooling lubricants represent an increasing economic burden and amount to some 7% to 17% of proportional part costs in the automotive industry. Calculations for gear making indicated that between 16% and 30% of hobbing costs result from the use of cooling lubricants. In view of restrictive environmental legislation reshaping regulations for the disposal and reutilization of special wastes, it may be anticipated that lubricant-related costs will rise even further.

Potential of new or optimized gear cutting tools. Together with cost reductions through the elimination of cooling lubricants, it is possible to increase productivity by using higher cutting parameters. Apart from innovative tool materials, tool coating with hard, thin films should not be neglected in this respect.

PVD coating technology in particular opens the way to improved cutting parameters as compared to the use of uncoated tools in machining technology. Coating technology has consequently undergone rapid development in recent years. The results of this development include new hard, thin-film systems that can be deposited with consistent results on tools of any degree of complexity. The effect has been to make the use of fully coated complex tools, especially hobs, state-of-the-art technology (Ref. 8).

Current commercial systems include TiN, Ti(C,N), (Ti,Al)N and other hard, thin films based on the elements titanium and aluminum, which can be deposited either on high-speed steel or on carbide. Because of their wide availability and differentiated mechanical properties, TiN and (Ti,Al)N coating systems will be considered in greater detail below.

Machining Tests

Tool wear behavior and tool lives for hobbing operations with HSS tools using cooling lubricants. All tests were carried out with a maximum crest chip thickness according to Hoffmeister (Ref. 9) of $h_{cu\ max} = 0.18$ mm. Cutting speed was increased in 30 m/min stages from $v_c = 90$ m/min to $v_c = 180$ m/min. The width of wear land versus tool life for cutting speeds from $v_c = 90$ m/min and $v_c = 180$ m/min shown in Figure 2 are representative for all analyzed cutting parameters.

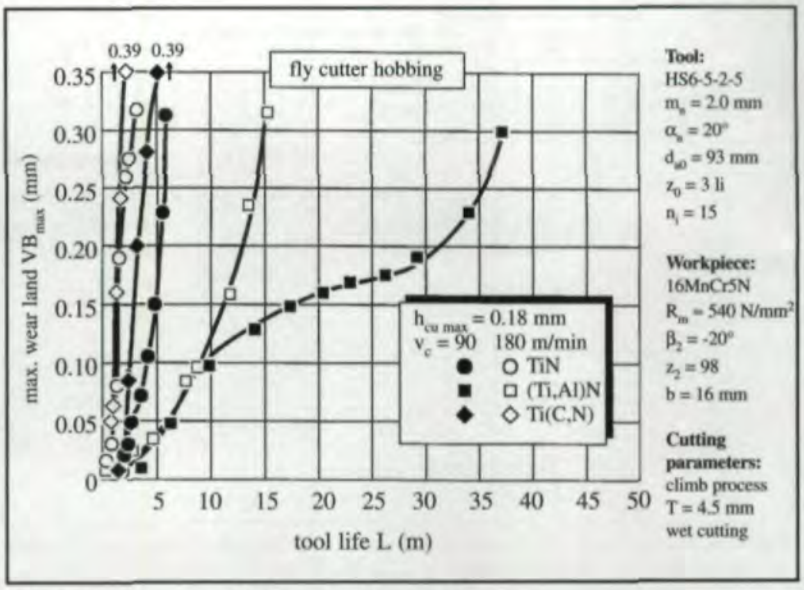

Fig. 2—Wear curve at different cutting speeds.

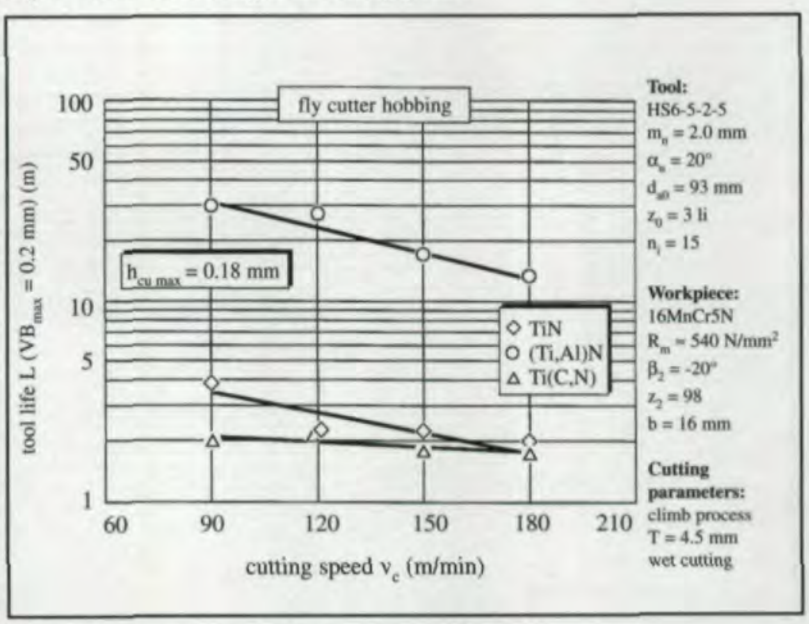

Fig. 3—Comparative tool life as a function of cutting speed.

Initially, the tool life criterion aimed at was a maximum face wear of $VB_{max} = 0.3$ mm. The measured wear curves indicate, however, that a tool life criterion of $VB_{max} = 0.2$ mm is more effective in reducing progressive wear (Fig. 2). The tool life comparison is therefore presented for a tool life criterion of $VB_{max} = 0.2$ mm (Fig. 3).

Shorter tool life was realized as cutting speed was increased from $v_c = 90$ to $v_c = 180$ m/min, irrespective of the coating system. The reason for this is the increased thermal stress on the tool caused by the high relative velocities of the tribological partners and the corresponding

Prof. Dr.-Ing. Fritz Klocke
is Director of the Chair of Manufacturing Technology at the Institute for Machine Tools and Production Engineering (WZL) of the Aachen University of Technology (RWTH Aachen) and Director of the Fraunhofer-Institute of Production Technology (FhG-IPT), Aachen.

Dipl.-Ing. Claus Kobialka
is a research engineer working in the field of gear manufacturing at the Chair of Manufacturing Technology at WZL-RWTH Aachen.

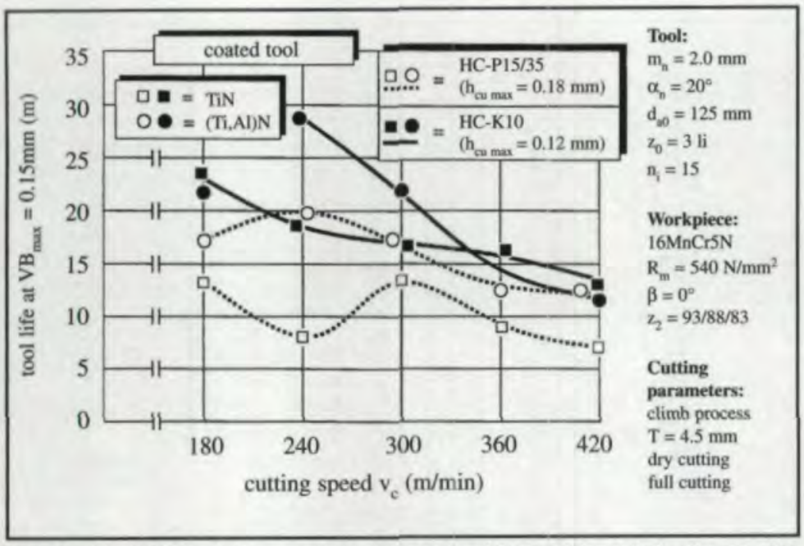

Fig. 4—Tool life for fully coated carbide tools with tool-life-optimized crest chip thicknesses and a maximum width of wear land VB_{max} = 0.15 mm.

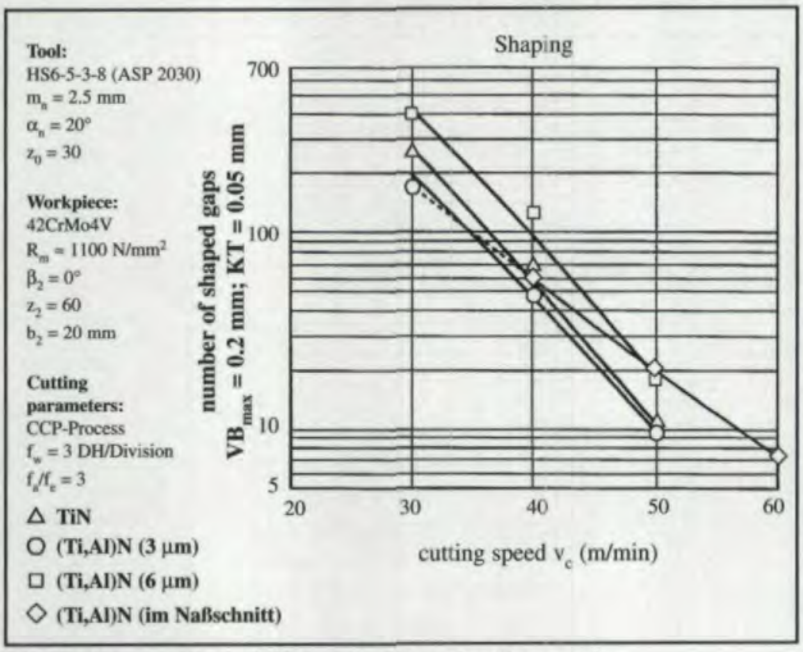

Fig. 5—Comparative tool life as a function of cutting speed.

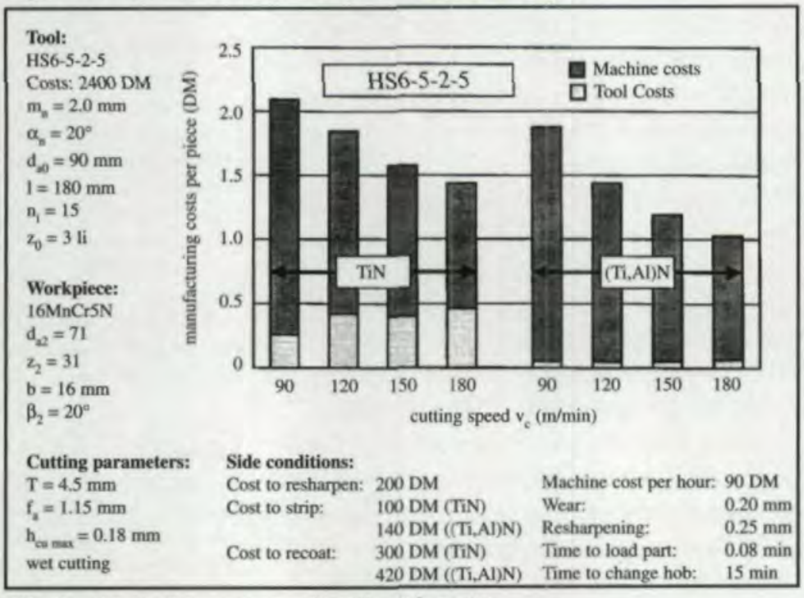

Fig. 6—Production costs as a function of coating.

increase in frictional power. The relatively long tool life seen at a cutting speed of v_c = 180 m/min is nevertheless surprising. The exceptional wear resistance of HSS tools at high cutting speeds may be attributed partly to the insulating effects of the hard, thin film and partly to the shortened chip length in hobbing a workpiece with a width of 16 mm. A calculation of the maximum chip length according to Hoffmeister (Ref. 9) indicates chip lengths of 19.5 to 21.4 mm as a function of the feed rate. This maximum chip length is not reached, due to the workpiece of 16 mm to be machined helically with β = 20°. The thermal stress on the high-speed steel during hobbing of a narrow gear is lower than for solid hobbing of a broader gear.

Whereas tool lives achieved with (Ti,Al)N-coated tools were on average higher than those for TiN-coated tools by a factor of roughly 7, the tool lives of Ti(C,N)-coated tools were even shorter. Almost irrespective of cutting speeds, the maximum attainable tool life for Ti(C,N)-coated tools is approximately 2 m.

Dry hobbing with carbide tools. Carbide hobs have been available on the tool market as an alternative to HSS hobs for a number of years and have been used increasingly in series production since the introduction of hobbing machines designed for dry cutting. Studies of the wear behavior of coated carbide hobs reveal face wear versus tool life trends identical with those already shown for HSS tools in Figure 2.

On the basis of thermal emissions generated by the machining process and proportional to the maximum width of wear land, industry uses carbide tools up to a maximum wear land width of VB_{max} = 0.15 mm. At larger wear land widths, the generated heat may also affect the fixture during a dry cutting operation, leading to fixing problems for new blanks.

Studies on coated carbide tools have shown that maximum tool lives consistent with reliable process behavior are achieved with carbides in applications group P15/35 at a maximum crest chip thickness of $h_{cu\ max}$ = 0.18 mm. Axial feeds in which a maximum crest chip thickness of $h_{cu\ max}$ = 0.12 mm are realized are advantageous in the case of applications group K10 carbides.

Against this background, a comparison of test results for wear land width VB_{max} = 0.15 mm and optimum substrate-dependent crest chip thicknesses with HC-P15/35 and HC-K10 carbides is of interest (Fig. 4).

Longer tool lives are achieved with (Ti,Al)N-coated tools than with TiN-coated tools on identical substrates. In the range of cutting speeds of interest for dry cutting ($v_c \geq 300$ m/min), longer tool lives are achieved with HC-K10 carbide substrates than with HC-P15/35 equivalents. The number of feed markings on a tooth flank must, however, be taken into account separately for each specific application in terms of subsequent production processes for a gear. If, for example, a subsequent shaving process is envisaged in the process chain, values may fall neither above nor below a range of feed markings on the tooth flank, and this fact must be taken into account in selecting the tool substrate or geometry.

Tool lives in shaping. Shaping comes second only to hobbing as a significant production process for the generation of cylindrical parts. Coated HSS tools are mainly used for shaping, because mechanical machine concepts allow high cutting speeds to only a limited extent, and the use of cost-intensive carbide tools for soft cutting does not appear cost-effective. Shaping is used wherever the penetration resulting from the tool and workpiece geometries cannot be generated by a hob. A characteristic example is the generation of internal gear teeth.

Figure 5 summarizes the tool lives that can be achieved with variously coated tools as a function of cutting speed for the case of highly-tempered internal gears. The tool life curves can be approximated very closely by straight lines in the logarithmic presentation.

Tool lives vary inversely with rising cutting speed with all coating systems in the tests. This phenomenon may be attributed to the sharply increasing thermal stress on the tool as the cutting speed rises. Only very slight differences in tool life are observed for all coating systems in the high cutting-speed range. The wear behavior of the tools may be regarded as process-reliable in all the cutting parameter fields shown in the figure.

Of interest is the significant lengthening of tool life when the coating thickness is increased. Doubling the film thickness from 3 µm to 6 µm virtually doubles the number of gaps which can be shaped. Approximately 380 gaps were machined at v_c = 30 m/min, corresponding to a tool life length of roughly 7.5 m. In the logarithmic presentation, increasing the coating thickness leads to a parallel shift in the wear curves.

An increase in tool life of some 20 machined gaps per tool tooth as compared to dry cutting methods is achieved by using cooling lubricant. The tool life curve also climbs less steeply when cooling lubricant is used.

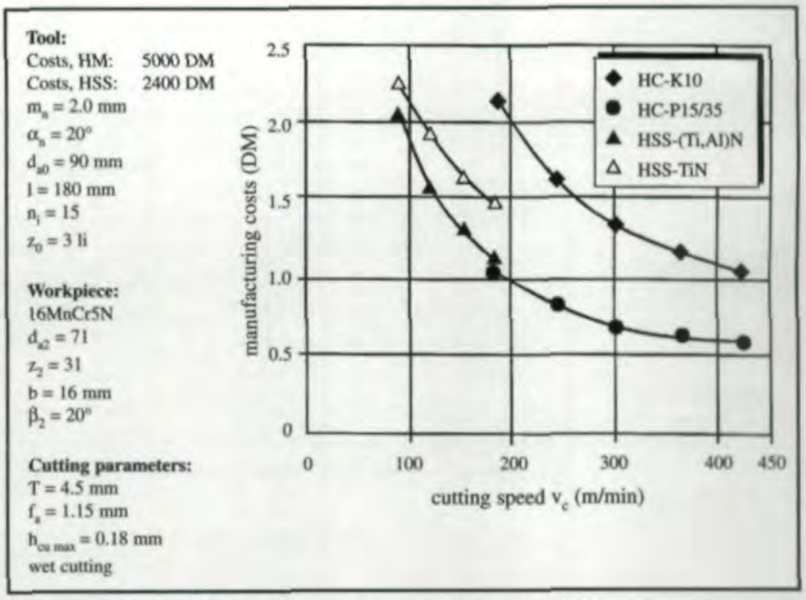

Fig. 7—Part costs in hobbing as a function of cutting speed.

The effects of the selected feed rate on the wear behavior of the tools will not be discussed in greater detail. It may, however, be stated that a reduction in tool life results from an increase in the feed rate, irrespective of the coating. The decrease in tool life is, however, smaller than from an increase in cutting speed. These data have already been described (Ref. 10) for the shaping of 16MnCr5 steel cylindrical gears.

Economic Analysis of Tool Lives

A knowledge of attainable tool life is not in itself sufficient to justify the use of a specific tool system. Of greater interest for the industrial user is a knowledge of part-related production costs. In this section, the technological test results presented above are analyzed for a fictional case to determine the production costs resulting from the tool life.

A machine hourly rate of 90 DM (approximately $60) was assumed for hobbing or shaping operations, rising to 100 DM (approximately $65) per hour if cooling lubricant is used. The tool costs presented in the following figures are based on current cost structures for medium-sized tool batches of roughly 10 to 20 tool inserts per month. (Ti,Al)N coatings are more expensive than TiN coatings, and a cost supplement of 40% was calculated for coating and stripping.

Hobbing. Analysis of the production costs per finished gear using HSS tools indicates lower costs at higher cutting speeds both for TiN- and (Ti,Al)N-coated tools (Fig. 6). The analysis is based on the constraints described in the figure and on the tool lives determined as a function of the coating system and cutting parameters for the case of fly cutter hobbing.

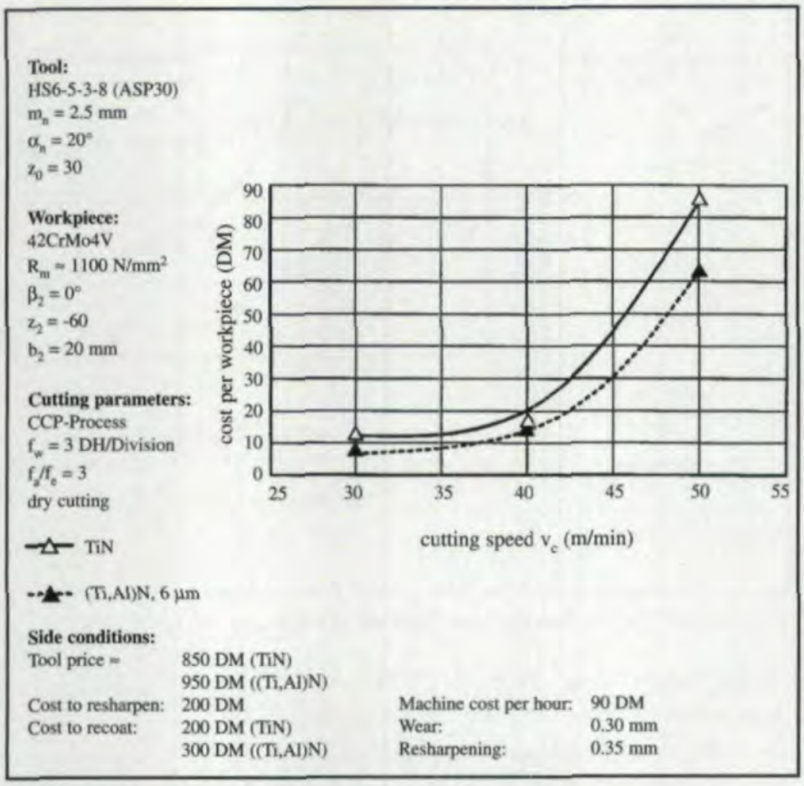

Fig. 8—Part costs for shaping as a function of cutting speed.

The pure production costs take into account the hourly machine rate, the tool purchase costs and the tool conditioning costs (regrinding, stripping and recoating).

Two cost trends emerge with rising cutting speed. On the one hand, the machine costs per part diminish, since more pieces are produced over the same period when the cutting speed is increased. On the other hand, the tool costs per part increase since tool lives shorten as the cutting speed rises, and fewer pieces are produced for each regrinding of the tool. Cumulatively, however, the decrease in machine costs outweighs the increase in tool costs.

Taking hobbing with TiN-coated HSS tools at a cutting speed of $v_c = 90$ m/min as a basis, an increase in cutting speed to 180 m/min results in a cost saving of roughly 15%. This benefit results from the 41% fall in machine costs, although tool costs rise by 100%.

The tool cost component of production costs per part for hobbing with (Ti,Al)N-coated tools at a cutting speed of $v_c = 90$ m/min amounts to no more than 3%; at $v_c = 180$ m/min, the corresponding figure is 11%. This means that potential cost reductions should be sought mainly by shortening machining times and diminishing machine costs, and less by reducing tool costs. If part quality permits an increase in the feed rate from $f_a = 3$ mm to $f_a = 5$ mm, the resulting increase in maximum crest chip thickness $h_{cu\,max}$ from 0.18 mm to 0.24 mm may be used to exploit an additional cost reduction potential through low tool costs and machine costs.

Taking hobbing with TiN-coated tools at a cutting speed of $v_c = 120$ m/min as standard practice in this module range, there is a saving in production costs per part of roughly 47% with (Ti,Al)N-coated HSS hobs and a cutting speed of 180 m/min.

The influence of cutting speed on the production costs determined for HSS tools in the test is also applicable to carbide tools. The basis of calculation is a 10% lower machine hourly rate for dry as opposed to wet cutting. This is due to the elimination of cooling lubricant costs as discussed in Figure 1. Because TiN-coated carbide tools are less expensive than (Ti,Al)N-coated tools, but also attain shorter tool lives, an analysis of the results shown in Figure 4 established no significant difference in production costs between TiN- and (Ti,Al)N-coated tools at the same cutting speed (Fig. 7).

The analysis was based on a 40% higher cost component for coating with (Ti,Al)N as opposed to TiN. In the future, when (Ti,Al)N coatings are in more widespread use, costs are likely to be more favorable.

At the same cutting parameters, a reduction in production costs may be expected simply from the increase in cutting speed (see Fig. 7) because machine costs are such a dominant factor. The increase in tool costs with rising cutting speed is marginal compared with the potential machine cost savings.

The same result is evident if production costs for HSS tools and K10 carbides are compared. Owing to the small chip thicknesses, which can be achieved with HC-K10, a higher gear-cutting rate is possible at a lower feed rate and identical production costs of roughly 1.10 DM per part, because the cutting speed is more than doubled from 180 m/min to 420 m/min. At the same time, a lower feed rate improves part quality due to the lower kinematic roughness.

Shaping. Unlike hobbing, production costs for the shaping of highly-tempered work materials are dominated by disproportionate tool wear and the resulting tool cost component. Coating costs are again assumed to be 40% higher for (Ti,Al)N as opposed to TiN. Because of the technological advantages of a (Ti,Al)N coating, however, a reduction of between 25% and 50% in production costs is feasible. The higher coating costs are outweighed by the longer tool lives (Fig. 8).

Conclusion

It has been shown that improved performance and cost savings of roughly 50% can be achieved with coated HSS tools in a wet cut on conventional hobbing machines if (Ti,Al)N coatings are used and removal rates are adapted accordingly.

The same trends have been demonstrated for the dry cutting of highly-tempered internal gears using a shaping process with HSS tools. Although a higher cutting speed can be obtained with cooling lubricants, the tool life achieved makes dry cutting an ecologically and economically interesting alternative to conventional machining strategies with cooling lubricants. The basic precondition for eliminating cooling lubricants is, however, the use of coated tools.

Cylindrical gear production with carbide tools in a hobbing process reduces production costs simply through shortened machining times, although tool costs are significantly increased. The technological advantage of a (Ti,Al)N hard coating is not mirrored in lower part-related production costs, owing to higher coating costs as compared to the TiN coating. Savings are rather to be found in higher cutting speeds, which can be realized through the hard coating system, allowing reduced machine and production costs.

On both HSS and carbide tools, these cost savings are generated partly by significantly increased tool life, as opposed to conventional TiN coatings, with a corresponding reduction in the tool cost component; and partly through the faster cutting speeds allowed by the lower abrasive wear and greater high-temperature hardness of the coated tools. ○

Acknowledgment

The investigations described in this article were conducted at the Laboratory for Machine Tools and Production Engineering (WZL) as part of projects sponsored by the Verein Deutscher Werkzeugmaschinenhersteller (VDW/AiF).

References

1. König, W., K. Peiffer and D. Knöppel. Die Produktion umweltverträglicher gestalten. Kühlschimiermittelfreie Fertigung, Industrie-Anzeiger, 94 (1991), p. 23-25.
2. Klocke, F., C. Escher and M. Vüllers. "Dry Hobbing—Efficient and Ecological." *Proceedings of the International Conference on Gears*, held April 22-24, 1996, Dresden.
3. Ophey, L. Hochleistungs-Wälzfräsen ohne Kühlschmierstoffe, Werkstatt und Betrieb 127 (1994), Heft 5, Carl Hanser Verlag, München 1994, p. 362-368.
4. Sulzer, G. "High Speed Dry Hobbing of Gears—The Technology." Firmenschrift Liebherr Verzahntechnik GmbH, Kempten, 1995.
5. Peiffer, K. Trends beim Verzahnungsfräsen, Vortrag anläßlich des Seminars "Praxis der Zahnradfertigung," Technischen Akademie Esslingen, March 25-27, 1996.
6. Phillips, R. "New Innovations in Hobbing—Part II." *Gear Technology*, November/December 1994, p. 26-30.
7. Weinert, K., F. J. Adams and D. Thamke. "Was kostet die Kühlschmierung?" Technika 7 (1995), p. 19-23.
8. Peters, W. Hochleistungs-Wälzfräsen von Zahnrädern in PKW-und Nutzfahrzeuggetrieben, Spanende Fertigung, 1. Ausgaben, Vulkan-Verlag, Essen 1994, p. 265-269.
9. Hoffmeister, B. Üden Verschleiß am Wälzfräser, Dissertation RWTH Aachen, 1970.
10. Forschungsheft, forschungsvereinigung Antriebstechnik e.V., Forschungsvorhaben Nr. 106/II, Beschichtete HSS-Werkzeuge, Einsatz TiN- und TiC-beschichteter HSS-Werkzeuge bei der Zylinderradherstellung, Abschlußbericht, Heft 256, 1987.

This article was first presented at the 4th World Congress on Gearing and Power Transmission, organized by IET (the French Institute for Gearing and Transmissions), held March 16-18, Paris, France.

Tell Us What You Think . . .
If you found this article of interest and/or useful, please circle **204**.