Dry Machining for Gear Shaping

Jürgen Schmidt, Oliver Doerfel and Andreas Hühsam

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Introduction

Economic production is one of the main concerns of any manufacturing facility. In recent years, cost increases and tougher statutory requirements have increasingly made cutting fluids a problematic manufacturing and cost factor in metalworking. Depending on the cutting fluid, production process and supply unit, cutting-fluid costs may account for up to 16% of workpiece cost. In some cases, they exceed tool cost by many times (Ref. 1). The response by manufacturers is to demand techniques for dry machining (Ref. 2).

Fundamentals of Cutting Kinematics

Gear shaping is one of the continuous generating processes in metal-cutting gear manufacture. The arrangement of cutter and workpiece during the shaping process corresponds to the configuration of a spur gear pair, with three movements (Ref. 3):

- Cutting movement of tool,
- Rotary movement of cutter and workpiece, and
- Radial movement of cutter.

Basically, there are three in-feed processes that may be distinguished by radial movement (Fig. 1) (Ref. 4):

Plunging without rolling movement. In plunging without rolling, radial in-feed is effected without a rotation movement of tool and workpiece. Radial feed remains constant throughout in-feed. After the in-feed depth has been reached, the gear is rolled out once at tooth depth, whereby the rolling feed is relatively low, due to the large overlap of tool and workpiece.

Plunging with rolling movement. In plunging with a rolling movement, the in-feed rate of the tool and the in-feed depth are achieved with simultaneous turning of the tool and the workpiece, whereby the rolling angle covered is usually less than 180°. Similar to plunging without rolling, this process causes the teeth to be rolled out to in-feed depth.

The radial in-feed processes of plunging with and without rolling are among the "conventional" in-feed processes and are comparable in terms of their characteristics. The radial and rolling feeds are similar.

Helical process with degressive-control radial feed. The in-feed rate and in-feed depth in the helical process with degressive-control radial feed is effected continuously over a number of workpiece revolutions. The speed of radial feed decreases over the rolling path, i.e. at the beginning of machining, radial feed rate is high, and it decreases with increasing overlap of workpiece and tool. That results in a linear relationship between radial feed rate and time. The current rolling feeds are higher by a factor of two or three compared with plunging with or without rolling, with comparable main production times. That is due to the lower amounts of radial feed.

The advantage of the helical in-feed process compared with the processes mentioned above is that there is homogeneous tool load over the

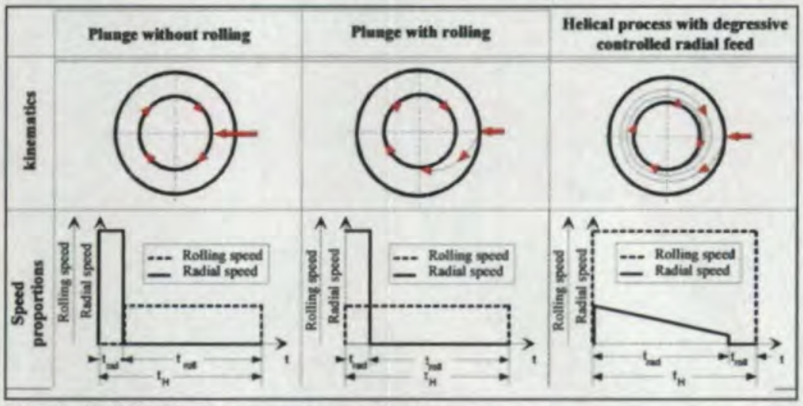

Fig. 1—Radial in-feed processes in gear shaping.

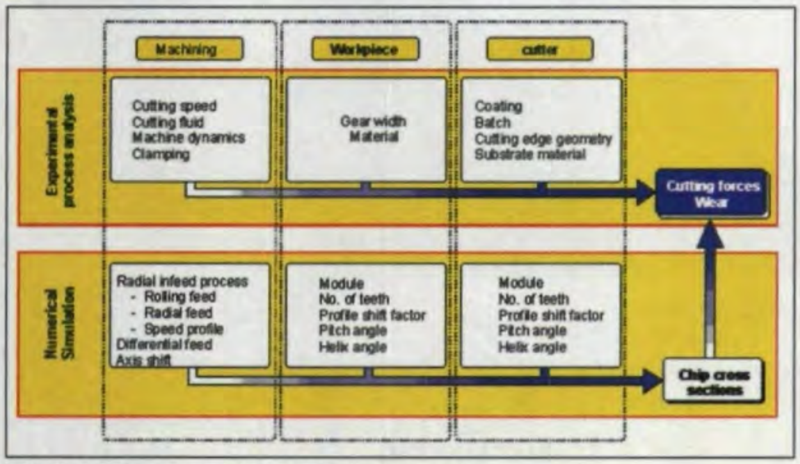

Fig. 2—Main parameters in gear shaping/approach.

entire machining process. It is known that helical degressive radial in-feed causes cratering wear of the tool face, while conventional radial in-feed processes (plunging with or without rolling) cause flank wear. The causes and optimization strategies are presented in the numerical simulation.

Approach

The aim here was to find a universally applicable way of eliminating cutting fluids in gear shaping processes. A two-part process has therefore been specified, based on the main process parameters (Fig. 2). There are two main sets of parameters that influence wear and cutting forces. One set includes geometry-dependent parameters that directly affect chip cross section, which influences cutting forces and cutter wear. The other set includes parameters that have a direct impact on cutting forces and wear, without any change in the chip cross sections. Both sets of parameters can be broken down into machining, cutter and workpiece parameters. In order to achieve comprehensive optimization of gear shaping, it is necessary to consider both the chip cross sections and the technological parameters.

Keeping chip cross section constant, an experimental process analysis was conducted to analyze the influence of technological parameters on wear behavior and cutting forces. A numerical simulation was done to systematically analyze the cutting process by a geometry-related model, to determine and optimize the chip cross sections. The results were used to obtain assessment criteria for chip cross sections, and the model presentation was then verified in experiments.

Experimental Process Analysis

The aim of the experimental process analysis was to characterize the influence of various technology parameters while maintaining constant chip cross section. Cutting force measurements were used to analyze the loads occurring on the cutter under different machining conditions, in order to understand the process as a whole. The resulting wear analysis was then used to determine form and wear amount, so the knowledge could be used to improve coatings and optimize cutter life in dry machining.

Cutting force measurements to optimize technological data. Cutting force measurements were used to analyze the influence of manufacturing conditions on cutter load, both in the radial in-feed techniques (plunging with and without rolling) and in gear cutting with degressive radial feed. The comparison was based on equal main production times. The analysis showed that, depending on the

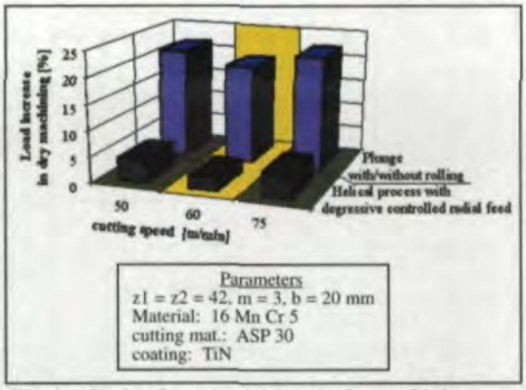

Fig. 3—Cutting force comparison in dry machining.

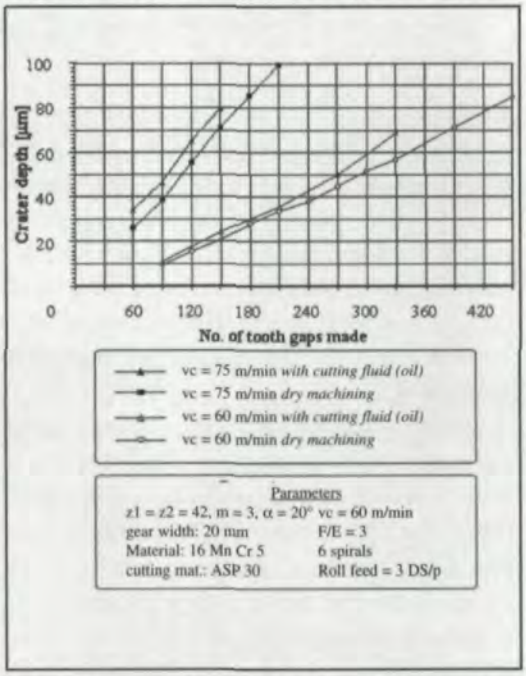

Fig. 4—Influence of cutting fluid and cutting speed on crater depth.

gear cutting process, dry machining increases cutter load by up to 25% (Figure 3).

In conventional gear cutting processes (plunge with or without rolling), the load increase in dry machining is between 15% and 25%, depending on the cutting parameters used (shown with the example of cutting speed). In helical degressive radial in-feed, the omission of cutting fluid means that increase in cutting speed causes considerably less increase in main cutting force (about 5%). That is due to the high rolling feeds, with only short contact times between the tool and the chip. Also, the proportion of frictional work in chip formation is small. The "lubricating" function of the cutting fluid only plays a minor part under those contact conditions. The cutting force measurements show that the helical degressive radial in-feed technique is more suitable for dry machining than the conventional in-feed processes. That technique is therefore used in the subsequent investigations.

Tool life analysis in dry machining. The pur-

Prof. Dr.-Ing. Jürgen Schmidt

is speaker of the common board of leadership at the Chair and Institute of Machine Tools and Production Science, University of Karlsruhe, located in Germany. A mechanical engineer, he also is sponsor of the institute's manufacturing technology group.

Dr.-Ing. Oliver Doerfel

works for DaimlerChrysler AG. A mechanical engineer, he heads a team of mechanical engineers that plan production concepts and systems for material flow. Previously, he was a scientific employee at the Chair and Institute of Machine Tools and Production Science, where he earned his doctorate in 1998 on gear shaping.

Dipl.-Ing. Andreas Hühsam

is a scientific employee in the manufacturing technology group of the Chair and Institute of Machine Tools and Production Science. A mechanical engineer, he works on developing innovative manufacturing procedures for gearing, especially gear skiving.

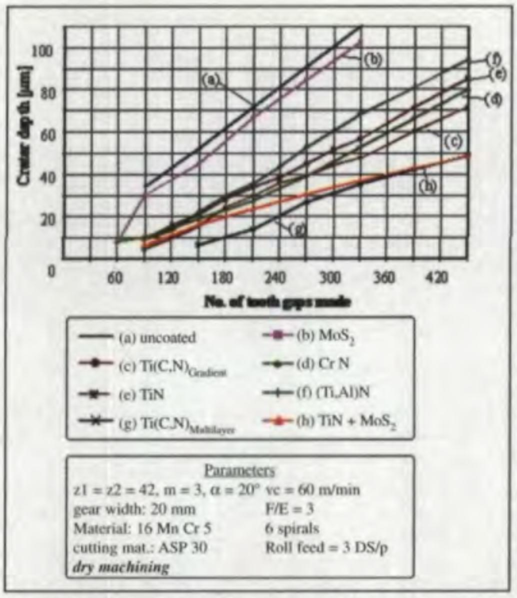

Fig. 5—Influence of coating on cutter life in dry machining (Ref. 6).

pose of the tool life analysis was to determine the effect of cutting fluid and cutting speed on tool life and workpiece quality. Further analysis was conducted to show the potential of innovative tool coatings.

Figure 4 shows the influence of cutting speed and cutting fluid on crater depth, using the example of tools coated with standard titanium nitride (TiN). The figure shows that an increase of cutting speed from 60 m/min. to 75 m/min. (25%) increases crater depth, regardless of lubrication conditions. Extrapolating the values to a crater depth of 100 μm, cutting speed increase reduces tool life to 30% of the original level.

It is also clear that, for the same cutting speed, there is very little difference between tool life achieved in dry machining and conventional cutting fluid application. For a specified tool life, dry machining always gives less crater depth than wet machining. The higher temperature of the chip and the related shorter chip path also reduce crater lip distances in dry machining. But, there is no premature breaking of the crater lip in dry machining.

Influence of coating. Recent developments in coating technology have given major benefits in cutter wear resistance (Ref. 5). Firstly, production processes for coating manufacture have been optimized. Secondly, new layer systems have been developed and adapted to specific production processes. With that background in mind, innovative layer systems have been examined to determine suitability for the specific requirements of the gear shaping process. The aim of the experimental study was to achieve a major increase in cutter life.

Apart from the commercially standard hard layers—like chromium nitride (CrN), titanium aluminium nitride ((Ti,Al)N) and titanium carbonitride gradient ($Ti(C,N)_{gradient}$)—the following new types of coating also were applied to the tools and tested in experimental trials to determine possible increase in performance in gear shaping:

Ti(C,N) multilayer coating. The titanium carbonitride multilayer coating was applied by an optimized process. That involved frequent alternation of TiN and Ti(C,N) layers in the multilayer deposit, with standard layer thicknesses (3μm) to achieve low inherent stress. That resulted in improved adhesion combined with good microhardness, compared with the standard Ti(C,N) gradient coatings (just one continuous transition from TiN to Ti(C,N)).

Solid lubricant layer (MoS_2). The solid lubricant layer molybdenum disulfide (MoS_2) on the cutting wedge was intended to replace the cutting fluid's "lubrication" function. The solid lubricant layer featured a very low friction coefficient (μ = 0.04–0.09 with steel). The coating was applied in a sputter process at low coating temperatures.

Hard coating layer + solid lubricant layer ($TiN+MoS_2$). This system separated the functions at the cutting layer, with suitable combination of a hard layer (e.g. TiN) as a base coating on the substrate and a solid lubricant layer (MoS_2) additionally applied to the hard coating. The hard coating improved the wear behavior of the tool, while the solid lubricant layer reduced friction between chip and tool.

Figure 5 shows the effect of the layers described above on cutter life in dry machining. A comparison with uncoated tools shows that a hard coating (e.g. TiN) always has a positive impact on tool life.

For identical cutting conditions, the different standard coatings—$Ti(C,N)_{gradient}$, (Ti,Al)N, TiN and CrN—resulted in only minor differences in tool life. There was only slight difference in crater depths between these tools for a tool life of 450 tooth gaps cut. The tools sputtered with MoS_2 had very unfavorable tool life. Wear investigations showed that the MoS_2 layer was no longer present after cutting just a few tooth gaps. Further wear depended on the substrate core, and the wear characteristic was almost identical to that of uncoated tools.

The use of $TiN+MoS_2$ coated tools gave quite different results, with very favorable tool life. Direct comparison with the standard coatings showed that for 450 tooth gaps cut, the crater depth was only half as great. Visual assessment of this coating system showed that, here again, the MoS_2 layer was no longer present after cutting just a few tooth gaps. The solid lubricant was present in the surface structure of the TiN layer, as shown by metallographic examinations. A combination of hard material and solid lubricant layer gave double the tool life on extrapolation of the wear curves.

A good wear characteristic similar to the "combined layer" TiN+MoS_2 also was given by the Ti(C,N) multilayer coated tools. The improvement in coating methods means that dry machining, like the TiN+MoS_2 layer, gives double the tool life compared with standard layers.

Numerical Simulation of Chip Cross Sections

The superposition of the three main movements combined with the three-cutting-edge tool gives a wide range of chip cross sections in gear shaping. To improve the dry machining of a workpiece, the chip cross sections have to be varied, and optimized with a defined target magnitude. Purely experimental adjustment of chip cross sections to each specific application involves a great deal of effort. Experimental optimization of chip cross sections means a lot of work for each customer-specific gear design and is not always an appropriate method.

The complexity of the situation makes it essential to use computer-aided optimization of chip cross sections, based on analysis of the relationship between workpiece and tool geometry and the machining parameters. A simulation program has been created to permit personal-computer-based modelling of the chip cross sections, using a systematic and universal program structure. The simulation is based on knowledge of the existing tool geometry and of the exact movement equations, dependent on in-feed method. The chip cross sections can be shown by coupling the geometry of the tool with the movement equations of the gear shaping process, and the cut with the respective workpiece contour, whereby the kinematics of the gear shaping process are shown by coordinate transformation between different reference coordinate systems. That coupling gives the chip cross sections of the process and the derived chip attributes. Chip cross sections are determined for a given workpiece/tool geometry and for specified machining parameters, and evaluation is done on the basis of chip attributes (e.g. area, maximum chip thickness) and chip shape.

Comparison of in-feed processes. Figure 6 shows the major chip attributes of the radial in-feed processes (plunging with or without rolling), and helical degressive radial in-feed. For plunging with rolling, one tool tooth is considered, rolling into the workpiece at in-feed depth. Comparison of the characteristic of maximum chip thickness shows that plunging with rolling gives the values for chip thickness maxima that are several times lower than for helical degressive in-feed. That is because the rolling feed in the process is smaller by a factor of three or four. Helical degressive in-feed gives only a small amount of radial feed in the individual rotations, and yet maximum chip thicknesses are still very great. That means that the division of in-feed depth over a number of machining rotations has only minor influence on maximum chip thickness.

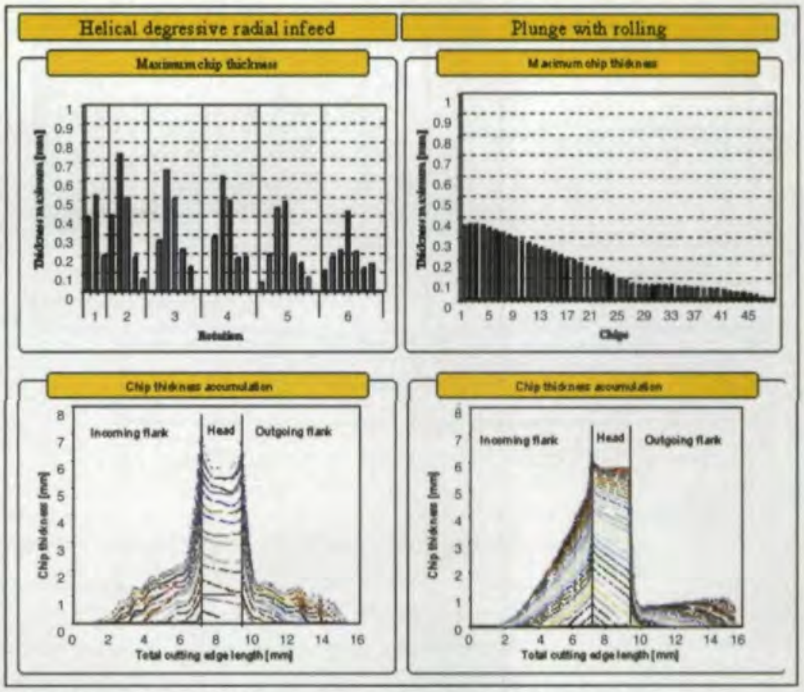

Fig. 6—Comparison of chip cross section for various in-feed processes.

According to Victor (Ref. 7), the chip thickness (alongside chip width and specific cutting force) is a major parameter for the amplitude of the cutting force, and thus has a direct influence on tool wear. For every individual chip cross section, it is possible to analyze the characteristic of chip thickness along the developed absolute cutting edge length of the tool. The large number of chip thicknesses in the manufacture of a gear produces a whole host of information, too much to analyze. A cumulative presentation of chip thicknesses is therefore used here, described as chip thickness total, the total cutting edge load occurring at the various tool cutting edges. The characteristic of chip thickness total for one cutter tooth is obtained by adding the respective chip thickness characteristics of each chip cross section. The distance between two characteristics in

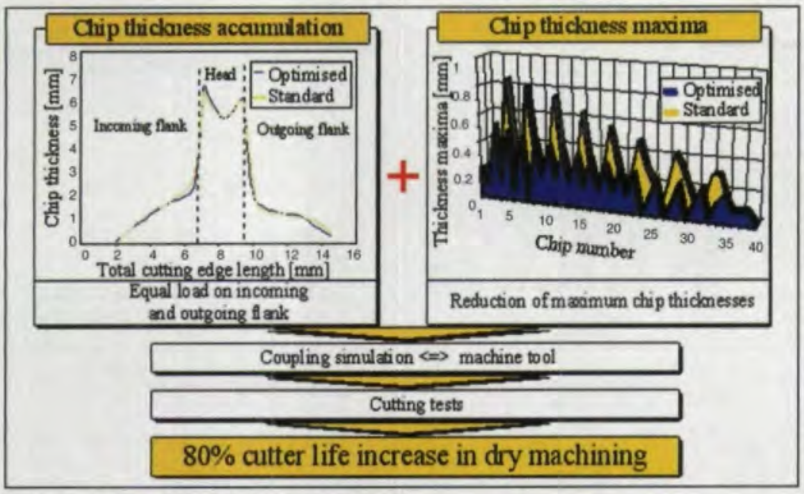

Fig. 7—Optimization of chip cross sections.

Figure 6 thus shows the chip thickness for one chip.

Comparison of the calculated chip thickness totals shows very clearly why plunging with rolling gives wear on the flank at the transition zone from the tooth head to the end of the flank. The low gear shaping feed means that the major part of the workpiece gap is cut by the incoming flank and the tooth head. In the transition zone between tooth head and end of flank, the overall result is only very thin chips, which cause frictional wear on the flank. Due to the small amount of rolling feed, that wear is not caused by chip formation, but can be attributed to the crushing of thin chips. The overall cutting edge load for helical degressive radial in-feed is characterized by uniform loading of incoming and outgoing flank, which causes crater wear development without wear of the flank.

A comparison of the in-feed processes shows a strategy for definition of goals to optimize in-feed parameters:

- Uniform loading of incoming and outgoing flank areas to achieve crater wear on the tool,
- Reduction of maximum chip thickness to reduce wear on the assumption of "crater wear formation," and
- Avoidance of very thin chips.

Optimization of chip cross sections. The major technological data of helical degressive radial in-feed were varied with the goal of crater wear formation and thus constant tool quality during cutter life.

Figure 7 shows the aggregated chip thickness and the resulting maximum chip thicknesses for a standard technology data set, and an optimized data set, in comparison. Uniform loading of incoming tool flank and outgoing tool flank gives crater wear of the tools (compare chip thickness aggregation). Compared with standard machining cases, this optimized data set considerably reduces maximum chip thicknesses. Validation in the cutting test shows that optimization of technology data can increase cutter life by 80%. This shows just what potential there is in optimizing chip cross sections. In order to improve wear form and wear amount, it therefore makes sense to conduct a computer-aided analysis of chip cross sections in advance, in the course of production planning.

Summary

Dry machining is currently one of the most widely discussed subjects in metal cutting, due to issues of ecology, economics and industrial health and safety.

A two-part approach has been chosen, derived from the main parameters of the gear shaping process. Experimental investigations showed that optimization of cutting conditions will already permit dry machining with conventional coatings. Targeted improvement of the layer made it possible to double tool life. Numerical simulation of chip cross sections can be used to analyze wear form and nearly halve tool wear.

The two-part approach used here makes it possible to adapt a wide range of workpiece geometries to the changed parameters of dry machining. Further investigation will be required to determine how far existing machine tool concepts are suitable for dry machining. ○

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