Dry Cutting of Bevel and Hypoid Gears

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Introduction

High-speed machining using carbide has been used for some decades for milling and turning operations. The intermittent character of the gear cutting process has delayed the use of carbide tools in gear manufacturing. Carbide was found at first to be too brittle for interrupted cutting actions. In the meantime, however, a number of different carbide grades were developed. The first successful studies in carbide hobbing of cylindrical gears were completed during the mid-80s, but still did not lead to a breakthrough in the use of carbide cutting tools for gear production. Since the carbide was quite expensive and the tool life was too short, a TiN-coated, high-speed steel hob was more economical than an uncoated carbide hob.

It is now known that the coating is a key factor in the use of carbide tools. The coating lowers the friction between the chip and blade front face, and it protects the porous surface of the carbide. Heat and friction cause chemical reactions between the chip and the carbide binder material and "wash out" the carbide grains on the cutting front face. This causes a crater-like wear pattern. The combination of fine grain carbide with the well-known TiN coating is sufficient for skiving operations and leads to reasonable tool life (Ref. 1).

Improvements in carbide grades and sintering processes, in combination with new coating methods and the use of CNC machines, has led to a significant new trend in the way cylindrical gears are produced: High-speed hobbing using coated carbide tools without coolant. Provided that process parameters are set optimally, extremely short cutting times can be achieved with long tool life and high part accuracy. Process development in bevel gear cutting also benefits from the carbide and coating developments.

The Gleason results in carbide cutting with coolant are the product of substantial research work. Besides dramatically reduced cutting times of about 50%, improved surface finish and gear geometry quality are realized in comparison to conventional production with high-speed steel. This is largely due to the high stiffness and good dynamic behavior of the Phoenix® machines used for the cutting studies. The Gleason POWER-CUTTING™ process, as opposed to the carbide rough-cutting methods discussed by other machine tool manufacturers at the present time, is a finishing process which is suitable for later short-time lapping or grinding. AGMA Class 12 and 13 gear quality was achieved in all development studies.

Bevel Gear Dry Cutting

After successful investigations of the high-speed carbide cutting process with coolant (Ref. 2), the next logical step was to follow the general trend and proceed with the process development of a bevel gear dry cutting method. It was found that nearly all geometrical and technological parameters of the carbide wet cutting method also could be applied to bevel gear dry cutting. The surface cutting speed of the newly introduced method is 1000 ft/min.; that is, four times the value of conventional cutting. The cutting process combines conventional cutting in the continuous face hobbing method and plunge cutting in the single-index face milling case. Cutting feed rates of 70% of conventionally applied rates were found to be optimal as a result of the investigations.

Since the index speed of the single-index face milling cycle is the same for both POWER-DRY-CUTTING™ and conventional cutting methods, cycle time reduction

Fig. 1 — View into the work area of a Phoenix machine during continuous-index Power-Dry-Cutting (quarter of plunging depth).

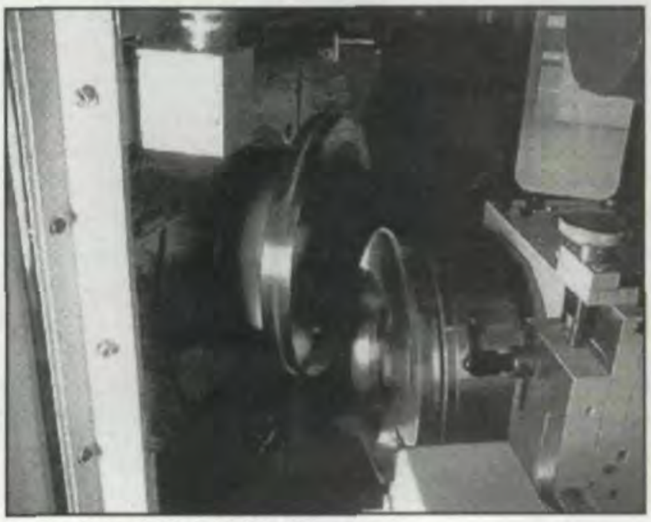

Fig. 2 — Power-Dry-Cutting (full depth).

Fig. 3 — Chips from dry cutting; plunging on the left, roughing in center, finishing to the right.

Fig. 4 — Phoenix 450HC-DRY with aerodynamic chip channel.

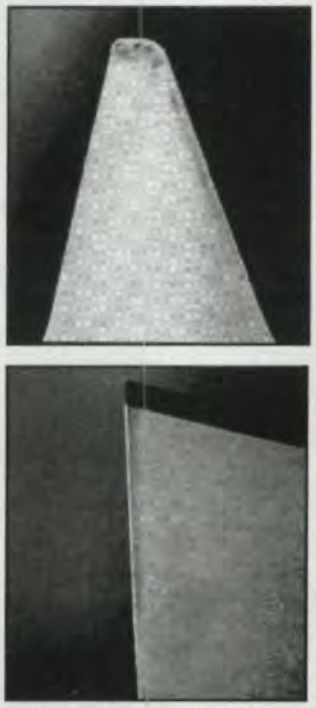

Fig. 5 — Blade wear pattern after cutting of 201 ring gears.

of 30 to 40% is possible in the case of face milling. In the continuous-index face hobbing case, the indexing speed is proportional to the cutter rpm, which reduces the cutting times by 75%. This and other advantages show the enormous economic potential of this method, especially if it is applied to the continuous indexing face hobbing process.

Fig. 1 gives an impression of the high surface speed and the high chip removal rate of the Gleason process. About a quarter of the plunging cycle has already been completed. The thin oil film for rust protection on the blank surface does not cause a noticeable smoke development at the beginning of the cycle.

Fig. 2 shows the end of the plunging cycle. The illustrated gear is a face-hobbed ring gear with 45 teeth and a module of 5.9 mm. The complete cutting time was 1.5 min. (as opposed to 6.5 min. for conventional cutting).

The carbide stick blades were TiCN coated. The projected tool life corresponds to three times that of high-speed steel tools. Even higher tool life times are expected in the future.

Fig. 3 shows chips from a ring gear, which was cut in the course of the parameter studies. The feed rate used to generate the chips was 0.005 in/blade. The highest temperatures of the chips in Fig. 3 were around the tempering temperature. Only parts of the chips turned blue. The chips to the left in Fig. 3 were created during the beginning of the plunging cycle; they are small and thick and have been cut by the tips of the blades. The chips in the center of Fig. 3 originate from the roughing portion of the cycle; they are wide and U-shaped and were generated simultaneously from the cutting edge, the blade tip and the clearance side of the blade. The chips to the right in the figure are wide and thin; they were cut primarily by the cutting edge of the blades near the end of the plunging cycle. At this time, the blades were completely engaged with the workpiece in the tooth profile direction.

The long and wide cut engagement between the blade and the work in case of bevel gear cutting prevents the generation of microchips. This is the reason why, in contrast to cylindrical gear hobbing, no chip welding in the root area occurs. The temperature of the workpieces amounted to 47°F above room temperature. The temperature of the cutter head stabilized at 90°F (12°F above room temperature).

A cost comparison to evaluate the economic viability of this method is based on the following factors:

- Cost of carbide blade sticks (four times price of HSS)
- Sharpening of carbide blades (last about three times longer than HSS)
- Coating of carbide blades (only once necessary for HSS)
- Building of blades in cutter head (1.5 times longer than HSS)
- Tool life of carbide (1.5 to 3 times that of HSS)
- Manufacturing time = machine occupation (20 to 30% that of HSS)

The cost of the carbide and the coating is more than compensated for by fewer resharpenings, requalifications and so forth. In this example, the total tool cost per manufactured gear is reduced by 28%.

Machines and Tools for POWER-DRY-CUTTING

To apply this method, it is necessary to use Phoenix bevel gear generators equipped with special high speed spindles. Cutter spindle speeds up to 1000 rpm cannot be realized with conventional machines that have the traditional cradle design. The complicated gear train in a conventional machine (with play between each gear set) cannot produce smooth coordinated motions and maintain stable temperatures at high cutting speeds. The six-axis, free-form Phoenix machine, however, has the cutting spindle motor mounted directly to the same vertical slide that houses the cutter spindle. Complicated couplings and mechanisms are then not required to transmit power to a tilted cutter head, as on cradle style machines. The new method can be applied to single-index face milling or continuous-index face hobbing and is always a completing operation.

To set up the cutting machine for the dry cutting process, a chip guiding channel was developed that takes advantage of the kinetic energy and the aerodynamic shape of the chips to remove them out of the work zone. In spite of cylindrical cutting, the chips fly tangentially to the cutter in the direction of the back guard, where they get removed into a chip container using a Venturi system. Except for two pressure air nozzles, no energy is applied

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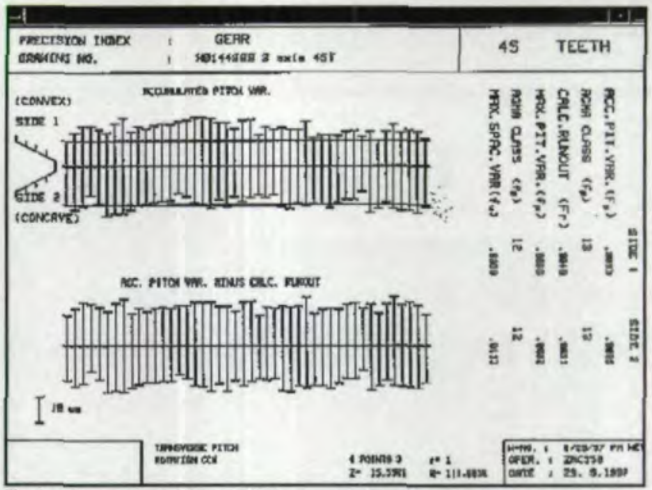

Fig. 6 — Power-Dry-Cutting results from a spacing measurement.

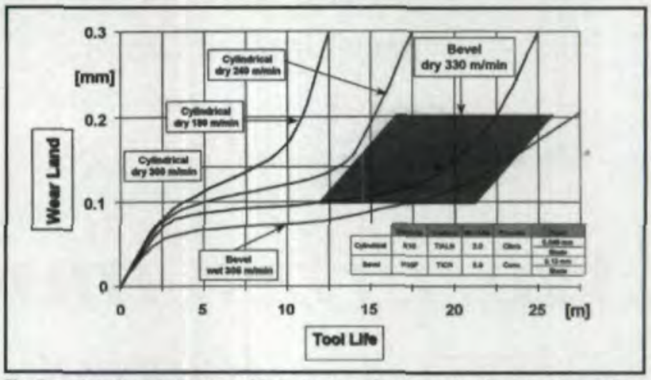

Fig. 7 — Relationship between blade wear, surface speed and cutting length (partially according to F. Klocke, Ref. 3).

to remove the chips and maintain a perfectly clean machine interior. This chip removal and the oil-free cutting process make for an environmentally and enery-saving overall concept. Up to 80% of the process heat is removed from the machine together with the chips without any heat transfer to the machine elements.

As a dry cutting option, the Phoenix machine has no oil tank and no chiller unit for cutting oil, as well as no chip conveyor. This results in a 30% reduced floor space and a very compact appearance of the machine tool. Fig. 4 shows a photograph of the Phoenix machine. The chip channel is visible in the center, surrounding the complete work area of cutter head and workpiece. The front part of the channel can easily swing aside and allows a convenient change of the cutter head.

The tools for dry machining are RSR® or TRI-AC® cutter heads. Solid carbide stick blades were used to conduct the cutting trials reported in this article. This simplifies the manufacturing of the blades and allows for the highest possible number of resharpenings. The carbide blades are resharpened on the Gleason 300 CG cutter/grinding machine with a diamond-coated grinding wheel. Fig. 5 shows photographs of "healthy" appearing blade wear after cutting 201 ring gears with dry cutting. The side relief wear land of 0.006" width leads to the conclusion that cutting of at least 50 more gears would have been possible.

The carbide grade with the best result in the parameter studies was Sandvik

H10F, with fine grain structure. The blades must be coated at least on the front face. In the reported investigations, a TiALN coating had been applied to the blades with a PVD method. The side relief angle was 6° (common value also used with high-speed steel). The side rake angle was ground to a positive value of 10°, which is about half the common value of a high-speed steel blade. The hook angle results from the tilted slots in the cutter head and therefore was a positive value of 12°.

The presented results of high-speed dry cutting were conducted in the continuous face hobbing and the single-index face milling method. The primary target of this new method is the manufacturing of both pinions and ring gears. Significant economic advantages exist for the high-speed cutting of Formate® ring gears. Due to the higher number of teeth, the cutting time savings is in general greater for the gear than for the pinion member. Besides, the elimination of the roll motion guarantees optimal and constant cutting conditions during the entire cutting cycle. The continuous change of the effective or dynamic blade angles always requires a compromise when generating a pinion. In spite of the smaller potential to reduce machining time and these additional complications, parameter studies for POWER-DRY-CUTTING of pinions are conducted parallel to the development of the ring gear cutting, since the gear manufacturing of the future shows a trend toward dry manufacturing, especially for small and medium-sized jobs.

Summary

The Gleason Works presents initial development results of a new dry cutting method for bevel and hypoid gears. An enormous potential will be available if the promising results of the laboratory investigations can be applied to daily manufacturing practice. Fig. 6 contains the graphical results of a tooth spacing measurement. Surface finish, tooth spacing and flank form correspond to a gear quality of AGMA Class 12.

An interesting comparison of the tool life potential can be seen in the diagram in Fig. 7. The tool life graphs for dry cutting of cylindrical gears, the tool life results of bevel wet cutting and expectations of the new process are compared in one diagram (Ref. 3). The definition of the tool life (cutting length) in metric units is defined as the length of material cut by one blade until a certain wear land occurs. The abscissa of the diagram in Fig. 7 shows the cutting length and the wear land width shown along the ordinate (Ref. 3).

The comparison of the bevel gear cutting graph in Fig. 6 with the cylindrical hobbing graph shows that today's results with Gleason wet cutting already have higher cutting lengths than the previous cutting results with cylindrical dry hobbing. 201 parts with 45 teeth and a face width of 45 mm results to 37 m, using an eleven-start cutter. With 1000 ft/min cutting surface speed and feed rate and 5/1000 in/blade, the projected tool life of POWER-DRY-CUTTING falls in the gray underlayed area.

The successful world premier of this method at the International Machine Tool Show (IMTS) in 1996 in Chicago was the result of development over more than two years, which subsequently led to the described method. The dry process version was introduced to the technical community at the 1997 EMO Machine Tool Show in Hannover, Germany. In addition to the dramatic reduction of cutting time, an advantage in surface finished gear quality is obtained in comparison to cutting with conventional high-speed steel tools. This was possible to a large extent because of the high stiffness and optimal dynamic behavior of the Phoenix machines. ○

References:

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