CNC Technology and the System-Independent Manufacture of Spiral Bevel Gears

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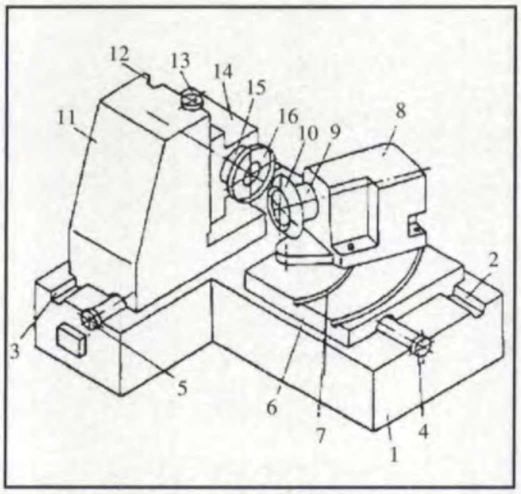

Fig. 1 - Russian machine with X-Y cradle.

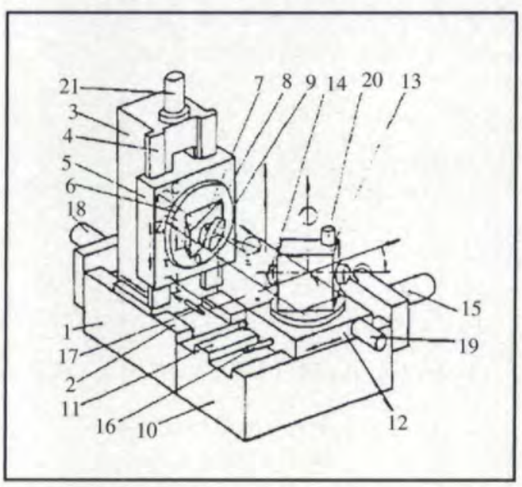

Fig. 2 - Modul machine with CNC-controlled X-Y cradle.

Introduction

CNC technology offers new opportunities for the manufacture of bevel gears. While traditionally the purchase of a specific machine at the same time determined a particular production system, CNC technology permits the processing of bevel gears using a wide variety of methods. The ideological dispute between "tapered tooth or parallel depth tooth" and "single indexing or continuous indexing" no longer leads to an irreversible fundamental decision. The systems have instead become penetrable, and with existing CNC machines, it is possible to select this or that system according to factual considerations at a later date.

This article, by giving a brief overview of the machines and systems available on the market or currently at the development stage, discusses the possibility of using different types of gear cutting on the same machine. It also contrasts the characteristics of different gear cutting systems, and, finally, discusses the possibilities of gear cutting optimization offered by current calculation and manufacturing technology in connection with CNC measurement technology.

CNC Machine Systems

Former Soviet Union system - The first machine known to us with a cross slide working at the workpiece side is shown in Fig. 1. It has the Russian Patent Application No.SU 724487 A, dated March 30, 1980. On the figure's left side, the cross slide with its ways "3" and "12" describes the circular motion of the tool. The actuation of the cross slide is a mechanical-hydraulic system.

Modul system - A CNC-controlled bevel gear cutting machine with cross slide is mentioned in Patent Application No. 255 296 A 1 of the company Modul in the former German Democratic Republic. The principle of this machine is shown in Fig. 2. The generation motion of the tool is achieved by overlaying slides "F" and "E." This machine is also equipped with a computer controlled tilt axis and swivel axis. These are the axes "D" and "C."

If the workpiece is cut with "tilt," the C-axis has be moved in a certain relation to the axes "F" and "E" (continuous path controlled), while the tilt-axis D is only a fixed setting axis.

Japanese system - In the Japanese Application for Patent No. 3643967 (Fig. 3) a machine is introduced in which all the motions are determined by the CNC control as well. As with the previously mentioned machines, the generating motion is achieved by a cross slide. The X-axis and the Y-axis are used to achieve the generating motion of the tool. As in the case of the Russian machine, no tilt and no swivel is provided.

Grinding Machine - Fig. 4 shows a full CNC-controlled bevel gear grinding machine, WNC 80, made by Klingelnberg. The generation motion of the tool, in this case the grinding wheels, is performed by the Y-axis (cradle motion). The advantage of this system is the fact that only three axes are in motion during the generating process: the Z-axis (workpiece rotation), the Y-axis (workhead), and the X-axis (helical motion). By intelligent superimposition of these three axes, the tilt setting is unnecessary. The double spindle wheelhead allows the grinding of pinions, which were cut by the traditional five-cut method at the concave and the convex flanks separately in one setting.

Phoenix - On the Phoenix machine (Fig. 5) made by Gleason, the generating motion of the tool is done, as with the first three machines, by the cross slide, visible in the left side of the picture. The ways 16 and 20 are the machine ways for the cross slide. Therefore, the cross slide motion is performed by the tool in the direction opposite to the previously described

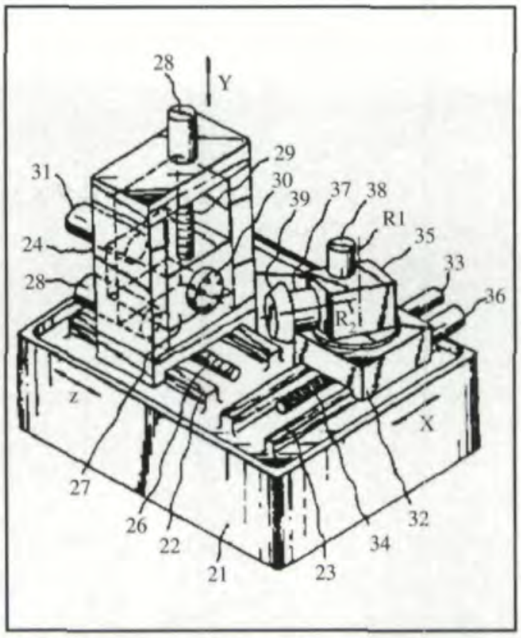

Fig. 3 - Japanese CNC machine.

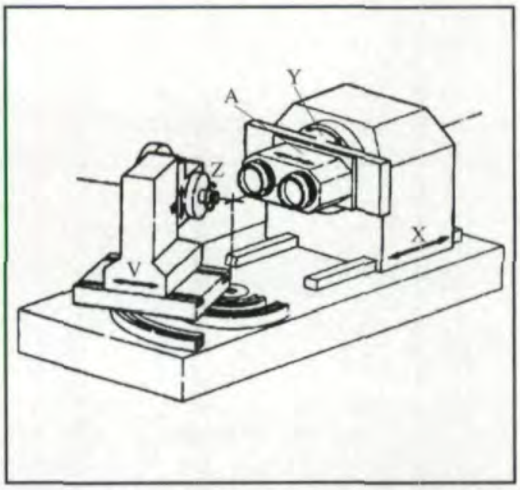

Fig. 4 - CNC bevel gear grinding machine, Klingelnberg WNC 80.

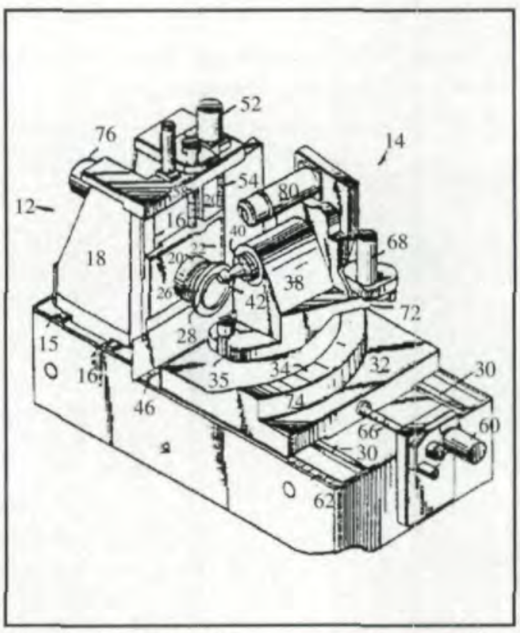

Fig. 5 - CNC bevel gear processing machine, Gleason Phoenix.

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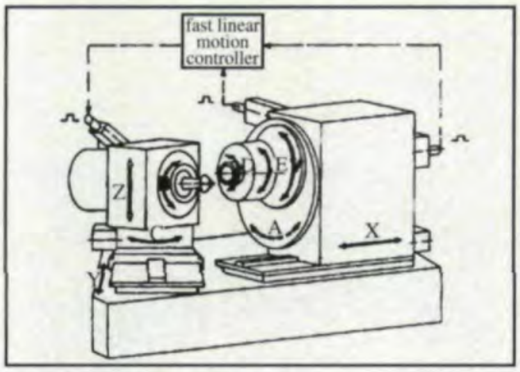

Fig. 6 - CNC bevel gear generating machine, Klingelnberg KNC 40/60.

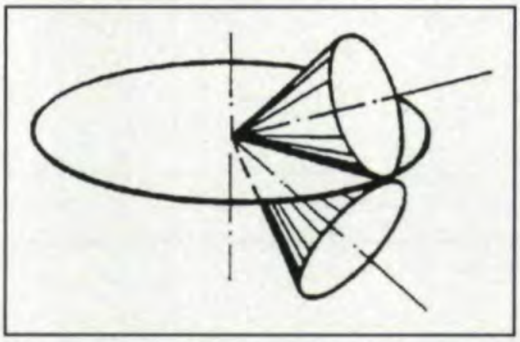

Fig. 7 - Manufacture on precise pitch cones.

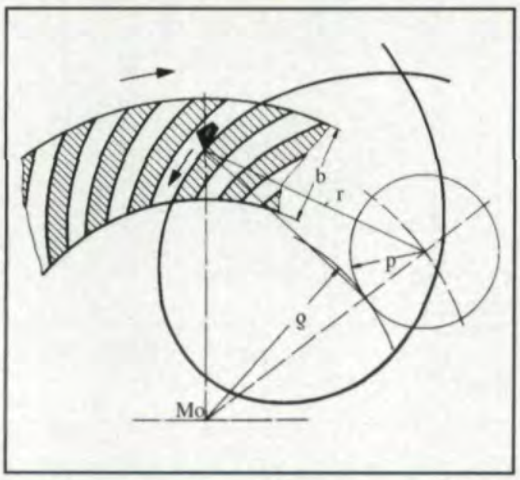

Fig. 8 - Tool radii in a continuous process.

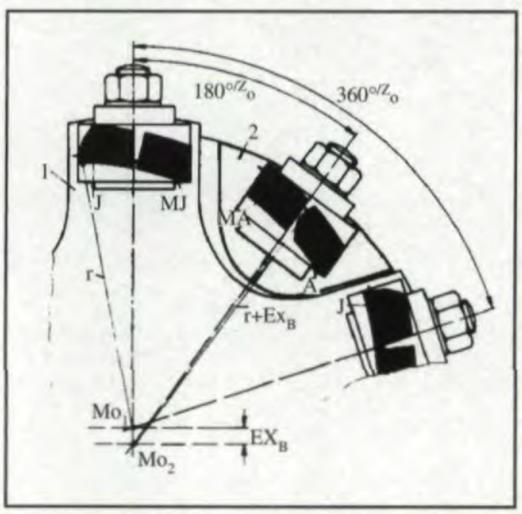

Fig. 9 - Split blade head for individual and small series manufacture.

machines. This machine has the characteristic of continuously moving the machine root angle during the generating process. This motion eliminates the tilt setting and the swivel setting.

KNC - Fig. 6 shows a full CNC bevel gear cutting machine, the KNC 40/60 series by Klingelnberg. On this machine all the axes are CNC controlled. The E-axis is only used for single piece and small lot size production. This axis sets the crowning eccentricity automatically when cutting bevel gears with the divided cutter head. This axis is not used for high-volume production, regardless of whether the face milling or face hobbing process is applied. The advantage of this machine is its great stiffness, since in the single indexing process, only three axes are in motion at the same time: the workpiece rotation axis B, the workhead rotation axis A, and the infeed axis X.

Gear Cutting Systems

The two decisive differentiating features of gear cutting systems are the continuous indexing or single indexing processes and the parallel tooth depth or the tapered tooth system.

In principle, all varieties can be combined with one another, but in practice, however, the following principle combinations are common: Continuous with parallel tooth depth and epicycloid, and single indexing with tapered tooth and arc.

In the case of parallel tooth depth, manufacture is performed on precise pitch cones (Fig. 7). Unless corrections are made, no crowning will occur. The gear generating process is precise and does not result in profile bearing, and as a result of the identical tool radii of the concave and convex flanks in a continuous process (Fig. 8), without a desired correction, no longitudinal convexity is produced. The advantage is that it is simple to conduct all calculations on the imaginary crown gear in question; the complicated three-dimensional bevel gear problem becomes a simple two-dimensional crown gear problem. Profile bearing is produced precisely and specifically via the tool, and the longitudinal crown via the difference in radius of the tool flanks for convex and concave flanks. The difference in radius is achieved via a separated blade head (Fig. 9) in individual and small series production; and in large series production (Fig. 10), via the tool inclination or the gear generating process.

The continuous process is always a completing process: both flanks of the gear and pinion are completed simultaneously in each case.

The tapered tooth depth is normally not arrived at according to a theoretically precise process and, therefore, necessitates a precise pre-calculation. Depending on the branch, highly different methods are used: They are the five-cut method, in which the ring gear is prepared in two cuts (roughed down) and completed (finished), the pinion is roughed down, and each flank individually finished; and the completing method, in which the gear and pinion are completed in a single operation. As in circular arc gear cutting, the blades for the inner and outer cutters have different radii, and the completing method requires a special design, e.g., using the duplex-helical method. For circular arc gear cutting, highly efficient processing methods have been developed which can be used to particular advantage if the ring gear can be produced in a plunging process on the basis of the transmission ratio.

Very often the question arises whether there is a difference of load carrying capacity between parallel tooth depth and tapered tooth depth. (See, for example, Krenzer, AGMA Paper 91-FTM-1.) Apparently, other design criteria are more important than the gear cutting system, provided the main drive data are similar.

One definite advantage of circular arc gear cutting is that it is possible to grind completing designs very economically with cup wheels . It is also possible to grind a continuously produced gear cutting using a cup wheel with an epicycloid as the longitudinal tooth line. The difference between the arc form of the grinding wheel and the epicycloid form of the tooth in lengthwise direction is within the stock allowance. However, this form of gear cutting requires separate processing of the right and left flank. The completing design of the circular arc gear cutting, on the other hand, enables completion of both flanks via grinding in a single step.

Calculation

For all processes, calculation methods have been developed which simulate the manufacturing process and the running conditions in the drive unit. The important factor is that the calculations function independently of the system. Only in this way is it possible to achieve a comparison which is independent of the process. In addition to the pure design calculation on the

Fig. 10 - Single-part blade head for series manufacture.

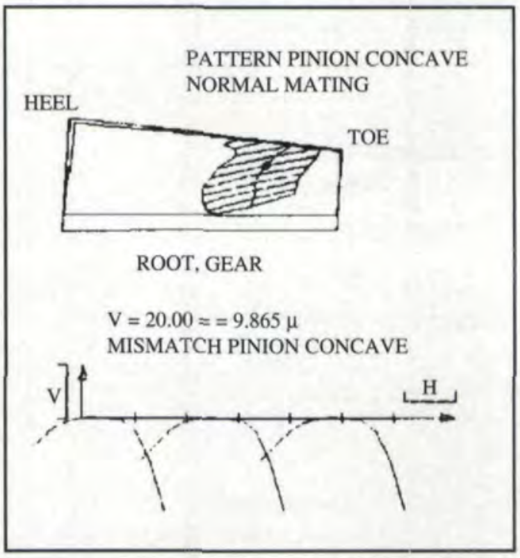

Fig. 11 - Contact area and single-flank gear generating error of a gear set (original design).

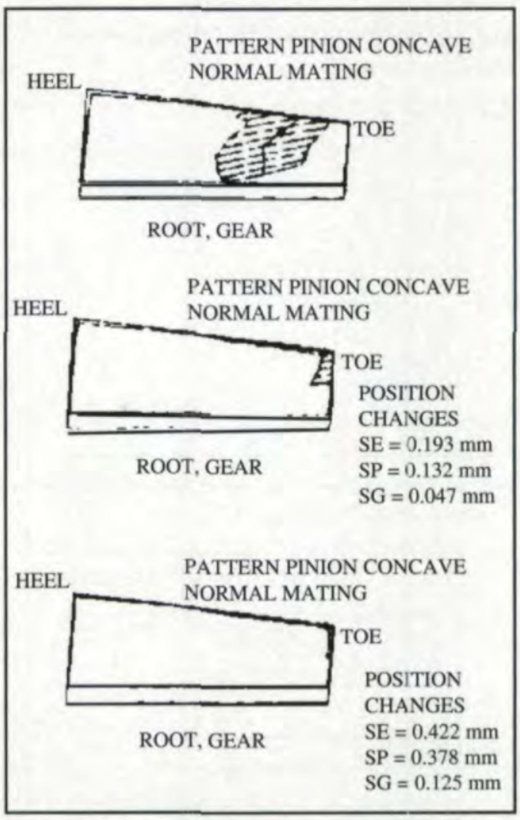

Fig. 12 - Contact areas with zero-load and two-load classes (original design).

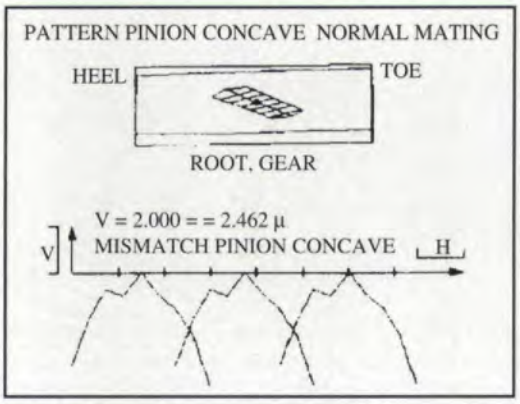

Fig. 13 - Contact area and single-flank gear generating errors optimized.

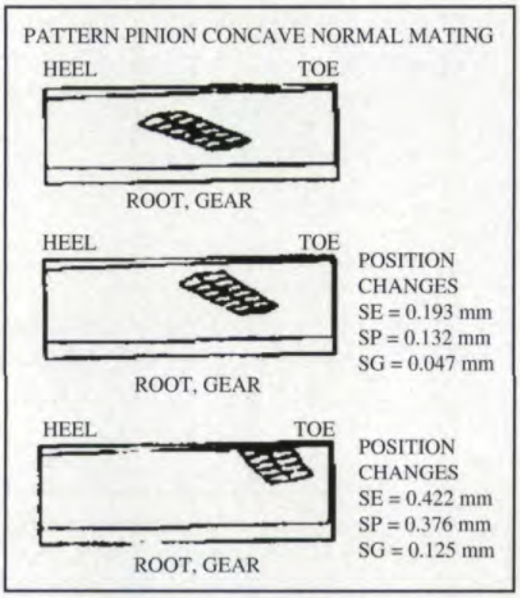

Fig. 14 - Contact area at zero-load and two-load classes optimized.

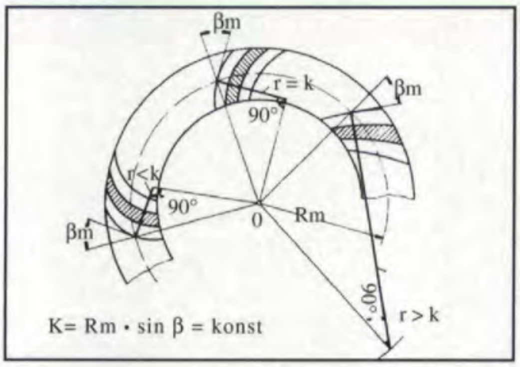

Fig. 15 - Arrangement of bevel gear and cutter in a "right-angled case."

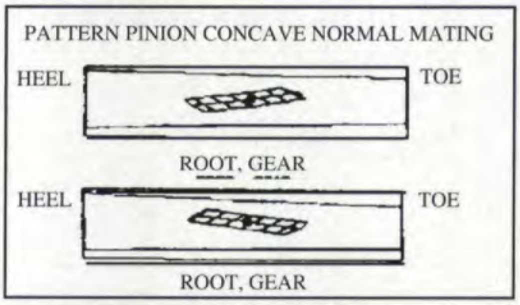

Fig. 16 - Contact area, example 2.

basis of the load capacity calculation according to AGMA or DIN standards, contact area analysis provides a reliable indication of the running behavior of a bevel gear in the drive unit. Optimization of a truck bevel gear set is given as an example.

Optimization With Regard to Noise Behavior - As the gear set is noise-critical in the original design, importance was attached to a low single-flank gear generating error.

Fig. 11 shows the contact area and single-flank gear generating error (motion curve) of the original design. The design has low convexity values due to the high noise requirements. For the drive, dislocation values below Load Classes I and II are known. These load classes correspond to 30% and 100% nominal load. Fig. 12 shows load-free contact areas for the zero position and for the dislocations which correspond to Load Classes I and II.

The large contact area indicates small crownings. Even at 30% nominal load, sharp edge wear occurs, which worsens at full load.

With knowledge of dislocation values, a gear cutting method was designed which was far less sensitive to dislocations, although the single-flank gear generating error was further improved (Fig. 13). The relevant contact areas are illustrated in Fig. 14. The load-free area appears smaller, but nevertheless, the single-flank gear generating error is improved by a factor of 2.5. No edge wear occurs at partial and full load (Fig. 14). The drive is far quieter in the entire load area than in the original design.

The following measures were implemented:

- As the contact area tends to wander in the direction of tooth length, the contact area sensitivity was reduced by switching from a large to a small cutter design. Sensitivity to contact area dislocations in the direction of tooth length is least in the so-called right-angled case (Fig.15).

- By means of the pinpointed use of helical contacts (bias in) the overlap ratio was improved for all load areas without making the gearing more sensitive to dislocations.

The bevel gear set ground in this way is quieter than a conventionally manufactured gear set. Lapping would worsen the noise.

Optimization with Regard to Load Capacity - Another example is intended to show how the load capacity of a gear set can be optimized using calculation and CNC-controlled manufacture. The gear in question is an offset gear set for a rail drive. The gear set suffers pitting, which occurs initially as micro-pitting on the tooth head of the pinion, in case of overloading. Obviously the Hertzian stress is too high.

Standard tooth contact area analysis reveals a good contact pattern in the lengthwise direction (Fig. 16.) Only the tooth contact analysis (Fig. 17) under load demonstrates that the tension level at the tooth flanks gets too high under overload. The pitting stress can be reduced by increasing the profile crowning, which is simply done by altering the input data for the grinding process. One then receives a contact pattern which is more distinctive in the direction of the tooth height (Fig. 18). The tooth contact analysis indicates a decrease of the maximum Hertzian stress from 2,600 N/mm to 2,120 N/mm, but tension peaks appear in the root relief of the pinion at the top of the gear. This can be prevented by means of tip relief at the gear root relief at the pinion. In this case, the Hertzian stress is not increased, but the tension peaks at the top of the gear teeth are avoided (Fig. 19). The extended lines indicate that these tension peaks are reduced from 2,180 N/mm to 2,135 N/mm. By means of special software, the tip relief can also be conducted in a circular motion or elliptically (Fig. 20).

Closed Loop of Correction

With today's methods of calculation, manufacturing, and inspection, it is possible to achieve a closed loop from the calculation (including contact area analysis with ease-off and single-flank gear generating error) to manufacture and inspection (Fig. 21). The figure shows an example calculation on a PC. The machine setting data resulting from this are transferred to the cutting machine and the grinding machine either via a data storage medium (diskette) or via a direct line. At the same time, performance data for the coordinate measuring machine are produced during the calculation. If deviations from the performance data are revealed during inspection, then the machine setting is automatically adjusted so that the desired geometry is produced. This "development" is particularly necessary if existing master gears need to be duplicated. ■

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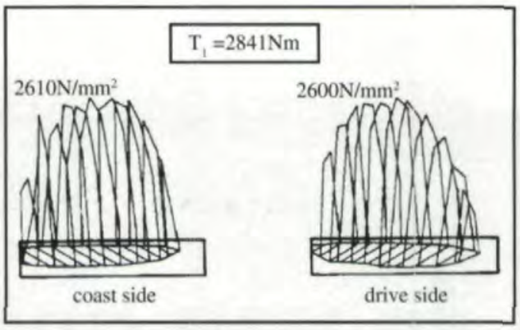

Fig. 17 - Load distribution.

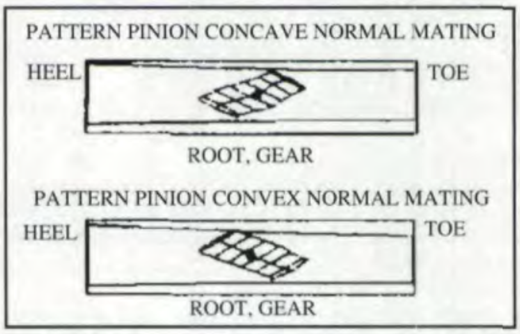

Fig. 18 - Contact pattern with smaller profile crowning.

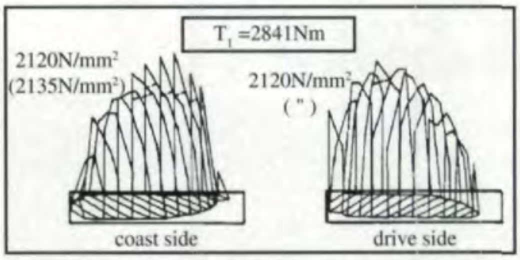

Fig. 19 - Load distribution with greater depth convexity.

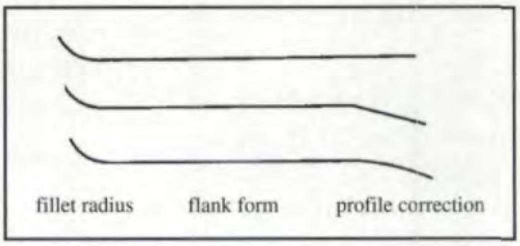

Fig. 20 - Circular tip relief.

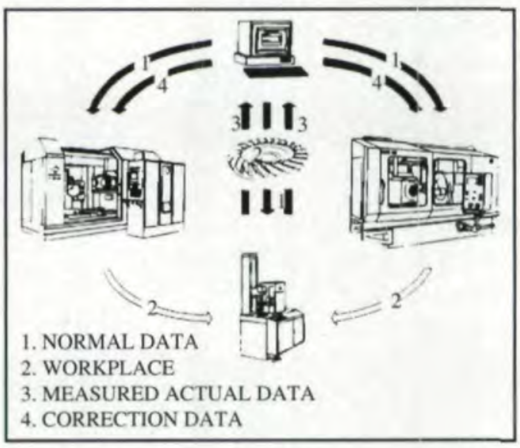

Fig. 21 - Closed loop of calculation, manufacture, measurement, and correction.