Hard Finishing and Fine Finishing

Part 1

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Introduction

Profitable hard machining of tooth flanks in mass production has now become possible thanks to a number of newly developed production methods. As used so far, the advantages of hard machining over green shaving or rolling are that elaborately modified tooth flanks are produced with a scatter of close manufacturing tolerances. Apart from an increase of load capacity, the chief aim is to solve the complex problem of reducing the noise generation by load-conditioned kinematic modifications of the tooth mesh.[2,3,5,6] In Part II, we shall deal with operating sequences and machining results and with gear noise problems.

Geometry of Gear Flanks

Noise generation of teeth in mesh has two causes. The first, a modulation of gear mesh rigidity,[3,5,6] is mainly influenced by the implemented geometry, such as the helix and pressure angles chosen, the addendum/dedendum modification on high tooth design, etc., and, thus, depends only to a small extent on the precision geometry of flanks via contact rigidity.[5-6] The second cause is meshing errors,[8-9] which, however, are due directly to the precision geometry of flanks as a function of the load. Fig. 1 shows influences on the geometry precision of flanks determined by the load and by manufacturing, and from the qualitative viewpoint, the relative tooth contact and generating behavior.[1,8,9]

The left column lists the reasons for various tooth modifications. The second column shows the topological modification of flanks, while the third column illustrates the tooth contact without load and under load. The fourth column is a qualitative representation of the single flank displacement error without load and loaded on account of the modifications of individual flanks.

Suitably designing modifications require that the generated impact and torsional vibrations produced by the single flank displacement errors are kept within close tolerances over the total load range of the gear unit. In practice, such modifications are determined by means of the measurement analysis of the noise emission under operating conditions. The result is a flank geometry having several superimposed modifications as shown in the lower part of the illustration. Since the modifications are within a range of a few micrometers, their kinematic effectiveness requires a production method with the least possible scatter of tolerances.

As an empirical value, tooth quality grade 5 - 6 acc. DIN 3962 is sufficient for the finished flank. The possible ranges of scattered tolerances could then be absorbed by the modification band width (such as crownings) of the gear flanks without producing harmful single flank displacement errors.

Fig. 2 shows the reduction of tolerance from precut tooth quality grade 9 to finish tooth quality grade 5-6, and also the percentage to which the influences of the systems' components on the result should be evaluated.

It will be noted here that the column "machine + tool" has the highest influence altogether. The reason is that deviations of the tool or of machine kinematics will show directly, while other deviations, such as those of fixtures, will only have an indirect influence. This means that, in case of profile error, the machine together with the tool may have profile errors of $\pm 3\,\mu m$. The influence of only $\pm 0.5\mu m$ for reclamping and measuring will be possible only if the toothing deviations are referred to the same position as for machining. This would require a theoretical definition of the tooth gearing axis. This is feasible by a computerized alignment of the topographies of several flanks that are distributed over the work gear periphery.

With conventional measuring instruments the influence by reclamping and measuring should be assumed to be higher.

With such demands on precision, the border line for metal cutting processes in mass production has been reached. A solution will only be possible with processes featuring a minimum of kinematic settings and where the tool flank geometry is either an accurate conjugated mating gear or a conjugated linear section with reference to the flank geometry required.

Kinematics of Hard Finishing and Fine Finishing

Since the work gear flank geometry is composed of linear elements, the linear contact also applies to the gear mesh when machining with a conjugated tool.[8] The three setting parameters which have precedence for generating a conjugated tool flank geometry from a preset cylindrical gear flank geometry are

a. crossed-axes angle
b. externally or internally tool
c. center line distance of crossed axes.

Fig. 3 shows the tool used for the crossed-axes angle range

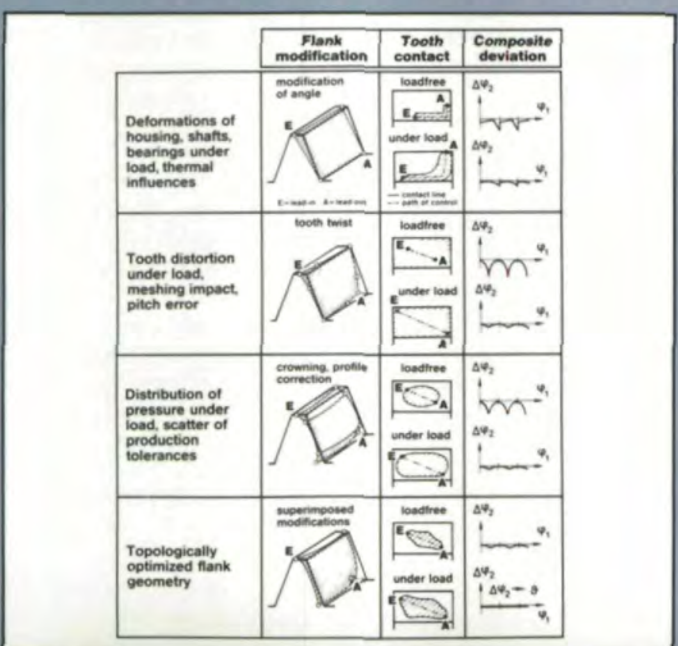

Fig. 1 – Systematic diagram of superimposed modifications of flanks for noise reduction.

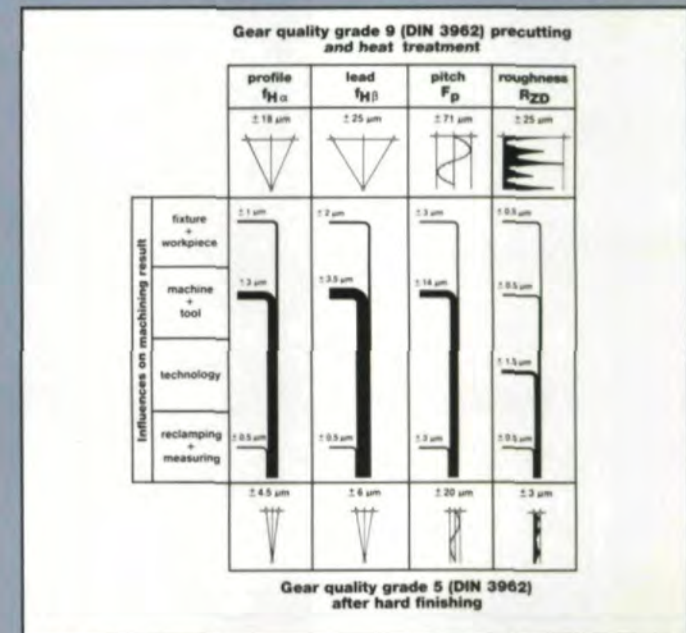

Fig. 2 – Reduction of tolerance from premachining to finishing of tooth flanks.

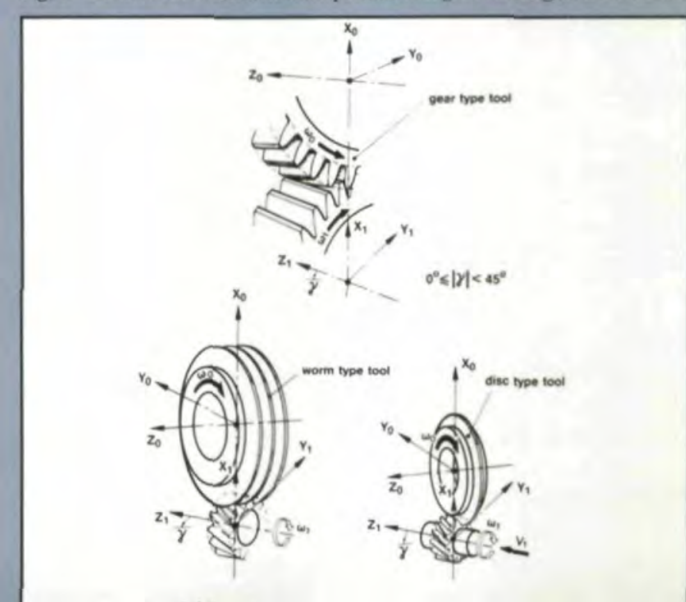

Fig. 3 – Relative position between the tool and work gear.

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$0° < /\gamma/ \leqslant 45°$.[4] A conjugated crossed helical gearing is produced. The effective cutting velocity is the vector sum of the sliding velocity along the profile v_H and along the lead $v_L = v_U \cdot \sin\gamma / \cos\beta_1$. Assuming the peripheral velocity v_U of the tool and the helix angle β_1 of the work gear to be constant, the longitudinal velocity v_L depends sinusoidally on γ.

Assuming further that the external tool diameter is constant, an increasing γ will result in a lower number of tool teeth, since $\gamma \approx \beta_0 + \beta_1$.

Chip Forming Mechanisms During Hard Finishing and Fine Finishing

Fig. 4 shows a tooth of a work gear in conjugated mesh with a tooth of the abrasive tool. Chip removal occurs at every point of the momentary contact line only in the direction of $v_{\vec{Rel}} = v_{\vec{L}} + v_{\vec{H}}$.

The momentary kinematic condition of a cutting edge when cutting into the material could be described as a rolling and sliding of the rolling circles ζ_0 and ζ_1 in the direction of $v_{\vec{Rel}}$. The direction of $v_{\vec{Rel}}$ depends mainly on γ. If $\gamma = 0$, $v_{\vec{Rel}}$ will be oriented exclusively from addendum to dedendum. If γ moves towards $(90° + \beta_1)$, $v_{\vec{Rel}}$ will be increasingly parallel to the lead direction.

Accordingly, the relative conditions of curvature diverge considerably from each other. If the circles of curvature are small, as shown in Fig. 4, the cutting grain will penetrate very steeply into the material and will leave the cutting path after a short contact length. The condition for the next cutting grain to have sufficient material for actual penetration and not be shoved elastically away will be decisive for the structure of the cutting surface.[10,12]

With small effective circles of curvature and high rolling velocities, the cutting structure requires a higher density of cutting edges than for large circles of curvature and low rolling velocities. That means, with an increasing γ, the structure of the tool must be more open.

This short survey of metal cutting mechanisms is intended to illustrate that in gear finishing, the geometric and kinematic process parameters dependent on the tool and the work gear will substantially affect the choice of a suitable cutting and bonding material, as well as optimal structure of cutting surface.

Drive System For Hard Finishing and Fine Finishing

Another essential mark of distinction between these two modes of finishing is the type of drive system used. Fig. 5 shows

Fig. 4 – Operating conditions of a cutting grain during relative sliding and rolling of the momentary equivalent circles of curvature.

the various modes of current drive systems.

The left side of the picture shows the radial load connection with a two-flank contact.[4] The work gear is in free mesh with the tool without controlling the drive gear. This hard finishing process is similar to the green shaving process and produces similar quality grades, but before heat treatment. The two-flank method is not discussed in this paper.

The drive mode shown in the middle of the illustration can only be used to improve the microstructure of the flanks, for flank modifications, and for removing defects from gears. Due to the braking force, there is only a one-flank contact, so that the various divergences of right-hand and left-hand flanks have no influence.

Both drive modes shown are not able to specifically generate a definite flank geometry, since the tool follows the pitch geometry produced by premachining.

From Fig. 2 we see that in order to produce a specific definite flank geometry based on a usual premachining, a stock removal of about 50 to 100 μm per flank is required. To this effect the tool and the work gear must be in constrained mesh, as is shown symbolically on the right side of the illustration.

The left part of Fig. 6 shows a mechanically constrained mesh using helical toothed conical gears.[4] The relatively simple and safe mechanically constrained mesh meets the requirements for high torsion rigidity and dynamic transmission. The tool – a CBN-coated cutter – and the work gear are coaxially mounted on the spindles of the helical toothed gearing, work being done with single-flank contact. The stock is removed by a relative tangential displacement.

Relative tangential displacement is achieved by obtaining a contact of flanks of both gearings beyond the nominal center line distance. When the gearings approach radially up to their nominal center line distance, they must make way for each other while rotating; this is achieved by making one flank of the tool penetrate into the flanks of the work gear during rotation.

By knowing accurately the relative tangential displacements on a change of the center line distance, one will be able to maintain accurate backlash tolerances.

Tools For Hard Finishing and Fine Finishing

As was said initially, the main problems with hard finishing processes are encountered in the high accuracy required in mass production, because the result of the machining must be reached with statistical reliability. Deviations from the tool flank geometry are reproduced on approximately a 1:1 scale as deviations of the work gear flank geometry. From the overall tolerances for the work gear profile, for instance, a separate tool tolerance of $\pm$ 3μm will have to be kept for the machine and the tool (Fig. 2).

Fig. 7 shows various possibilities of production for hard finishing and fine finishing tools.

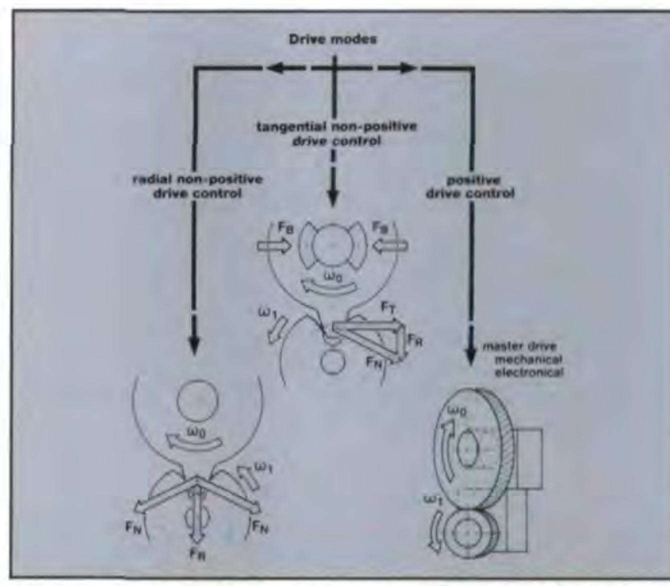

Fig. 5 – Drive modes for hard machining processes with a non-defined geometry of the cutting edge.

Fig. 6 – Mechanically constrained mesh of a CBN-coated tool with a crossed helical gearing.

The method for tool production shown on the left of the figure consists of producing a coarse positive replica of the tool by a technique like hobbing. From this gear a negative mold is made. A mixture of synthetic resin and abrasive grains is cast into this mold, which then sets to form the tool gear with an approximate shape of flanks.

The accurate flank profile of the tool is obtained by means of a diamond dresser. In its coated condition, this wheel has precisely the flank profile of the work gear flank desired. The synthetic resin bonded tool is used predominantly with drive modes without a constrained mesh. It is most suitable for improving surface finish and for removing damages.

The production of the vitrified bonded tool is shown in the central part of the illustration. The disk type gear is given a preliminary profile by a form grinding wheel, while the accurate flank profile is again obtained by means of a diamond dresser. This tool version is mainly used for drive modes with constrained mesh. The chip removal here is proportionately higher than for the synthetic-resin bonded tool version.

On the right side of the illustration is the drawing of a tool coated with abrasive material. The flank geometry, including all necessary modifications of flanks, is ground. After coating it may be possible to either dress the tool with a diamond dresser[7] or to use it directly for hard finishing.

The close admissible tolerances within a range of a few micrometers for the tool emphasizes the problem of tool wear. It may be solved either by dressing the tool in the machine with a diamond dresser or by using wear-resistant cutting materials which will be removed from the basic tool after the end of the service life. In this case, the basic tool could be recoated several times.

Computer Assistance

Since geometrical and kinematical correlations with regard to the production of basic hard alloy coated tools are quite complex, they require an extensive assistance by computers. Its aim would be to produce all manufacturing data and machine settings automatically on the basis of the data of the desired tool flank geometry.

Fig. 8 shows a detail of the manufacturing drawing for hard

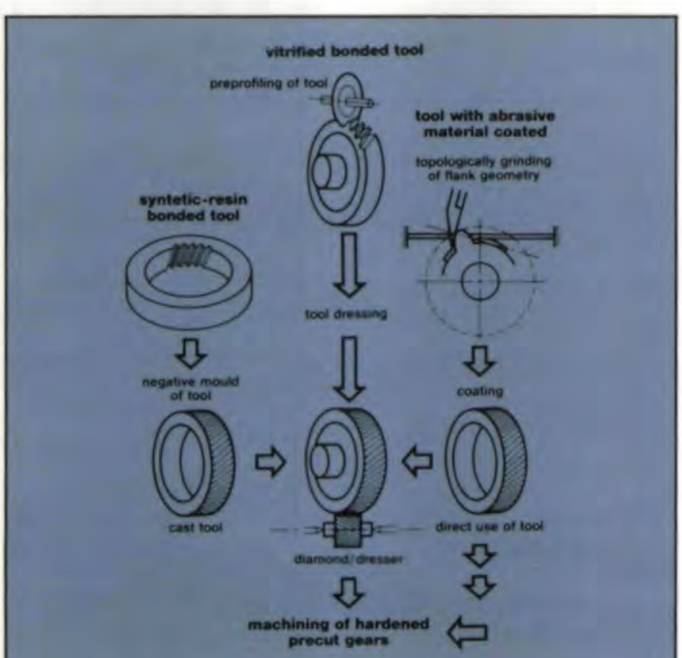

Fig. 7 – Basic possibilities of producing gear-like tools.

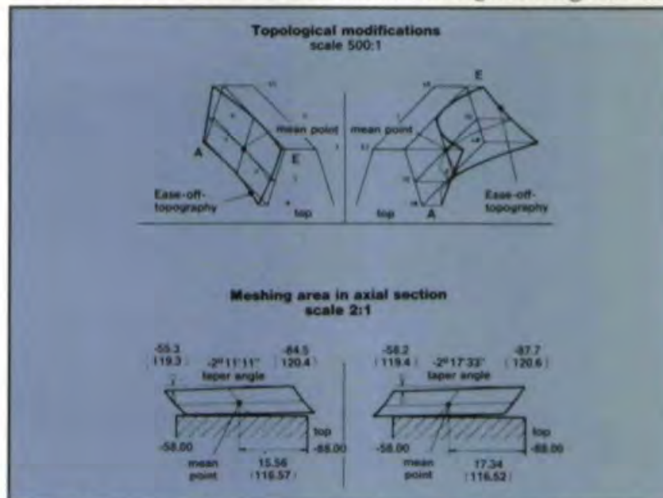

Fig. 8 – Detail of a workshop drawing for producing coated hard finishing tools.

alloy coated tools. The upper part of the illustration shows topological deviations with regard to the enveloped involute surfaces. Such deviations are strongly affected by the crossed-axes angle and by the axial position of the gearing with reference to the crossing of axes. The lower part of the illustration shows the meshing conditions of the tool in the axial section. The required flank limiting geometries of the tool can be gathered from these drawings.

Machinery for Hard Finishing and Fine Finishing

Machinery for hard finishing and for fine finishing have similar designs. Essential differences, due to different aims, concern the drive system and the controls.

The "fine finishing" mode aims at removing damage and at improving the microstructure of flanks. The process is characterized by the unconstrained mesh of the tool and the work gear.

The "hard finishing" mode aims at producing gears ready for assembly, starting from the work gear that has been hardened before finishing. It is characterized by the constrained mesh of the tool and the work gear. On the one hand, this finishing mode should have a metal removing capacity of 10 to 100μm per flank, while at the same time, the microstructure of flanks should make further finishing unnecessary.

Editor's Note: Part II of this article will discuss Operating Sequences and Machining Results and Gear Noise With Hard Finished and Fine Finished Gears.

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