

## STATE OF PROCESS DEVELOPMENTS AND TRENDS IN HARD GEAR FINISHING

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This paper summarises and presents the dominant processes with a geometrically non-defined cutting edge. The review reflects on the methods of generating and profile gear grinding applied in these days industry. The analyses of the machine tools applied in several processes include functionality, machining quality, productivity and economy. I summarize the most important innovations linked to the elements of the manufacturing system, highlighting the economical application of galvanic bonded CBN grinding wheels trough the combination of processes. I display the processes and tools flexibility, productivity and it's field of application.

**Keywords:** gear finishing, combined process

### Introduction

The constantly developing automotive industry demands the production of gearboxes to become faster, more economical and precise. The requirements set up against modern gears pose new challenges to the constructors and the technologists. To reach the lowest possible weight, the top layer of the gearing must be hard and wear-resistant, while the gear core and the gear shaft must be high-strength to endure the dynamic effects and resist the fatigue. To compensate the load-dependent deformation of the gearing and guarantee the undisturbed tooth engagement at the same time, geometric modification of the gearing geometry, as well as form and position modifications are applied.

At the beginning of the process chain of gear manufacturing, we shape up the gear geometry before the part gets heat treated. The geometry of the wheel body and the gearing can be made by either forming processes like forging in dies or sintering or cutting processes. Pre-machining is usually in conjunction with the subsequent heat treatment, generally case hardening. Due to the heat treatment, the material characteristics of the gear are modified and the gearing geometry becomes distorted, which necessitates hard finishing of the wheel-body and the tooth flanks. The major problem of the treatment is the unpredictable nature of these distortions. Thus gear hard machining is the necessary final process step to achieve the most important goals: maximum load capacity and minimum running noise.

The hard fine machining of the gears can be achieved applying processes either with geometrically well defined or with non-defined cutting edges. Regarding the wheel body, a strong competition can be observed between hard turning cylindrical and face grinding because

environmental awareness receives increasing emphasis besides productivity. The hard fine machining of the tooth flanks is mostly performed with geometrically non-defined cutting edges due to its maximum achievable gear quality. The following section is focusing on the most productive processes of gear grinding [1].

### The comparison of gear grinding processes

Heat treatment is the core step of the high quality production of high-speed and high-loadability gears. These gears are case hardened to maximize the strength of the tooth flank and tooth dedendum, in addition to minimising their dimensions and weight at the same time.

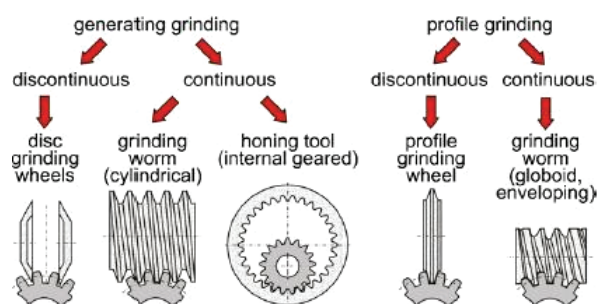


Figure 1: Abrasive processes for hard gear finishing [4]

The hard fine machining of gears is unavoidable due to the fact that the parts are deformed during heat treatment. The most economical way of machining the parts with 50HRC or harder surface is by grinding, where only a layer of about 0.1–0.15 mm is ground off the tooth flank. In the following section, I classify the gear grinding processes after Fig. 1 [4].

*Discontinuous profile grinding*

With discontinuous profile grinding, the tooth flanks of a gear can be either ground separately or jointly depending on the number and set up of the grinding wheels. The profile of the grinding wheel is usually identical to the profile of the workpiece in normal section. The wheel must always be set up with the helix angle  $\beta$  to the normal section of the workpiece. In order to reduce the deformation of the grinding wheel occurring due to grinding, the axial forces must be reduced and their occurrence avoided. There are several variations in the set up of the grinding wheels to avoid these effects. Discontinuous profile grinding is currently applied for modules of 1–35 (40) mm for internal and external spur gear manufacturing [3, 4].

*Continuous profile grinding*

Continuous profile grinding of tooth flanks is an attempt to increase productivity by using a globoid worm-shaped grinding wheel. The tool surrounds a determined part of the workpiece. The globoid worm grinding wheel can only be used for one specific workpiece geometry. Therefore, this process is recommended for serial or mass production.

This process was developed to the level where it was suitable for serial production around 1980. Due to the microscopic grinding structure, which often causes a wheezing noise in the gearbox, gear honing is usually applied after continuous profile grinding. In 1997 a special machine tool was introduced on the market which included continuous profile grinding and the honing process in one setting. A noticeable increase in productivity could be reached compared to the high technology of the time. Further advantages of this process are high precision and the repeatability of the gearing quality. In spite of the improvements the process is no longer competitive compared to the continuous generating grinding [3, 4].

*Discontinuous generating grinding*

During discontinuous generating grinding the tooth flank of the spur gear will be shaped stroke by stroke with a double conical grinding wheel by polygonal small cuts. This process was industrially applied for the first time around 1930. Within the technology of discontinuous generating, single flank and double flank grinding can be distinguished. Single flank grinding generates better grinding accuracy compared to double flank grinding because the tool can be optimally adjusted to the machining task. This flexible process is able to machine workpieces with a module of 35 mm and a diameter of approximately 4000 mm. Combining the advantages of the two processes, it is possible to perform the roughing operation by double flank grinding and the finishing process by single flank grinding on modern machine tools [4].

*Continuous generating grinding*

During the continuous generating grinding process a single pass or multi pass worm-shaped grinding wheel is continuously moving along the gear like a hob. The shape of the grinding worm corresponds with the profile of a straight gear rack. The geometry of the worm grinding wheel only depends on the workpiece geometry, i.e. module and penetration angle. During the process the machine tool has a multi point contact with the workpiece, which is responsible for the high productivity due to the fact that more than two flanks can be ground. Because of the limited width of the grinding worm, this process cannot be used for the machining of large-size gearings. It is currently limited to small and medium sized modules of 8 (10) mm and a diameter of 1000 mm.

Several process options are distinguished. During pendulum grinding, the worm grinding wheel is fed for a constant small amount at the upper and lower dead centres. In between it is shifted in axial direction to make use of unworn abrasive grains. This process version is called diagonal generating grinding. During shift grinding new areas of the grinding worm are screwed in the cutting zone to compensate wheel wear [3, 4].

**Process developments and trends**

In the following section, I am presenting the main process developments applied in the hard finishing of case hardened gears at gearbox manufacturing.

*Developments regarding the work piece*

During the manufacturing process a kind of heat treatment follows pre-machining, which results in the distortion of product geometry. The major problem of the heat treatment is the unpredictable nature of these distortions. Experiments were made to eliminate this effect by applying the FEM analysis on the process. In recent years, attempts have been made to replace gear hobbing with precision forging in the gear process chain. The high costs of die making and complicated optimisation qualify this concept exclusively for large batch production. This results in new challenges for the grinding processes. The most critical area to be dealt with is the control of the stock allowance. Thermal distortions especially for helical gears might result in unacceptable high allowance on individual tooth flanks bearing the danger of grinding burn [4].

*Developments of the clamping system*

In recent years radical changes have been applied both in the machine tool and the workpiece clamping system due to the variable demands. Naturally, machine tools possess extremely stiff clamping devices to hold the tool-set containing two or four grinding tools in the right position.

For example, one specific tool set is applied for the roughing and finishing of gearing in case two different tools are assembled on the grinding spindle. For the concentric clamping of gears shafts and gears, hydro expansion clamping mandrel or collet are applied, which is part of the gear grinding monitoring system due to the sensors built in [6, 7].

#### *Development of the machine tool*

Trendsetting is the construction of special machine tools for particular applications, which can be offered at very reasonable prices. On the other hand, the target has been set to grind high precision gears in any claimed size and geometrical modification. This goal is achieved by applying machine tools in varying sizes but with identical kinematics. All in all the time of universal machine tools is gone in mass production. Current high-tech is the use of thermally stabilized machine tool structures with integrated dressing units with their own NC-controlled axes. To absorb harmful vibrations polymeric concrete is applied in the frame structure. To reach high precision workpiece movement, linear movement drives are built in the machine tool, fitted with measurement and sensor technology. In order to fulfill the "first part good part" philosophy, gearing measurement technology is applied with grinding, measuring, grinding [6].

#### *Developments of the tool set*

For the sake of larger productivity, single-layer electroplated CBN grinding wheels gain ground in the area of mass production. CBN grinding wheels are usually fabricated with a single layer of abrasives that are applied to a steel core using a layer of electroplated nickel. The plating thickness on these wheels is maintained at 50% to 70% of the nominal crystal size. The size of the CBN crystals and the topographical characteristics of the wheel can influence the surface roughness and the grinding texture. In case of wheel selection, the most important factors are CBN crystal toughness and nickel plating thickness. The best performance is obtained with a combination of higher toughness crystals and thinner plating layers. The useful life of these wheels is restricted by the single abrasive layer that exists and the limited amount of crystal exposure above the nickel plating [2, 5].

Because of the high tool costs of non-dressable CBN worm grinding wheels, the use of dressable CBN worm grinding wheels is considered. Experimental investigations of the dressing of vitreous bonded CBN worm grinding wheels reveal the possibility of grinding gearings. Contrary to single layer electroplated CBN worm grinding wheels, vitreous bonded dressable CBN grinding worms have an essential advantage regarding their flexibility during dressing and topography generation. These dressable tools are very common in the industry because the costs of procurement and maintenance make the tools very economical for small batch production. Nowadays it is an important requirement against machine tools and tool

sets to have the possibility of applying high level process combination. This means that two workpieces can be ground simultaneously or more than one tool applied in the same tool set [4, 6, 7].

#### *Developments of the control and diagnostic systems*

From the aspect of production stability, it is essential to follow the grinding process through a monitoring system. The most common machine tool control system applied in generating grinding machines is the Siemens 840D, which includes its own complex generating grinding software, which can significantly ease machine tool programming. The requirements against control systems are higher and higher in the aspect of both measuring cycle between roughing and finishing, and the adequate monitoring of the grinding process. For example in case of machine tools capable of performing discontinuous profile grinding as well as part generating grinding, it is not rare to have 12 controlled axes.

To avoid or detect grinding burn, the grinding process is observed by sensors and the control system maintains the process characteristics under a limit value. This can be done by power monitoring, when the power portion used for material removal is monitored. In case of acoustic emission systems, the harmful vibrations are detected, which are generated along with inappropriate technical parameters and lead to grinding burn. In case of micromagnetic measurement technologies, the changes in the physical characteristics of workpiece surfaces are observed [4].

#### *The examination of process combination*

The main goal is to increase productivity and benefit from the advantages of the two specific hard finishing processes, while avoiding their disadvantages; for this end, several types of process combinations are applied in the industry.

Roughing and finishing with different tools utilising the same process is considered the lowest level of process combinations. This is the case with continuous generating grinding and profile grinding. Advantages can be seen in the optimized specification of the grinding wheel.

The next level of process combinations is seen in the simultaneous use of different hard finishing processes in one machine tool. A great example for this solution is the process combination of discontinuous profile grinding and continuous generating grinding. It is possible to grind two gearings on one shaft. This solution is viable for gears shafts because all of the gearings can be completed in one clamp. One specific tool set is applied for each of the two gears, thus four different tools are assembled on the grinding spindle. In this case the machine tool can control the four grinding tools. The combination of processes is of course always combined with the increasing purchase costs of the machine tool, especially if the integrated processes have different kinematics. But a reduction of the manufacturing time

can be achieved, especially if otherwise the machining has to be done on different machines after each other.

Nowadays the highest level of process combination in the field of hard finishing processes is seen in the complete machining of a whole wheel body. This includes the inner diameter bore and/or ground bearing shoulders and plane surfaces and the tooth flanks [2, 4].

#### *Technical conditions of the experiments*

This investigation was undertaken to evaluate the effect of different process combinations on gearing quality. During the experiment I measured every tenth workpiece of the batch of 300 pieces applying the method described below. High gearing quality and process safety can be achieved with the combination of discontinuous profile grinding and continuous generating grinding. The use of the worm-shaped grinding wheel results in high productivity and the low occurrence of grinding burn instead of higher stock allowance, while the profile grinding disc warrants high gearing quality. During the experiment three versions of process combinations were investigated. The first version is the roughing and finishing of tooth flanks by profile grinding disc. The second version is roughing by grinding worm and finishing by profile grinding disc. The third version is roughing and finishing by grinding worm, which is a new field of application.

The comparison of process combinations is demonstrated through the grinding of the long gearing of a layshaft.

The conditions of the experiment can be seen below. The machine tool is a KAPP KX1 gear grinding center.

Tool data:

Roughing grain size: B252

Finishing grain size: B64

Grinding with worm-shaped grinding wheel:

Number of threads: 4

Tip diameter of worm:  $d_{m1} = 161.511$  mm

Mean skew angle:  $\beta = 83.8160^\circ$

Machined pressure angle:  $\alpha = 22^\circ$

Axial distance:  $A_b = 128.999$  mm

Spindle revolution:  $n_c = 5900$  min<sup>-1</sup>

Spindle inclination:  $B = 15.319^\circ$

Grinding with profile grinding disc:

Tool diameter:  $d = 109.981$  mm

Cutting speed:  $v_c = 35$  m/s

Spindle revolution:  $n_c = 6078$  min<sup>-1</sup>

Measuring was done using a Klingelnberg P26 type automatic CNC controlled gear measuring center. The technical data of the machined gear are as follows:

Number of teeth:  $z = 18$

Normal module:  $m_n = 4.7$

Transverse modul:  $m_t = 5.0691$

Pressure angle:  $\alpha = 20^\circ$

Lead angle:  $\beta = 22^\circ$ , right

Pitch circle diameter:  $d = 91.244$  mm

Addendum circle dia.:  $d_a = 106,5$  mm

Root circle diameter:  $d_f = 82.1$  mm

Profile displacement:  $x = 0.55462$

Face width:  $b = 36$  mm

Base tangent length:  $W_k = 51.765$  mm

Number of teeth:  $k = 4$

#### *Analysis of experimental results*

The measured parameters are as follows:

Base tangent length

Profile and lead

Pitch error

Composite pitch error

Radial runout

*Table 1: Results of the measurements*

Process combination	Profile-profile	Worm-profile	Worm-worm
Pitch error left +	2.2	2	3
Pitch error left -	2	2	3
Pitch error right +	3.2	2	3
Pitch error right -	4.8	2	3
Composite pitch error left	6	5.1	10
Composite pitch error right	20	6.9	11
Radial runout	14	2.5	10

The figures in the first table represent the average of the measured deviations expressed in micrometers.

The second column shows the first process combination, i.e. roughing and finishing using profile grinding discs. Due to its low productivity, this combination is only used when the other combinations fail. As it can be seen, the pitch error value on the left tooth flanks alternate between  $-2 \mu\text{m}$  and  $2.2 \mu\text{m}$ . However, on the right tooth flanks, this value increased to  $+3.2 \mu\text{m}$  and  $-4.8 \mu\text{m}$ . The profile disc was deformed by the axial forces, which were produced by the irregular stock allowance on the tooth flanks. The composite pitch error follows this trend as it shown in the chart. The radial runout value is  $14 \mu\text{m}$ , thus eccentricity is  $7 \mu\text{m}$ .

The second process combination is roughing applying grinding worm and finishing by profile grinding disc. The profiles of the right and the left tooth flank follow the same trend as roughing by the grinding worm had already resulted in even stock allowance. The worm has higher stiffness than the profile disc and the grinding forces cannot deform it. The quality of the profile and lead is ensured by the profile grinding disc during finishing. The values represent this high process stability and the low values of the deviations.

Finally, the process of roughing and finishing using the grinding worm is analysed. The profile and the lead are similar to the results of the previous process combination. The trend of the pitch errors is not as regular as seen at roughing and finishing by profile discs. On the left tooth flanks the pitch error alternate between  $+3 \mu\text{m}$  and  $-3 \mu\text{m}$ . On the right tooth flanks the same values seen. The radial runout value  $10 \mu\text{m}$  means  $5 \mu\text{m}$  eccentricity.

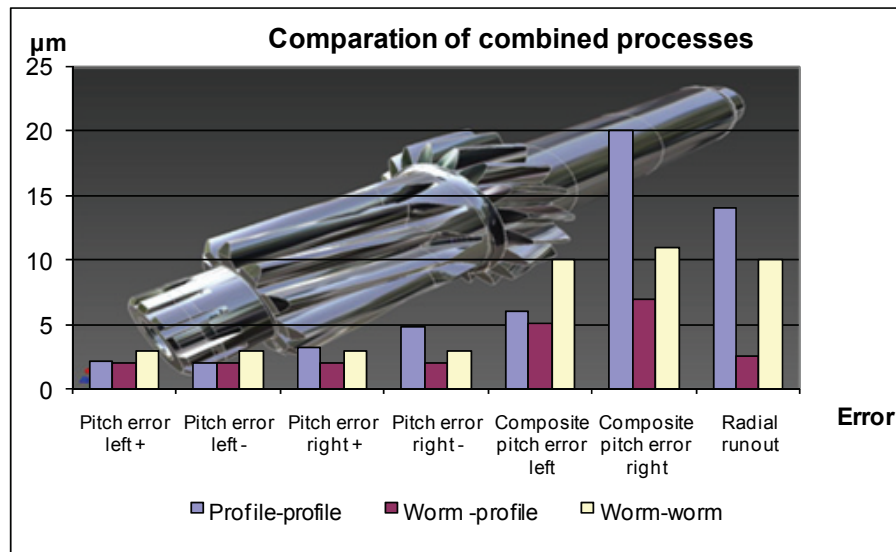


Figure 2: Conclusions

### Conclusions

Summing up the above described findings, we can say the application of grinding worms represents a significant improvement compared to the use of profile discs. The set of individual errors is the same in case of all the three processes but the trend of composite pitch error is more favorable when roughing is done by grinding worm and the finishing by profile disc. The best results can be achieved by combining the advantages of the two processes. Roughing by the grinding worm is very productive and the possibility of grinding burn is minimal. The profile disc ensures the quality of the tooth flank but the discontinuous process increases the primary processing time. This disadvantage can be eliminated with the application of grinding worms both during roughing and finishing but the increasing productivity is at the expense of gearing quality to a certain extent. All in all development points towards the application of grinding worms because of their high productivity and the low wear due to the increased grain number on the tool surface. The application of superabrasives like CBN revealed considerable cost advantage due to the number of gears that can be ground by one a tool with a single layer of electroplating .

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