Synthesis Report

in respect of the CRAFT Project:

"High Precision Shave-grinding System for Single Step Hard Finishing Operation of Gears"

Project No.: BRE2.CT94.1341

- non-confidential -

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1 Title, authors names and addresses

Synthesis Report or the CRAFT project No BRE2.CT94.1341 entitled "High precision shave-grinding system for single step hard finishing of gears”.

The report was written by:

- Prof. Dr. Ing. habit. E. Brinksmeier; Stiftung Institut für Werkstofftechnik (IWT); Badgasteiner Straße 3; D-28359 Bremen
- Dr.-Ing. U. Berger; IWT
- Dipl.-Ing. Ch. Schneider; IWT
- Dr.-Ing. W. Beuck; Bremer Institut für Betriebstechnik und angewandte Arbeitswissenschaft an der Universität Bremen {BIBA); Hochschulring 20; D-28359 Bremen

2 Abstract

Due to environmental requirements (noise and efficiency) and due to the extreme cost pressure suffered by European gear manufacturers there is an increasing demand for a hard gear finishing process that provides excellent geometrical quality and noise behaviour at very competitive costs. Shave-grinding seems to be a technology which could comply with these demands.

The most important field of application is in the manufacture of transmissions for automotive industries (cars, trucks, motor-cycles etc.). Tool and gear manufacturers are usually SMES working as subcontractors for bigger companies. Most of them don't have enough R & D capacities to develop new machine tool concepts.

Shave-grinding is a highly complex machining process with interdependencies between the process parameters. For this reason research work was mainly performed with a test bench, thus allowing technological modelling of the process. The basic idea of the test bench is to use a face grinding process at low speeds (0.5 to 3 m/s) and an axial offset between the axes of workpiece and tool to produce the characteristic texture. With final investigations on shave-grinding machine tools the obtained results were validated.

The following achievements were result of the project work and basis of a machine tool concept for improved hard gear finishing through shave-grinding technology:

- Constraint model for input and output parameters for shave-grinding
- Test bench and test method for tool specifications
- Cutting performance list for common shave-grinding tool specifications
- Improvement of an existing tool specification and development of a new tool generation
- Graphical visualization of shave-grinding process
- Video of process visualization
- Laboratory set-up for visual inspection of helical gear wheels

The principle effect is the strengthening of the market position of the proposers in the short run, Additionally, depending on the results of the exploitation phase, a new European cost and quality standard that overmatch Japanese and US standards may be introduced in the long run.

3 Introduction

Due to environmental requirements (noise and efficiency) and due to the extreme cost pressure suffered by European gear manufacturers an increasing demand exists for a hard gear finishing process that provides excellent geometrical quality and noise behaviour at a very competitive cost. Shave-grinding seems to be a technology which could comply with these demands.

Surveys among companies of the automotive industries [BAUS-94] have shown that actually the following machining sequence is mostly used in production:

- gear cutting [bobbing) → finishing (shaving process) → heat treatment (hardening) → hard finishing (if necessary}

The finishing process *before* heat treatment is to compensate the unavoidable shortcomings due to hardening (distortion). Nevertheless there is still a scattering in gear geometry [SCHR-94] that has eventually to be corrected by an additional hard finishing process.

A thorough investigation of the international state of the art, considering the expertise of industrial gear manufacturers, has shown that conventional hard finishing techniques (hard skive bobbing, hard shaving, continuous gear grinding and continuos profile grinding with globoid worm} have many restrictions *such* as danger of thermal damage of the subsurface or a possible insufficient surface texture leading to high noise emission, Moreover these finishing techniques are time consuming and expensive.

The shave-grinding technology is a new approach with high potential because it is free of thermal influence on the subsurface and produces a favorable surface texture [BAUS-94]. Conventional shave-grinding of gears has been widely used in industry (mainly smaller passenger car components) for more than 10 years. The existing equipment however allows only improvement of the surface structure. Typical material removal rates are 5-10 µm per flank. The geometrical accuracy has to be obtained by a previous hard finishing operation.

Shave-grinding is a complex machining process with interdependencies between the process parameters. For this reason technological investigations were performed with a test bench as technological model of the process. The basic idea of the test bench is to use a face grinding process with low speeds (0.5 to 3 m/s) and an axial offset between the axes of workpiece and tool to produce the characteristic texture.

4 Technical description

4.1 **Shave-grinding for hard finishing of gears**

Shave-grinding (Power Honing) is a new technology for the hard finishing of gears. The most important field of application is in the manufacture of transmissions for the automotive industry.

The combination of the shave-grinding tool and workpiece {see figure 1) can be compared to an internal, crossed helical gear pair. The internal geared tool-ring comprises abrasive grains and bonding agents. For material removal, both the workpiece and the tool have to rotate and the ensuing cutting process is caused by relative movement (sliding) between corresponding points on the surfaces of the tool and workpiece.

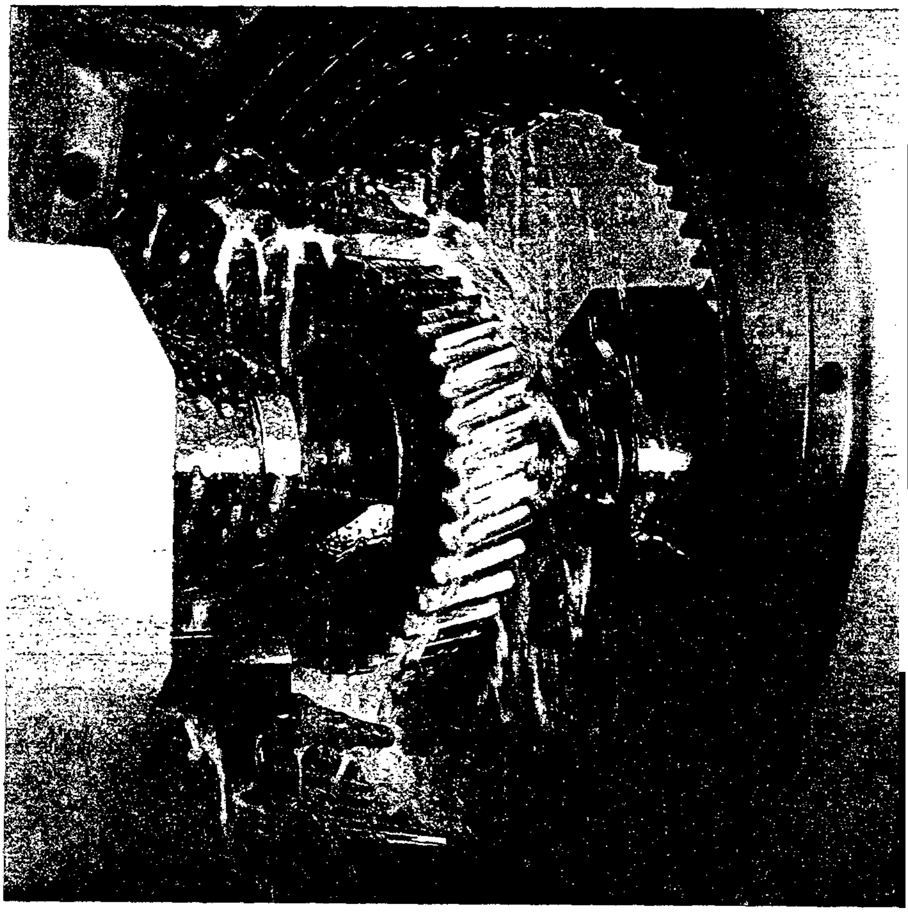

Figure 1 *Hard finishing of* gears *through shave-grinding*

Shave-grinding is a complex machining process with interdependencies between the process parameters. For this reason the machine tool development is performed with a test bench, thus allowing technological modelling of the process. The basic idea of the test bench is to use **a** face grinding process at low speeds (0.5 to 3 m/s) and an axial offset between the axes of workpiece and tool to produce the characteristic texture.

4.2 **Sliding speed for shave-grinding**

Figure 2 shows the scratches of active grains on a typical tooth manufactured by shave-grinding. The direction of the scratches is parallel to the direction of the relative movement between tool and workpiece responsible for material removal.

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Figure **2** *Scratches of active grains caused by shave-grinding*

The relative movement between the contact points of a helical gear pair has two speed components. There is a sliding speed in direction of helix v_{gs} and a sliding speed in direction of the involute v_{gev}. Both speed components are perpendicular. The relative movement between workpiece and tool is characterised by the mentioned speed components. The consideration of all speed components form a characteristic speed pattern that can be seen in figure 2. For description of the total sliding speed v_g the cutting angle α is introduced.

4.3 **Modelling of the shave-grinding process**

During sliding and rolling of the gear flanks the grinding situation is changing constantly because the changing curvature of the flanks and the changing velocity of the sliding movement. The analogous model has the advantage, that the grinding situation is constant.

The exact geometry of the workpiece is the geometry of a helical gear with standard modification of the flank shape. The exact geometry of the shave-grinding wheel is like a special internal geared globoid wheel. The geometrical deviations between the exact shape of the grinding wheel and a helical gear are small. On recommendation of PFAUTER, an assumption is made that the combination of shave-grinding tool and gear wheel is transferable to **an** internal, crossed helical gear pair. For analysis of the shave-grinding **process concerning** speeds and cutting situation the model of a helical gear pair is used,

The basic idea of the whole modelling research is to describe the shave-grinding process with the well known parameters of conventional grinding.

Figure 3 shows the principle relations between the shave-grinding process and the analogous grinding process. For realisation of the cutting angle α an axial offset between workpiece and tool axis has to be introduced. The figure also shows the transformation of main parameters of shave-grinding to main parameters of axial grinding.

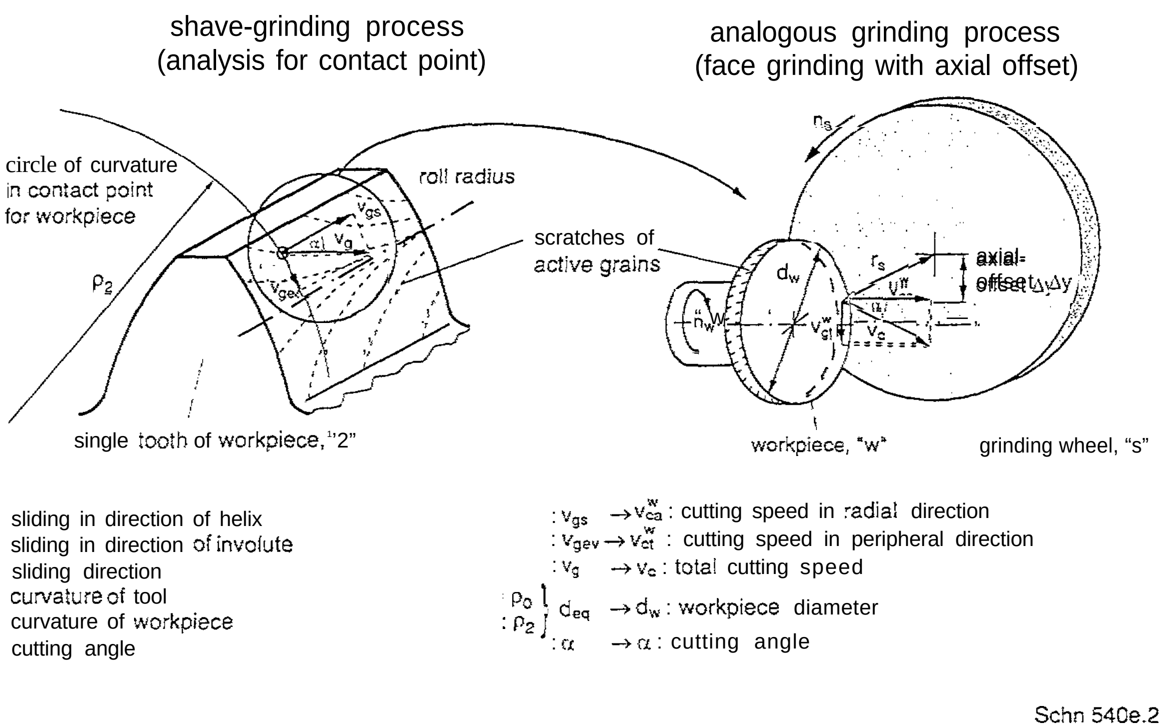


Figure 3 Principle relations between shave-grinding and analogous process

4,4 **Visualization of the shave-grinding process**

An appropriate software based on a geometric/ kinetic simulation system has been evaluated for the specific tasks. The development of such an **analogous** model presumes the knowledge of the main kinetic and geometric parameters. In order to investigate, which of the kinetic parameters are important, it has been necessary to investigate the basic principles of the contact conditions between workpiece and grinding tool. Therefore a mathematical / technical model has been built for the exact simulation of the real geometric parameters.

For the graphical simulation of the shave grinding process the software VIRTUAL-NC from DENEB ROBOTICS has been used. Machines, tooling and fixtures could rapidly be modelled using built-in component libraries and the integral CAD package, or by importing files from other CAD programs. The models easily could be enhanced to include machine attachments or articulated fixture. There is no limit to the number of machine tool axes that can be modelled.

For the modelling of cylindrical and helical gears the manufacturing parameters have been identified as input parameters. The modelling process of the gear wheel and the shave grinding wheel has been divided into two steps; first gears with spur tooth and second helical gears. This has been necessary to minimise the computing time during the starting phase.

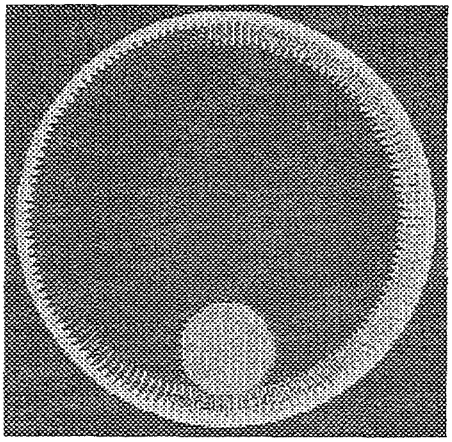


Figure 4: *Simulation of the manufacturing process (straight toothed)*

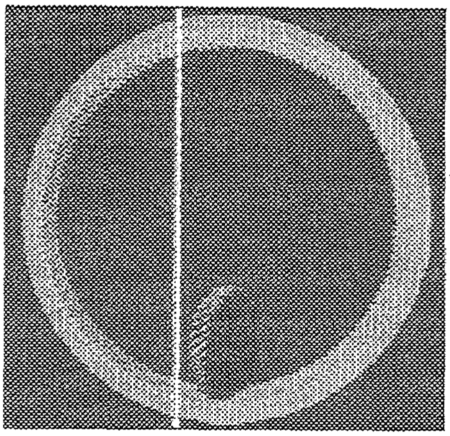


Figure 5: *Simulation of the manufacturing process (angle toothed)*

For the design of a helical gear wheel flank and the required tool there has been used an involute function from the literature. The design of the involute is based on intermediate connected polygons with adjustable length. The accuracy of this polygon based model in comparison to a real wheel is based on the numerical computing hardware restrictions of the used computer. The design of the geometric values of the shave grinding wheel have been done in a similar way.

After the flank of the gear wheel and the shave grinding wheel has been devised in rectangular grids (regarding geometric constraints of lateral and profile polygons, similar to these of a Finite-Element-Analy sis). As before, the grid dimension can be scaled down to infinitesimal small values.

To generate a true kinetic model of the shave grinding process a contact algorithm has been developed. This means, that each contact case of a gear wheel grid and a shave grinding wheel grid is visualized and numerically stored. After finishing of the simulation procedure a data set of all contact grids and their time based derivation for grinding velocity and acceleration can be gathered (figure 4 and 5}.

The material removal is continuously updated and critical machining data can be monitored (figures 6 to 9):

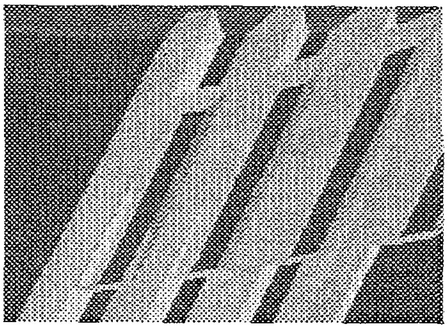


Figure **6:** *Contact of tool and* **war(f)**

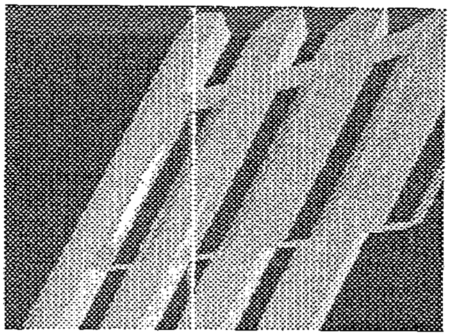


Figure **7:** *Contact of tool* **and** *gear (2)*

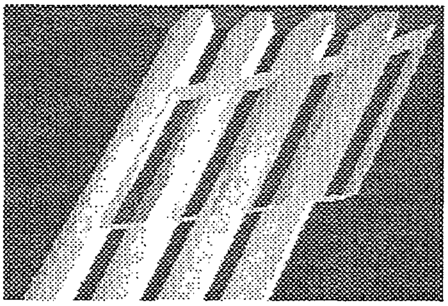


Figure 8: **Contact** *of tool and gear (3)*

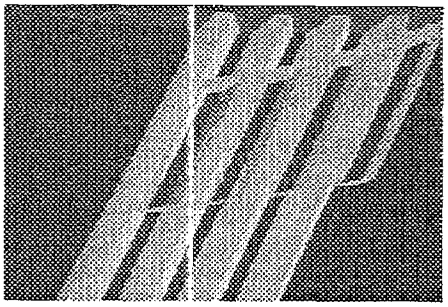


Figure **9:** **Contact** *of tool and gear (4)*

- **Depth of cut**
- **Volumetric rate of material removal**
- **Axis speeds, feedrates, positions and accelerations**
- **Gage point** location
- Cycle **times**
- **Dimensional relationships between any two parts**
- **Dynamic dimensioning**
- **Distance to go**

The display cycle information is displayed in **pop-up windows** or **strip charts. Configurable** colour **graphs enable a** quick **analysis.** The **advanced geometric analysis functions include:**

- **Part volume**
- **Surface area**
- Centre **of gravity**
- **Minimum straight line distance between two parts**

4.5 Laboratory set-up for modelling shave-grinding

As basis for the laboratory set-up **machine tool of the NAGEL company was because of** the **following reasons:**

- **simple (but sufficient) grinding kinematics** allow **easy measurement of e.g. forces**

- high precision of spindle motors (small run-out)
- high range of frequency of spindle motors
- high flexibility of machine tool structure (axial offset possible, easy movement of spindle motors in horizontal direction, possibility of integration of an oscillation movement)
- grinding wheels and workplaces are small enough for (non-destructive) SEM investigation

Figure 10 gives an overview of the laboratory set-up.

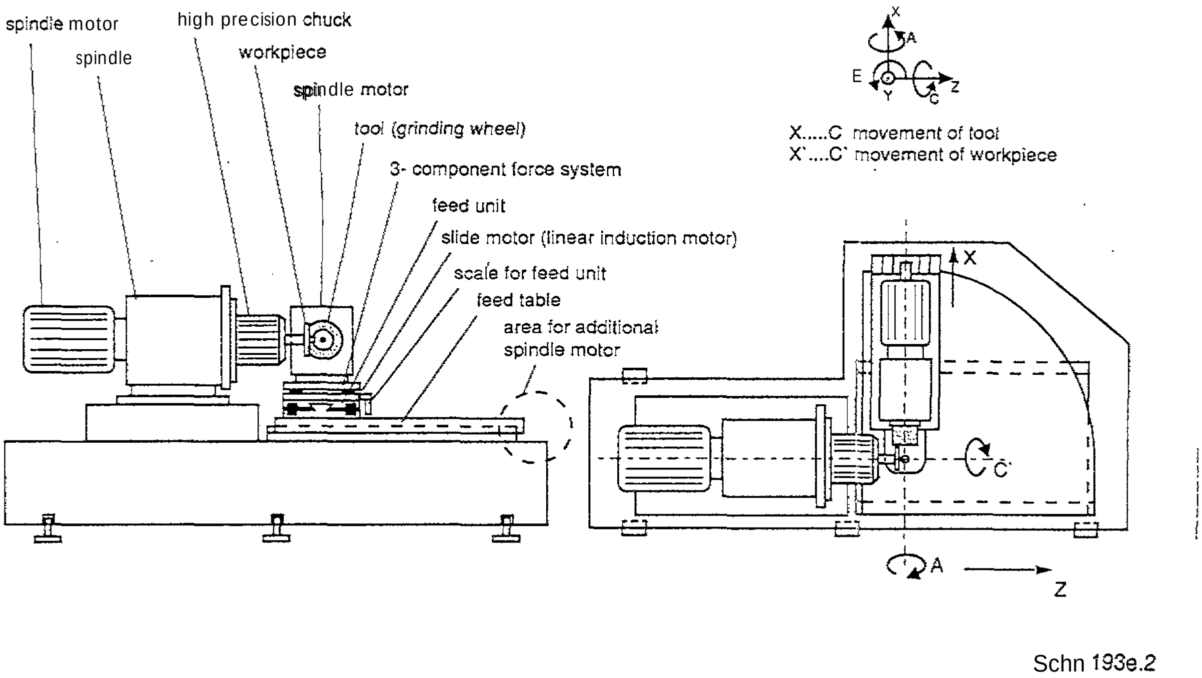


Figure 10 Principles of laboratory set-up for modelling shave-grinding

Due to the offset of axes the resulting process force has components in x-, y-, and z-direction. For registration of all these forces the measuring system has to be sensitive in all 3 directions of space,

4.6 **Visual Inspection system**

The experimental cell for the visual inspection of gear surface defects is characterised by an optoelectronic system working together with an industrial robot. This robot takes each gear wheel and rotates it, until each gear of the wheel has been moved into the same measuring position in front of the camera lens. So the robot ensures that the camera of the optoelectronic system always captures an image at the same position of each gear.

When the robot has positioned the gear in its specific position(figure 11), it gives a signal to the image processing unit. Every time the image processing unit receives this signal it samples an image and analyses it according to the given criteria. The result of this visual inspection of the gear describes whether the surface shows a defect or not. If a gear surface defect is found, the machine tool controller will get a message containing the information that a defect has occurred, what type of defect has been found and decides how to react,

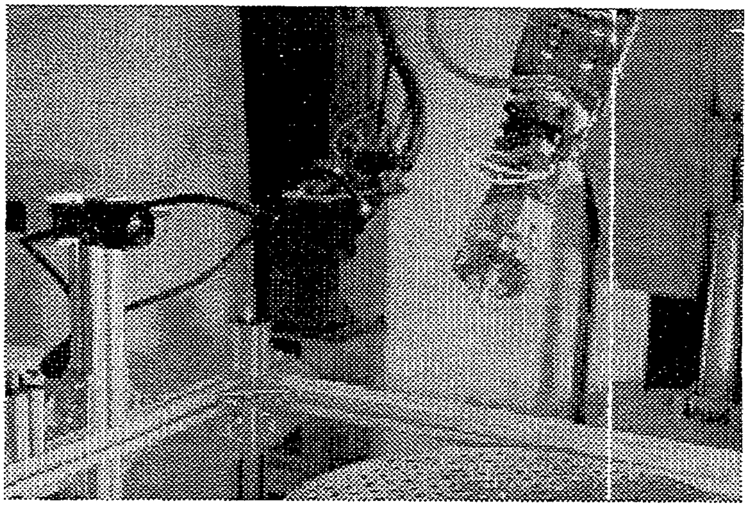


Figure 11: Photo of the experimental environment with the CLOOS industrial robot, Light Source and CCD-Camera

4.7 Visual inspection experiments

Basically three steps had to be done to test the equipment on the workplaces under real operating conditions. The first step is determining a strategy to use for developing applications for detection of gear surface defects. The second step is the programming of several applications according to the developed strategy for different workplaces with previously determined application parameters. Finally, the function of each programmed application can be tested by attaining the same correct result for several measurements of one gear,

In all applications the area toots and the path tools are used to find visual surface defects of gears. Area tools are used to find surface defects by adding the grey values in a certain area of a gear flank. In typical applications, between 24 and 36 area tools cover a whole gear flank (figure 12). Furthermore, eight path tools are used to find scratches on the gear surface by counting edges (figure 1 3). An edge is defined by a certain difference of the grey-values of adjacent pixels. Finally, the lightmeter is used in order to guarantee that the correct illumination conditions exist, while the locator determines whether the **part** to be inspected is in the right position *or* not,

In order to decide, if the result of a tool inspection is defined as a surface defect or an inspection error one additional parameter is given for each inspection tool. Each parameter is set as a value which is given by the typical result of a specific inspection tool added to an accepted offset from this typical result. Therefore, after inspecting several images of gears with no surface defects the typical inspection results of all path tools, area tools and the lightmeter have been found. The typical inspection result of the locator is zero, because it is just defined to measure an offset from the ideal gear position,

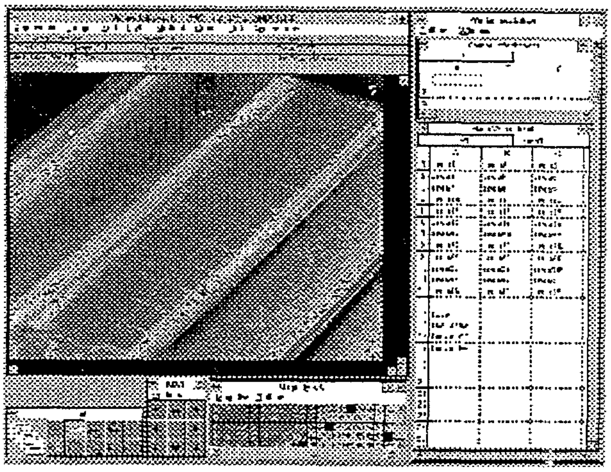


Figure 12: SensorEdit programmed application with 36 area tools

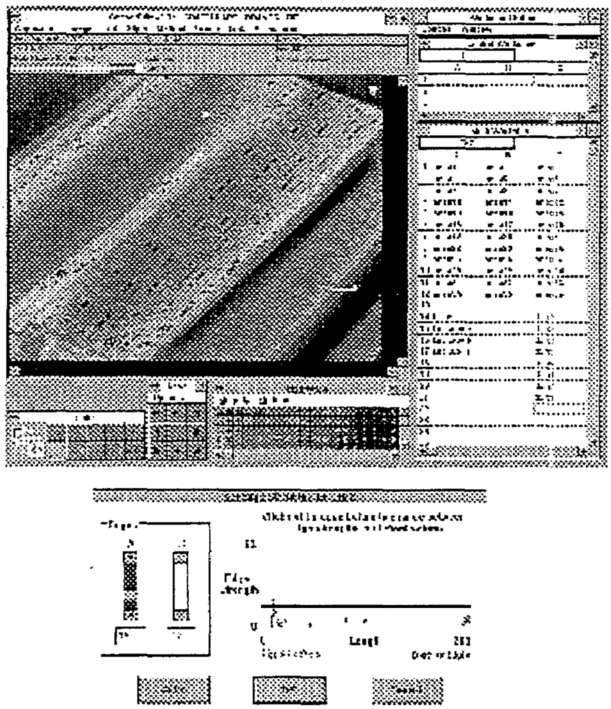


Figure 13: SensorEdit programmed application with 8 path tools

Several experiments have to be done to determine the acceptable deviations from typical values of the locator and the lightmeter. These deviations have to be so. small, that they will not affect the inspection results of the path tools and area tools. [f these deviations are too great, an inspection error has occurred. Obvious deviations of measurements from the area tools and path tools that are not caused by unstable illumination conditions or an incorrect gear position (inspection error) are defined to be either area defects or dimension defects.

The programmed applications are able to decide between the following status:

- Status 0: No gear surface defect has occurred.

- Status 1: An inspection error has happened.
- Status 2: A area surface defect has been found.
- Status 3: A dimension surface defect has been found.

Sometimes it is has been very critical to consider the status of an area surface defect and a dimension area defect, because the real defect of the tooth surface has been a combination of several surface defects. In the experiments a lot of tests have been done at test conditions as well as under real operating conditions in order to prove the function of the developed visual inspection system.

All obvious visual defects of the inspected teeth have been detected reliably. Thus, the developed visual inspection system is suited for the fast decision, if a manufactured gear wheel contains one or more teeth with surface defects or not.

4.8 Experimental scheme and comparison of tool performance

Forces are an important indicator for the grinding process. They are characteristic for the cutting ability of tool material (grinding wheel specification}. Low forces mean a high cutting ability of the grinding wheel.

Regarding the force over time plot {figure 14) forces mostly show a characteristic behaviour. After a maximum of force a steady state area is reached. For interpretation purposes the average force during the steady state behaviour was used. Compared with conventional grinding processes there are some interesting differences:

- Process forces take a rather long time to reach a steady state area. That is about 100 times longer than for conventional grinding processes.
- Forces F are about 2 times higher than for conventional grinding.

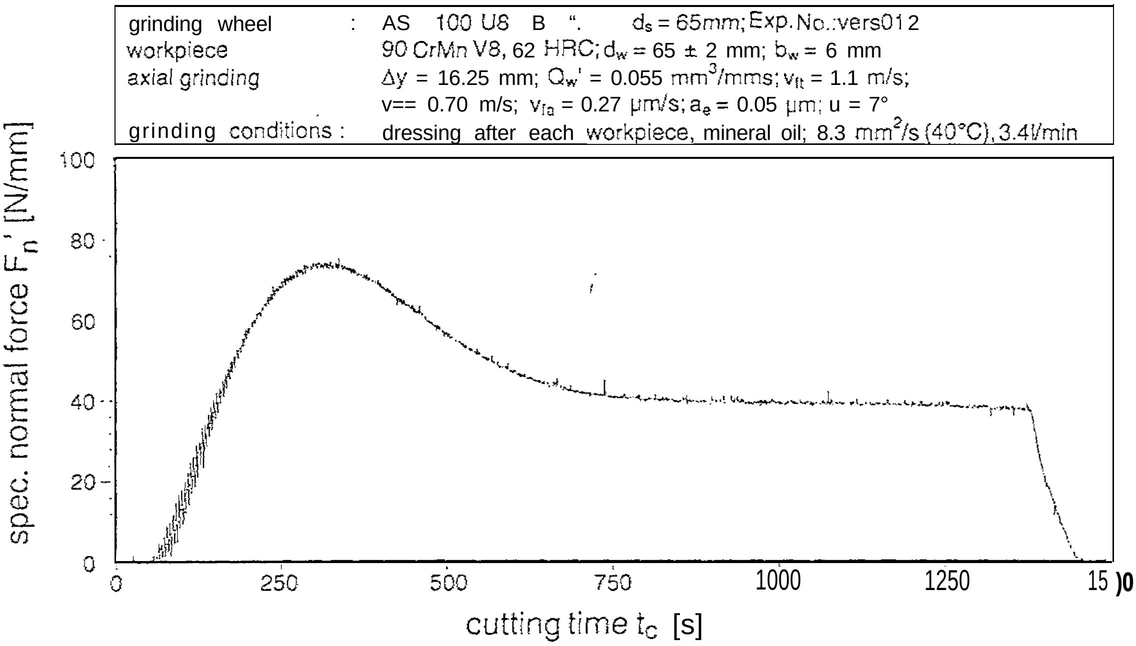


Figure 14 Normal force F_n versus cutting time t_c plot

Surface roughness R is an important factor for evaluation of the workpiece quality. Low roughness usually means low friction, low wear and high quality of workpiece. Surface roughness values of analogous process are representative for surface roughness of shave-grinding. They are not directly comparable because the shave-grinding process is in contrast to the analogous process performed with an oscillative movement which improves surface roughness.

A total of 12 different wheel specifications *were tested.* The mass of the specifications can be classified into different groups of wheels with similar attributes.

Figure 15 shows the performance far the different wheels specifications.

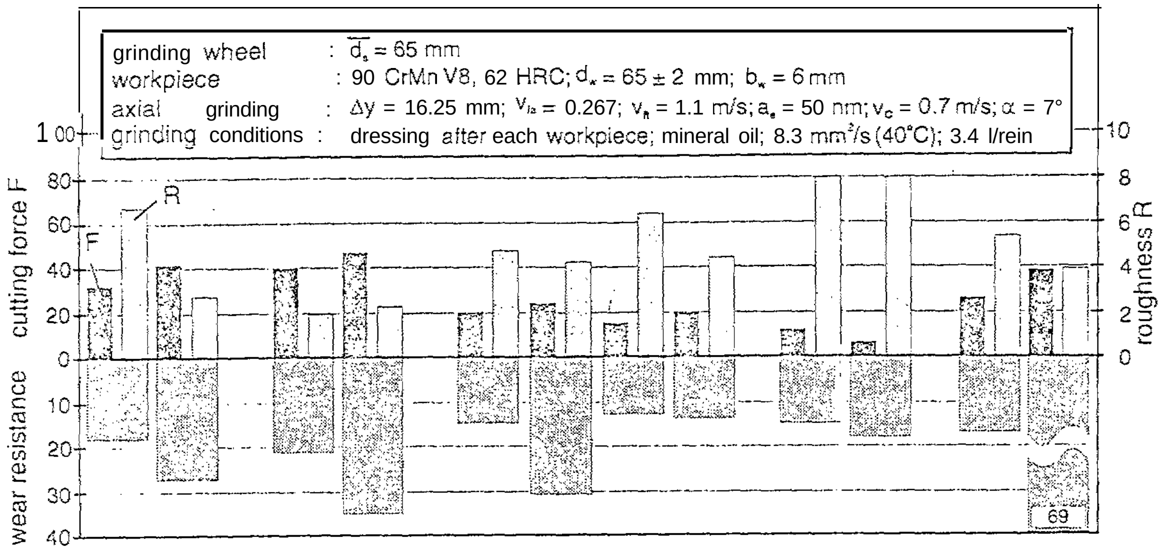


Figure 15 Comparison of wheel performance for different specifications

4.9 Practical investigations and evaluation of results

In parallel to the test bench work at Bremen numerous tests with real workplaces from the industrial partners and other companies were performed at PFAUTER ITALIA. The components machined cover a wide range of applications between car, truck and tractor applications. Relevant results from the test bench work could be evaluated in this way in real process applications.

The measurements performed on the test bench with respect. to cutting forces, roughness, wear and material removal helped a lot to understand the basics of this complex technology.

Conclusions taken from results gained by the analogous process were considered during the following improvements:

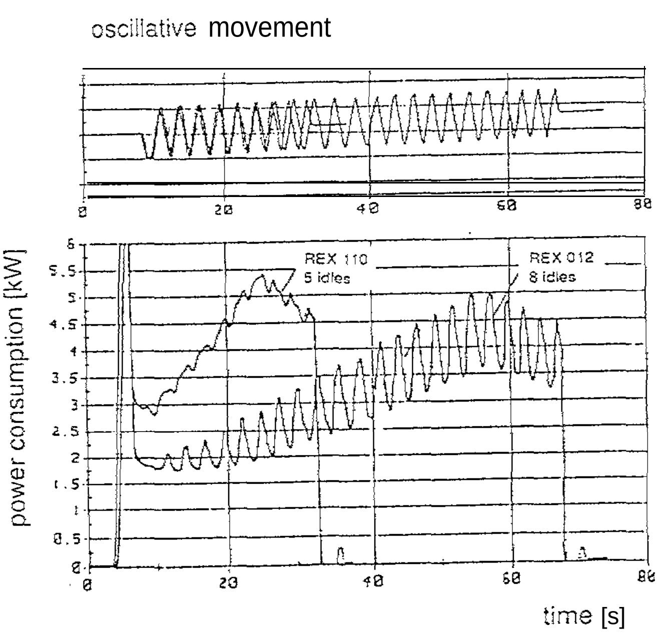
- enhanced machining parameters,
- development of new shave-grinding ring materials,
- geometrical lay out of dressers and shave-grinding rings,
- design of the next generation prototype machine tool.

A test series was performed with several equal gears to be finished under practical cutting conditions. Two different tool specifications were used to compare the cutting performance of different shave-grinding rings. Goal **of** the **experiment was** to **remove the** overmeasure of 20 µm **per** flank in a cutting time as short as possible. Moreover profile and mesh alignment has to be smoothened and the total profile error and the total alignment error has to be tolerable.

A typical result of the experiment is shown in figure 16. The power consumption of the spindle motor of the shave-grinding machine tool was recognised to be one of the most important process parameter during the finishing process. The figure shows the power consumption and the oscillative movement versus time. Due to the fact, that the infeed is related with the oscillative movement, the power consumption is alternating synchronously to the oscillation. The power consumption during the experiment with the one specification is higher than the power consumption for the other specification.

Both plots show a maximum power in the last third of the cutting time. The material removal capability of one specification is about twice as high as the removal rate of the other specification because the cutting time is only about half of the cutting time of the other specification.

For further experiments two typical gearing situation were selected for evaluation of the theoretical knowledge gained by the project according to the requirements of the industrial partners.



gear wheel : Z=57; m=3.0; 20°

shave-grinding wheel: Z = 107

removal :20 µm/flank

infeed :1 µm / stroke

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Figure 16 Comparison of shave-grinding performance for different wheel specifications

5 Results and Conclusions

As a result of the research, an existing wheel specification was improved. The new specification has a promising high wear resistance.

Moreover a totally new specification was designed utilising the knowledge gained by the fundamental research work. The grain mixture used with this wheel is considered to be responsible for an outstanding wear resistance.

The following achievements were result of the project work:

- Constraint model for main input and output parameters of the shave-grinding process
- Laboratory environment for technological simulation of shave-grinding.
- Test bench for new shave-grinding wheel specifications.
- Performance characterisation for commonly used shave-grinding wheel specifications.
- Improvement of an existing wheel specification and development of new specification.
- Application based software for graphical visualization of shave-grinding process.
- Laboratory set-up for a visual inspection system for on-line detection of surface defects of helical gears.

As consequence of the above described improvements the shave-grinding process can be conducted in a more stable way compared to the state of the art at the beginning of the project. This leads to shorter cycle times and tool cost. The economic advantage can be estimated to 20% . . . . 30% of the cost of the operation.

It can be stated that gears machined under above mentioned conditions do have a very favourable noise behaviour compared to gears machined with any other known finishing method.

This shows that shave grinding today can be considered as a technology which gives as far as gear noise is considered results at a very reasonable cost level that can not be achieved with any other process. New environmental laws require a new generation of engines especially in the truck industry that develop a considerably reduced noise level.

6 Acknowledgements

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