Properties of Tooth Surfaces due to Gear Honing with Electroplated Tools

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Introduction

In recent years, the demands for load capacity and fatigue life of gears constantly increased while weight and volume had to be reduced. To achieve those aims, most of today's gear wheels are heat treated so tooth surfaces will have high wear resistance. As a consequence of heat treatment, distortion unavoidably occurs. With the high geometrical accuracy and quality required for gears, a hard machining process is needed that generates favorable properties on the tooth surfaces and the near-surface material with high reliability.

Hard machining processes can modify properties such as surface roughness and topography, residual stress state, material structure and hardness in a wide range. From grinding, for instance, it is known that adverse process conditions may cause thermal overload that results in annealing zones, rehardening zones or even grinding burn. Those effects usually are characterized by the occurrence of high tensile residual stresses, as well as modifications of material structure and hardness in near-surface layers. Tensile residual stresses are especially regarded as causing cracks and crack growth. Consequently, a significant loss of fatigue life occurs. On the other hand, compressive residual stresses in near-surface layers have enhancing effects on fatigue life under dynamic load.

Different hard machining processes for gears were investigated at the Institute for Production Engineering and Machine Tools, at the University of Hannover, in Germany, to evaluate their effects on the properties of tooth surfaces. The emphasis of the results presented in this paper is based on the process of gear honing. That process's origin goes back to the 1970s, when Fässler AG of Dübendorf, Switzerland, first applied the kinematics of an internal geared tool meshing with an external geared workpiece. In the meantime, the process was adapted by several machine tool manufacturers and has gained increasing importance in the 1990s. In recent years, machine tool manufacturer Kapp GmbH of Coburg, Germany, developed the process of Coroning™, a power gear honing process with electroplated tools. The research work presented here is based on the Coroning process.

Gear honing includes several established terms, such as shave grinding, Coroning, power gear honing and spher-

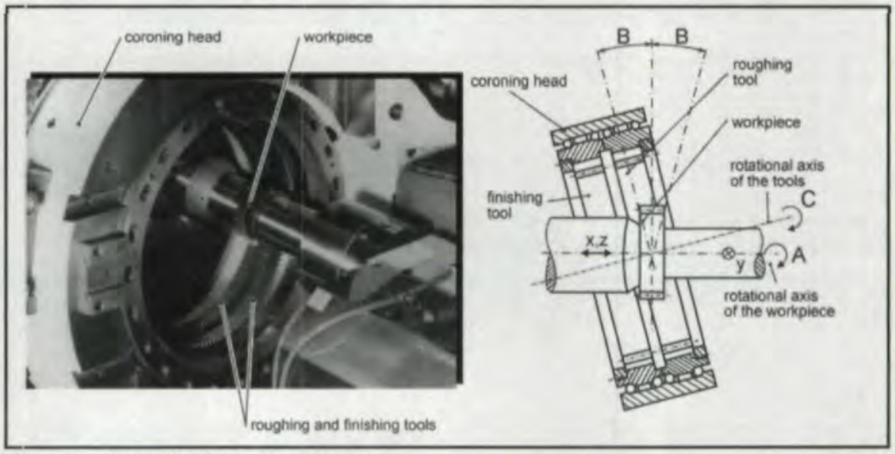

Figure 1—The principle of gear honing.

gear	m_n [mm]	z	β [°]	α_n [°]
A	4.32	32	25	17.5
B	4.32	31	24.8	17.5
C	2.48	65	26	20
D	3	45	15	20
E	2	9	15	20

Figure 2—Geometries of investigated gears.

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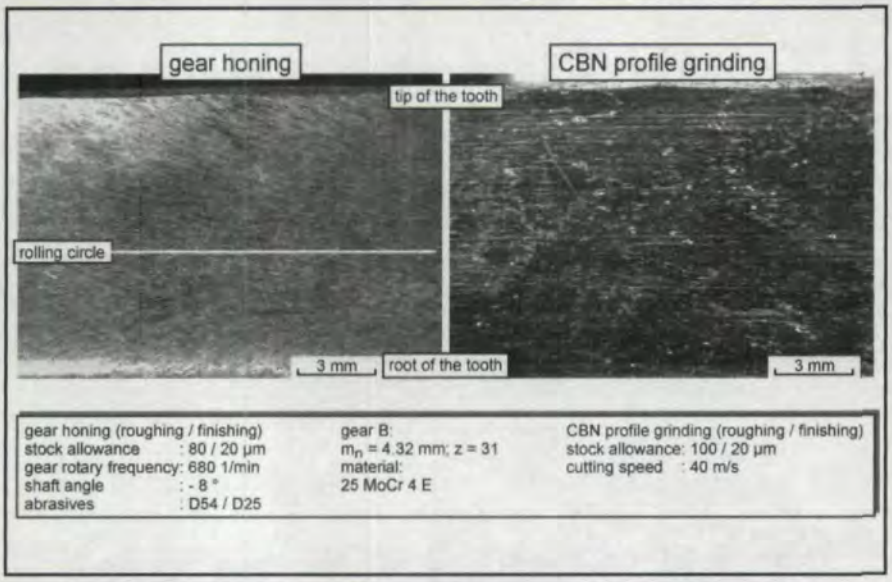

Figure 3—Machining groove lines due to gear honing and profile grinding.

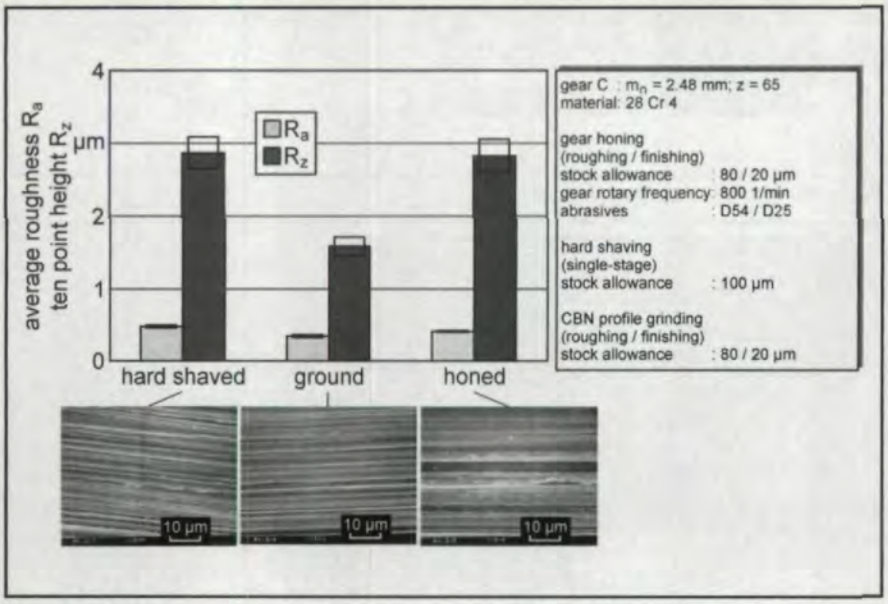

Figure 4—Surface roughness due to gear honing and alternative gear machining processes. The cutoff length was 5.6 mm.

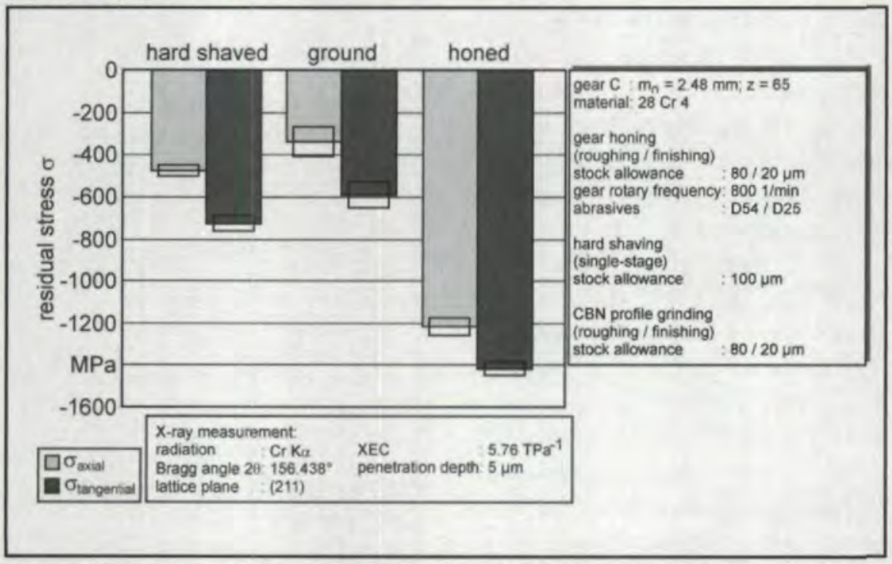

Figure 5—Residual stresses due to gear honing and alternative gear machining processes.

ic honing. Still, the expression "gear honing" will be used in this paper, as it is most widely used.

Machine Tool Concept and Process Characterisitics

All experiments on gear honing were performed on a Coroning machine VAC 65, manufactured by Kapp GmbH. The machine tool offers two spindles for the workpiece (A-axis) as well as for the tools (C-axis). Each spindle has a nominal power of 14 kW and enables rotary frequencies up to a maximum of 800 1/min. Gears up to tip diameters of 220 mm, maximum modules of 6 mm, maximum widths of 80 mm and maximum workpiece lengths of 500 mm can be machined in the working area.

Gear honing on the Coroning machine VAC 65 removes maximum stock allowances of 130 µm on the gear flanks. No premachining process is necessary after heat treatment. The heat-treated workpiece, whose permissible hardness is limited to 62 HRC, undergoes a roughing operation and a following finishing operation. The principle of gear honing and the working area of the machine tool are shown in Figure 1. The kinematics is based on the continuous meshing of an internal geared tool with the workpiece to be machined. During gear honing, the axes of the tool and the workpiece have a defined shaft angle that results in material removal because of the relative motion between the flanks of the tool and the workpiece.

A roughing tool and a finishing tool are mounted in the Coroning head. The tools represent internal geared metallic bodies whose tooth flanks are electroplated with a single layer of abrasives. In our experiments, diamond grit of the specification D54 (roughing tool) and D25 (finishing tool) was used. During tool life, no dressing operations are necessary. When the tools are worn, the abrasives are removed from the metallic body and a new layer of diamond grit can be applied.

To enable reduction of the pitch error during gear honing, the axes of the workpiece and the tools are electronically coupled via control of the machine tool.

The gears used for the presented

experimental research work are shown in Figure 2. Gears A and B, with a large module of 4.32 mm, are made of case hardened 25MoCr4 steel and built for truck gearboxes. Gear C, with a significantly smaller module of 2.48 mm, is a part of differential gearboxes for passenger cars and consists of tempered 28Cr4 steel. Gears D and E run in stationary gearboxes and are made of case hardened 16MnCr5 steel.

To evaluate the properties of the gears machined experimentally, residual stress state, surface roughness, surface topography, material structure and microhardness were investigated. The residual stress analysis was performed on an X-ray diffractometer using CrKa radiation. In order to obtain depth profiles of residual stresses, surface layers of tooth flanks were removed in several steps by electrolytic polishing. This process guarantees the absence of thermal and mechanical loads that would modify the residual stress state. After polishing, residual stress measurement was carried out in the determined depth before the cycle of polishing and measuring began afresh.

For roughness measurements, a contact stylus instrument Perthometer Concept was used. Photographs of the surface topography were taken by light-optical and scanning electron microscopy. Effects on hardness and material structure were detected by photographs of metallographic preparations and microhardness measurements. The most interesting results of the investigations on honed gear tooth flanks are presented in the following paragraphs.

Surface Roughness and Topography

The kinematics in gear honing is characterized by the meshing of the gear to be machined with the internal geared tool under a shaft angle. As a consequence, the relative motion between the tool and the workpiece is composed of a roll and a screw movement (Ref. 4). With a shaft angle of 0°, a mere roll movement occurs. But, a shaft angle different from 0° results in a screw component that causes an additional slide movement in tip-root direction. With regard to the single grain contact in gear honing, curved groove lines occur that are not parallel to the tooth trace. Figure 3 presents a comparison of typical surface structures generated by gear honing and CBN profile grinding. The microscopic photographs show tooth flanks of gear B, which were machined alternatively by the two processes.

Due to the axial feed direction of the grinding wheel, the ground tooth flank shows straight-lined grooves that are parallel to the tooth trace. In gear honing, machining grooves are only parallel to the tooth trace near the pitch circle. In the areas near the tip and the root, the directions of the machining grooves and the tooth trace include a cutting angle that increases as the distance from the pitch circle increases.

Besides the structures of the surfaces generated by different gear machining processes, surface roughness was also investigated. Samples of gear C were machined by gear honing, hard shaving or CBN profile grinding. Though shaving is a soft machining process in most cases, hard shaving is an application suitable for hardened gears.

The roughness values after machining are compared in Figure 4. Lowest ten point height values of only 1.6 μm were measured at the ground variant. Gear honing and hard shaving led to comparatively higher ten point height values between 2.6 and 3.1 μm.

In Figure 4, the surface roughness for honing may seem high. That is due in part to a misnomer. Gear honing with electroplated tools refers to a "honing" process, but it is actually a grinding process using a profiled grinding tool. The high roughness is also due in part to the tool specification.

Residual Stresses

The residual stress state plays an important role concerning fatigue life of components under dynamic load. In gear grinding, modification of the grinding conditions, such as increasing wear of the grinding wheel or varying cutting speeds, can cause residual stresses that widely vary from tensile to compressive range (Ref. 1). Tensile residual stresses are regarded as causing cracks and forcing crack growth. On the other hand, compressive residual stresses in near-surface layers have enhancing effects on fatigue life under dynamic load. Therefore, the interactions between different hard machining processes and the residual stress states generated are of high importance.

To investigate those interactions, machining of gear C was done by the three competing processes of hard shaving, CBN profile grinding and gear honing. The residual stresses measured at the surface of tooth flanks in axial and tangential directions are displayed in Figure 5. One can see that all of the mentioned processes induce compressive residual stresses. The lowest compressive residual stresses were found after profile grinding. Hard shaving induces slightly higher compressive stresses between –474 MPa and –729 MPa. But the highest compressive residual stresses occur due to gear honing. Depending on the direction of measurement, they range from –1,217 MPa to –1,419 MPa.

Similar investigations were done for gear B, which was machined by gear honing and CBN profile grinding. In this case, compressive residual stresses between –1,031 MPa and –1,304 MPa were detected after gear honing. As for grinding, lower compressive stresses of around –900 MPa could be measured.

When discussing those high compressive residual stress states after machining, the question arises whether the stresses were generated by machining or were already in the material due to the preceding heat treatment. To clarify that, residual stresses states after case hardening and after the roughing and finishing operations of gear honing were investigated. The investigations were done on gear A. Figure 6 shows a comparison of the depth profiles of residual stress obtained after case hardening as well as after roughing and finishing. Directly at the surface of the unmachined part, high compressive residual stresses of about –850 MPa occur. The maximum compressive residual stress was found at a depth of 10 µm. Because the roughing operation in gear honing removes a stock allowance of 80 µm (light grey area in the diagram), compressive residual stresses in those layers are of no importance. The surface generated by the roughing operation is equivalent to a depth of 80 µm, where the unmachined part shows only low compressive residual stresses of about –455 MPa.

In the diagram, the surface generated by roughing lies at a depth of 80 µm. The depth profiles of residual stress induced by roughing are marked by the dotted lines. High compressive residual stresses occur directly at the roughened surface. Dependent on the direction of measurement, they range from –1,026 MPa to –1,315 MPa. Compared to the initial state of the material (continuous lines), one can see an increase in compressive residual stresses of more than 600 MPa induced by the roughing operation in gear honing.

After roughing, the maximum compressive residual stress was found at the surface of the tooth flank. But a significant increase of compressive residual stress was also detected below the surface. The influencing of the residual stress state due to roughing reaches material regions up to depths of almost 40 µm.

As the finishing operation removes an additional stock allowance of 20 µm (dark grey area), the surface of the finished workpiece can be found at a depth of 100 µm, and the residual stress profiles after finishing are marked by the dashed lines. Again, the maximum compressive residual stress occurs at the surface, although the values between –968 MPa and –1,245 MPa are slightly lower than after roughing. The compressive residual stresses could be increased up to depths of about 30 µm.

High compressive residual stresses can be attributed to the high mechanical

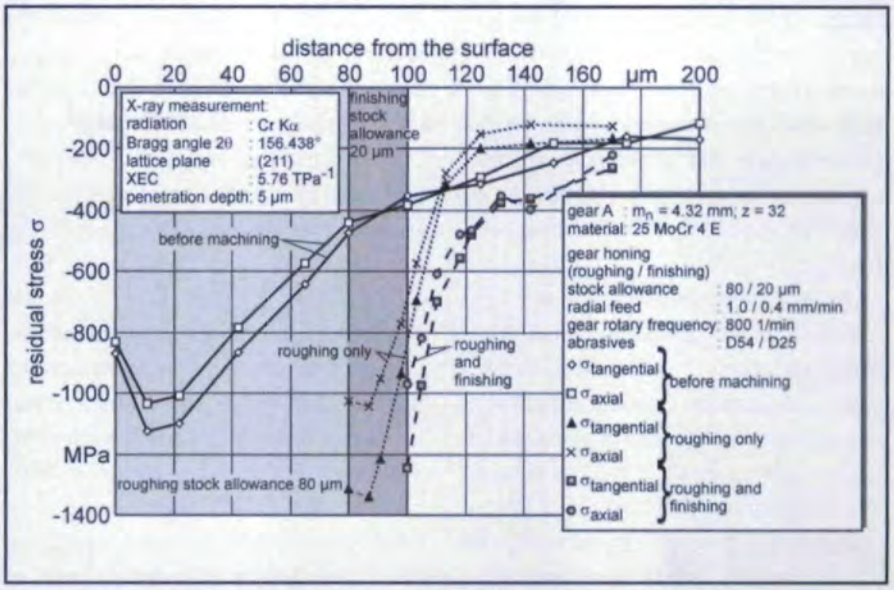

Figure 6—Depth profiles of residual stress after different production steps.

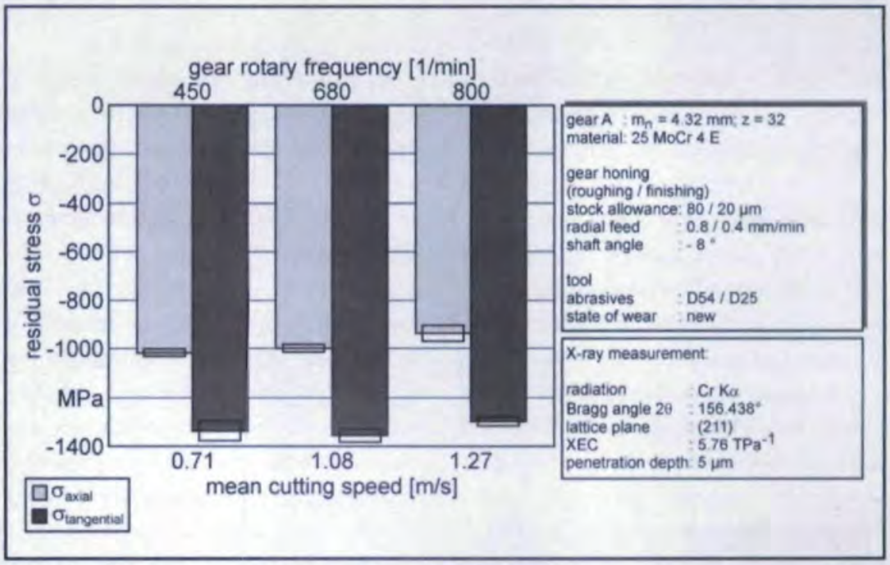

Figure 7—Residual stresses due to different cutting speeds.

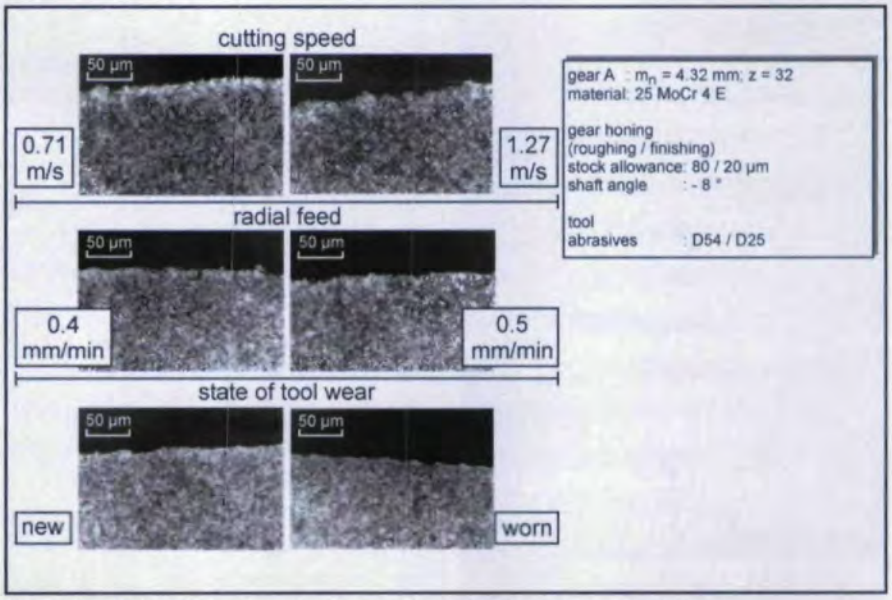

Figure 8—Material structure due to gear honing under various conditions.

forces in gear honing caused by machining with superhard diamond abrasives. In roughing, the machining forces are higher due to using the coarser diamond grit D54, which is why the increase in compressive residual stress and the effect on depth are higher than in finishing with D25 grit.

It has become apparent that gear honing with electroplated diamond tools leaves high compressive residual stresses in the near-surface material. Admittedly, the interactions between process layout of gear honing and the induced residual stresses had to be discovered. For that reason, gear honing experiments with varying cutting speeds were carried out using gear A as the workpiece. The variation of the cutting speed was realized by changing the workpiece rotary frequency. Figure 7 displays surface residual stresses dependent on different mean cutting speeds and gear rotary frequencies.

Cutting speeds of 0.71, 1.08 and 1.27 m/s were used, which correspond with rotary frequencies of 450, 680 and 800 1/min. For all mentioned conditions, high compressive residual stresses occur in axial and tangential direction. While no variations of residual stresses can be stated for cutting speeds of 0.71 and 1.08 m/s, a slight decrease was found for a cutting speed of 1.27 m/s. Measurements of the spindle's consumption showed a decrease with increasing rotary frequency. That indicates that lower machining forces can explain the slight decrease in compressive residual stresses when using high cutting speeds.

WHEREAS PRODUCTIVE EFFICIENCY OF GEAR HONING IS AT LEAST IN THE RANGE OF GEAR GRINDING, THE GEAR HONING PROCESS ALSO EFFECTS FAVORABLE PROPERTIES IN THE TOOTH FLANKS.

Structural Modifications

The generation of material properties when machining with geometrical, undefined cutting edges is always caused by the interaction of mechanical and thermal loads in the contact zone. While mechanical forces can induce compressive residual stresses that strengthen the material, the occurrence of high thermal loads shifts residual stresses to the tensile range and causes structural modifications, such as annealing zones or even rehardening zones, so-called white layers. Even though the phenomenon of white layers is not completely investigated yet, their formation is regarded as harmful to the workpiece (Ref. 1).

In gear honing, the already described generation of high compressive residual stresses can be attributed to strong mechanical forces. Thermal loads obviously play a minor role. That assumption is stressed when one takes into consideration the influence of cutting speeds in gear honing. In general, the amount of thermal load increases when using higher cutting speeds. Whereas in grinding gear B, a cutting speed of 40 m/s was used, the mean cutting speed in honing of the same gear geometry only amounts to about 1 m/s, which indicates low thermal influencing of the near-surface material.

To finish evaluating the thermal effects in gear honing, modifications of the material structure near the surface were investigated. Figure 8 shows microscopic photographs of near-surface structures due to gear honing under completely different conditions.

Variations of the cutting speed, the radial feed and the state of tool wear were used in the gear honing experiments to create favorable and adverse process conditions. The three photographs on the left side display the structures generated as a consequence of favorable process conditions with lowest thermal loads possible. Near the surface, no structural modifications can be seen.

The process conditions used for the specimens on the right side were chosen to create high temperatures in the contact zone. Gear honing with worn tools effects high friction, which results from the low cutting ability of the diamond grits' blunt and rounded cutting edges. A high cutting speed of 1.27 m/s also causes increasing friction. In spite of high thermal loads due to increased friction, the photographs on the right side show no modifications of the structure at all. Effects like annealing zones or rehardening zones can be avoided with high reliability. Those discoveries are stressed by additional microhardness measurements, which were performed on the discussed specimens. In all cases, no alterations of the microhardness due to gear honing could be measured. Those facts indicate that, in contrast to grinding, the temperatures in gear honing are too low to cause thermal damage even under the most unfavorable process conditions.

Conclusions

For ecological and economic reasons, the demands for fatigue life and load capacity of gears constantly increase. Under aspects of low development costs and risk, the design of gears often remains unchanged and the improved performance of the product has to be achieved by better quality due to improved and efficient manufacturing processes. In recent years, the process of gear honing with electroplated tools has been established as a competitive finishing process for hardened gears. In contrast to conventional gear honing with corundum tools, high stock allowances up to 130 μm can be removed, and premachining processes after heat treatment can be abolished.

Whereas productive efficiency of gear honing is at least in the range of gear grinding, the gear honing process also effects favorable properties in the tooth flanks. Surface structures with curved groove lines are generated. The surface roughness due to gear honing is slightly higher compared with competing gear machining processes. One further advantage of gear honing with electroplated tools is the generation of high compressive residual stresses directly at the surface, as well as in the near-surface material. Compressive residual stresses are regarded as a means of preventing cracks and stopping crack growth under cyclic load and therefore increase fatigue strength. In gear honing, the compressive residual stress states can be reproduced with very high reliability. Even when varying the cutting speed or the workpiece rotary frequency respectively, almost the same stress states occur.

The cause for high compressive residual stresses was found in the combination of mechanical and thermal loads in gear honing. On the one hand, high mechanical forces that strengthen the material emerge from machining with superhard abrasives. On the other hand, very low cutting speeds in the range of 1 m/s result in low process temperatures. Therefore, unfavorable shifting of the residual stresses to tensile range as well as modifications of the near-surface material structure are avoided with high reliability.

Acknowledgments

The scientific work presented in this paper results from a cooperative research project with the Institute for Production Engineering and Machine Tools, Hannover, and the companies Kapp GmbH, Coburg; Daimler-Benz AG, Gaggenau; Ford-Werke AG, Köln; and Lenze GmbH & Co KG, Extertal. The project was financed by the German Federal Ministry for Education and Science and supported by Research Centre Jülich.

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This paper was originally presented at the 4th World Congress on Gearing and Power Transmission in Paris, March, 1999.

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