An Experimental Study on the Effect of Power Honing on Gear Surface Topography

N. Amini, H. Westberg, F. Klocke and T. Kollner

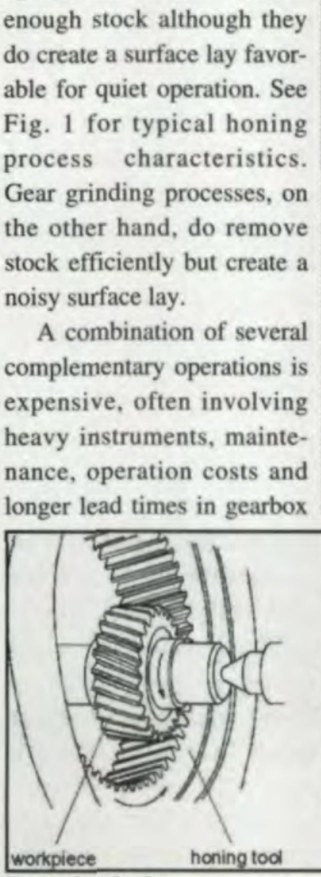
Introduction

Gear noise associated with tooth surface topography is a fundamental problem in many applications. Operations such as shaving, gear grinding and gear honing are usually used to finish the gear surface. Often, gears have to be treated by a combination of these operations, e.g. grinding and honing. This is because gear honing operations do not remove enough stock although they do create a surface lay favorable for quiet operation. See Fig. 1 for typical honing process characteristics. Gear grinding processes, on the other hand, do remove stock efficiently but create a noisy surface lay.

A combination of several complementary operations is expensive, often involving heavy instruments, maintenance, operation costs and longer lead times in gearbox fabrication. Power honing is one way to reduce gear manufacturing costs by reducing the number of process sequences.

According to Amini et al. (Ref. 1), gear surface topography can be characterized, due to the noise, by three parameters that describe the profile undulation. Undulation occurs on gear surfaces irrespective of the gear finishing process used, the differences appearing in amplitude, wavelength and the direction of the undulation. According to Amini and Rosen (Ref. 2), these three parameters significantly affect the noise characteristics. Moreover, they are directly correlated to the noise level, noise perception in the human ear and vibratory performance of the entire system in which the gear works.

Gear grinding operations (Fig. 2) create the worst conditions for these parameters. They produce undulations with the highest amplitude level, the longest wavelength and direction almost perpendicular to the path of contact. Conventional gear honing operations are used today to reduce the undulation amplitude and to create a new, more favorable direction of undulation (for more extensive discussion see Ref. 1).



Process characteristics:

- geometrically undefined cutting edge
- internally toothed tool
- crossed axis angle
- tooth height and width oriented surface structure
- low cutting speeds $v_c = 0{,}5...3$ m/s
- cutting conditions differ along tooth height

Fig. 1—Gear honing.

A few companies have recently introduced new honing machines on to the market. Most published papers on the technology of gear honing or shave grinding describe both the principle of such a process (Ref. 3) as well as the surface topography obtained. However, they do not discuss the surface topography in detail in terms of surface undulation parameters. The interesting question arises: What are the characteristics of this operation with respect to noise-related surface parameters?

The objective of this article is to evaluate gears manufactured using this kind of operation, particularly power honing, in terms of the three parameters mentioned. To do that, a set of gears with different operational conditions were produced in the Laboratory for Machine Tools and Production Engineering (WZL) of Aachen University of Technology (RWTH), Germany. These gears were then evaluated in the laboratory of Chalmers Surface Geometry Group (CSGG), Sweden. The surface evaluation was carried out using three-dimensional (3D) devices and 3D surface topography analysis.

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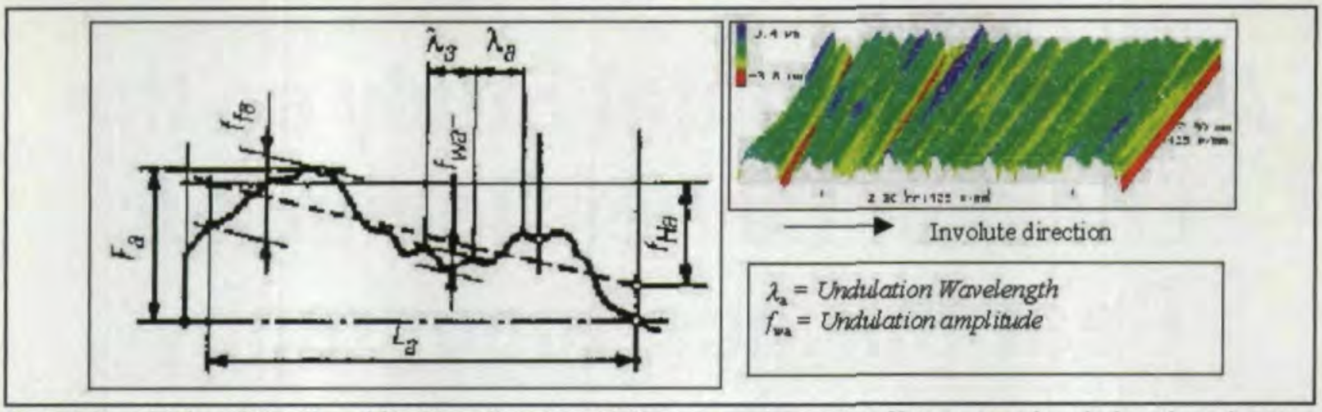


Fig. 2—Profile undulation definition. Upper right subfigure illustrates undulations on a ground gear surface. Measurement performed using stylus equipment.

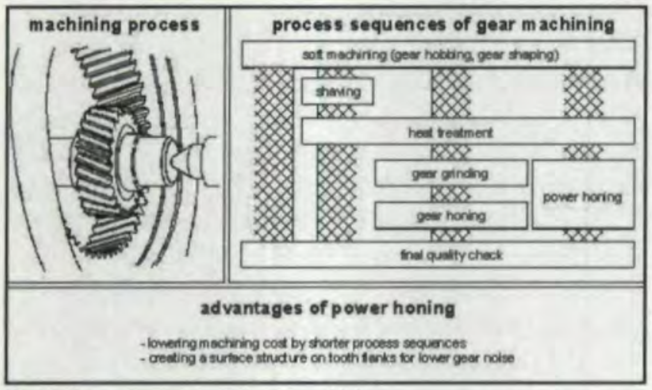
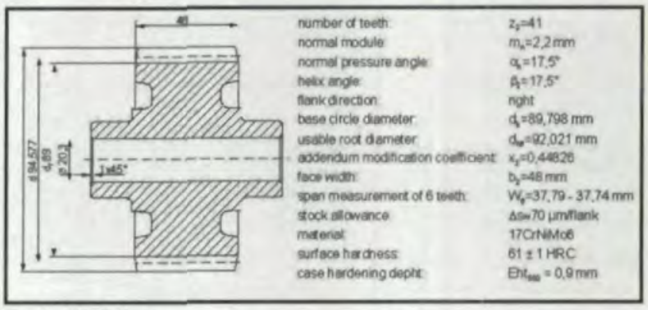


Fig. 3—Process sequences of gear machining.



number of teeth:	$z_2=41$
normal module:	$m_n=2{,}2$ mm
normal pressure angle:	$\alpha_n=17{,}5°$
helix angle:	$\beta_2=17{,}5°$
flank direction:	right
base circle diameter:	$d_b=89{,}798$ mm
usable root diameter:	$d_{Nf}=92{,}021$ mm
addendum modification coefficient:	$x_2=0{,}44826$
face width:	$b_2=48$ mm
span measurement of 6 teeth:	$W_6=37{,}79 - 37{,}74$ mm
stock allowance:	$\Delta s = 70$ µm/flank
material:	17CrNiMo6
surface hardness:	61 ± 1 HRC
case hardening depth:	$Eht_{550} = 0{,}9$ mm

Fig. 4—Workpiece.

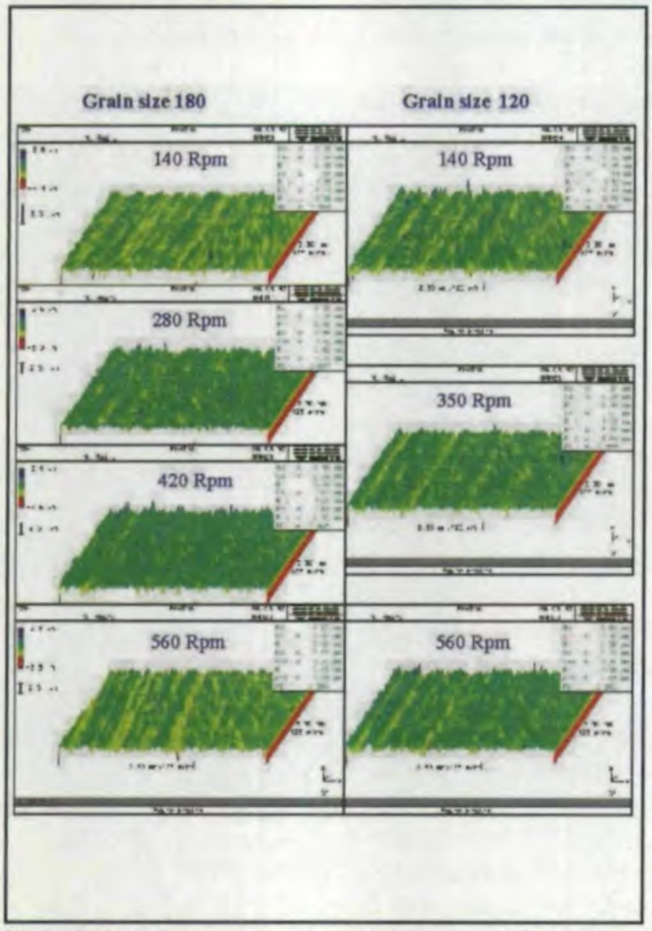


Fig. 5—Surfaces measured by stylus technique, sampling length 8 µm. Subfigures to the left were produced by a grain size of 180, while those to the right were produced with 120 grains. Different subfigures are the result of different tool speeds.

Gear Honing

Principles. Gear honing is a manufacturing process that uses geometrically undefined cutting edges for hard finishing gears. The tool forms an axis intersection angle with the workpiece axis. The resulting grinding motion, running at a cutting speed in the 0.5 to 3 m/s range, has an axial component in the tooth trace direction and a tangential component in the profile direction. This produces a tip-root-oriented surface structure that has improved noise qualities. This is in contrast to the gear grinding method that only produces machining marks in the tooth trace direction.

Because of minute periodic ripples in the tooth contact direction, ground gears tend to produce intensive narrow band upper harmonics in the tooth contact frequency. The machining marks run square with the generating motion, and this is seen today as a problem because it can lead to dynamic vibration and whistling noises (Refs. 14, 15). Because of this problem, gear honing is frequently employed subsequent to gear grinding to achieve a surface structure that produces less noise (Refs. 5, 6, 9, 13).

The kinematics of gear honing are similar to those of shaving (Refs. 5–7). Both methods use gear wheel shaped tools and are crossed helical gears with shallow axis intersection angles. They are also both based on rotation-symmetric workpiece and tool part-bodies that are spatially cross meshed. This leads to a relative sliding movement in tooth depth and face width directions, which results in machining marks that are typical for this machining method and run in the tooth depth direction. The work wheel flanks can be generated with both line and point contact (Ref. 14). In spite of these similarities, a normal

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Helix angle	16°
Face width	120 mm (4.8")
Outside diameter	376 mm (14.8")
Material	17CrNiMo6
Hardness	59 - 62 HRC
Grinding allowance	0.16 mm (0.0063"/flank) plus profile and lead modifications
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E-mail: info@hofler.com, Internet: http://www.hofler.com shaving tool cannot be used for machining hardened tooth flanks because of its geometrically defined cutting edges. All cutting edges would have to penetrate the hardened workpiece elastoplastically along the line of contact, resulting in very high contact pressures. For this reason, tools with geometrically undefined cutting edges must be used for gear honing in order to reduce the surface contact between the tool and the workpiece flank, thus also reducing the contact pressure (Refs. 5–7).

Generally, the grid materials used for tooth flank grinding can also be used for honing tools. Conventional internally toothed honing stones are made up of grains of refined aluminum oxide which are synthetic resin bound. The contact pressure causes the grinding grains to penetrate into the workpiece and remove very fine particles from the tooth flanks. The conventional honing stone is dressed with a diamond dressing tool before machining the first workpiece and whenever it starts losing its original form after machining a specific number of gears (Refs. 8, 16).

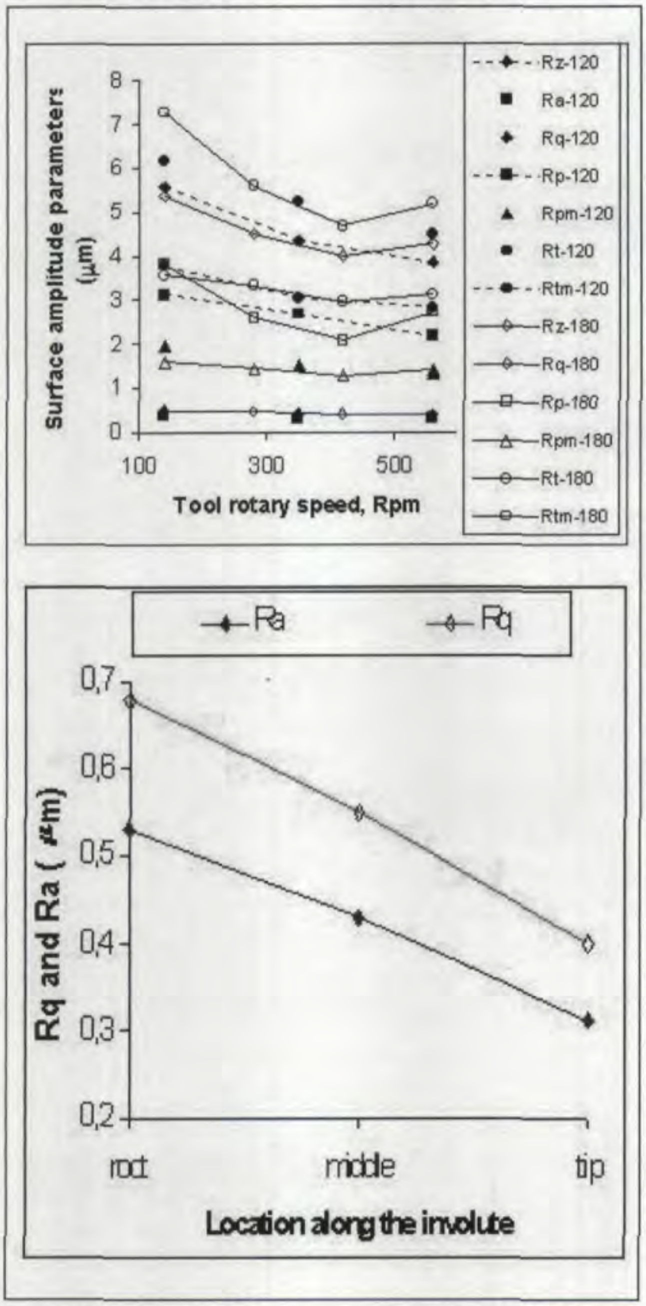

Figure 6: Conventional surface parameters. The subfigure to the left illustrates parameter variation as a function of tool speed. The subfigure on the right shows parameter variations along the involute.

The longitudinal table can be oscillated (longitudinal honing) to improve the regularity of the workpiece surface. The workpiece is driven parallel to its center of rotation, backwards and forwards, on the honing stone. The oscillation has a smoothing effect on the surface quality and results in less surface irregularities than plunge honing, a method that does not use oscillation.

Conventional Honing. The stock removal and machining quality of gear honing are dependent on preliminary quality, desired final quality, gear geometry and machining time. Comparative studies carried out within the framework of a research project (Ref. 12) using different hard finishing processes showed that gear honing possesses a high performance potential with respect to the quality achieved, influence on the workpiece surface zone, noise qualities and economic viability. It was also noted that this method was capable of generating a profile mismatch, in addition to improving the surface structure of the tooth flank. Owing to the above-described advantages, the importance of the process has increased, and it is currently used in various production chains with low stock removal of some 5-10 µm per tooth flank.

Power Honing. The pressure of international competition forces industrial users to reduce their number of manufacturing programs. The latest efforts aim at employing gear honing directly after case hardening with increased stock removal as a substitute for gear grinding and/or shaving, dependent on the prior manufacturing programs, in order to lower manufacturing costs (Fig. 3). This method is called "power honing" to distinguish it from conventional gear honing because stock removal rates of 20 to 40 µm are aimed at (Ref. 10). With power honing, it is possible to minimize the existing process chains and reduce production costs while producing high-quality, low-noise gear systems. The success of power honing depends both on appropriate process control for gear cutting with the gear hobbing process and on suitable gear honing machines with optimized technology.

Experiments—Test Setup and Manufacturing

Workpieces. The parts used for the surface topography tests were machined on a Fässler K-400 gear honing machine. This unit has five numerically-controlled axes of motion—two linear axes and three axes of rotation. The specimen workpieces were case-hardened industrial gears prepared by hobbing, the kind used as intermediate gears in highly-stressed utility vehicle gear systems. As will be apparent from Fig. 4, they were helical gears with z_2=41 teeth, normal module m_n=2.2 mm and a normal pressure angle α_n=17.5°. The helix angle is

$\beta_2=17.5°$. The specimen workpieces had a face width of $b_2=48$ mm and the flanks were modified with a tip relief of 9 µm and a crowning 7 µm.

The specimen workpieces were machined from 17CrNiMo6, a common material for highly-stressed large module gears. The surface hardness of the gears was approximately 61 HRC with a case hardening depth of $Eht_{550}=0.9$ mm. The hardness of the substrate was only about 39 HRC.

Internally toothed honing stone. An internally toothed honing stone with number of teeth $z_0=145$ was used to machine the specimen gears. As with the gears, the honing stone had a normal module of $m_n=2.2$ mm and a normal pressure angle of $\alpha_n=17.5°$. The helix angle of the honing stone was, however, $\beta_0=27.5°$, resulting in an axis intersection angle of $\eta=10°$ for the gear honing process. The honing stone is 12 mm wider than the workpiece, ensuring constant contact between the tool and the workpiece flanks in spite of the axial pendulum motion of the honing stone that typifies longitudinal honing.

The grit material was a mixture of refined aluminum oxide (70%) and Sol-Gel-Corundum (30%) with a grain size of 180. A mix with a grain size of 120 was used for comparison in order to determine the extent to which the surface roughness of the machined tooth flanks is influenced by the grain size. The grains in both mixtures were bonded in a synthetic resin.

Manufacturing. The gears were machined by longitudinal continuous-infeed honing with a honing time of 170 seconds. The honing stone was dressed after each test in order to ensure uniform constraints. The gears were machined with an axis intersection angle $\eta=10°$, a pendulum distance of ±2 mm, an oscillation speed of 72 mm/min and an infeed rate of 90 µm/min. The number of rotations of the honing stone was varied at values of $n_0=140$ (cutting speed vc=1 m/s), 280, 420 and 560 min^{-1} in order to establish influence on the surface structure.

Surface Topography Measurements

The Testing Machines. Two 3D measuring machines were utilized during the study, one stylus machine and one white-light interferometric measurement machine. The stylus machine was used to evaluate surface roughness parameters. It utilized a stylus with 2 µm tip radius set at a 90° con-angle. The sampling length in these measurements was 8 µm in both directions. The optical machine was used to investigate parameter variations on different parts of the surface and investigate the surface itself with a finer resolution than the stylus can provide. The sampling length in these measurements was 3.20 µm.

Surface amplitude parameters are shown on the upper right side of every subfigure in Figure 5. The expression for one, namely the arithmetic mean deviation R_a, is recalled here. Other parameter definitions can be found in the reference section.

Filters and Error Estimates. To remove the macrogeometry, a high-pass

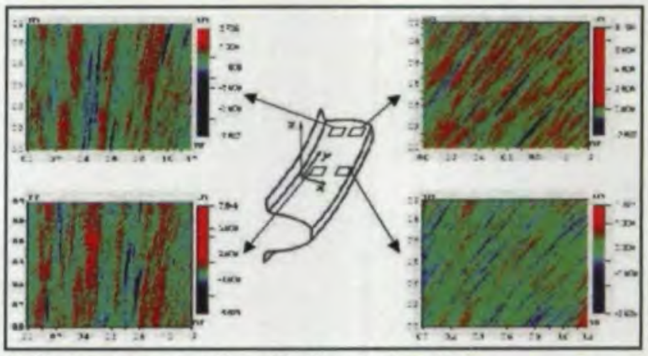

Fig. 7—Measurements performed by the optical machine.

gaussian filter with a cut-off length of 0.8 mm was used. Leveling (i.e. applying a least square plane removal of data) completed the filtering. The former was due to the removal of involute helix surface. The latter was due to the linear trend in the data. Trends originated from misalignment of the specimen during the measuring operation.

To estimate the profile undulation errors, spectral density analysis was used. The sampling strategy was optimized to increase the amount of information on the surface topography, focusing on the intrinsic information in the involute. The sampling length was shortened in the involute direction to 2 µm while the sampling length in the face width direction was increased to 100 µm. In "Optimization of Gear Tooth Surfaces" it was shown that the method, based on averaging 40 µm, is one of the most reliable ways of estimating profile undulations. It was also shown that parameters obtained by this kind of analysis are directly related to the surface amplitude parameters, i.e. the area under the spectral curve is linearly proportional to the surface Rq in square.

Results

Figure 5 shows measurements performed using the stylus technique. The surfaces are divided into two columns. The difference between the two columns is the grain size of the abrasive particles in the internally toothed honing stone. Each surface is the result of a different tool speed setting at the given grain size.

The overall view of the surfaces in Figure 5 indicates that they are dominated by undulations, especially in regions close to the root. This is typical behavior for a gear honing operation. It creates severe undulations close to the pitch line that diminish the further away they get. The pitch circle between the tool and the workpiece in this article was placed close to the root. The other important observation is that the pitch diameter is not located at the same place on these surfaces, although the tool's and the work's geometry had been the same. This is a consequence of the tool wear during its life cycle. As it redresses, the center distance between the work and the tool decreases; thus it changes the pitch between the two mating parts. Because of this, the conditions for making undulations on the surface change, altering the quality of the gear (see below).

Surface amplitude parameters versus the tool rotary speed, in Figure 6a, consistently decrease by increasing running speed. An alternation of running speed does not, however, change the surface parameters by more than 20% while the average error was estimated at 10% (parameter values were read from the subfigures in Figure 5). The grain size of the gear honing tool does not tend to affect these parameters significantly (changes in parameters were less than 10%). Therefore no figure is drawn for this reason.

Measurements performed by the optical measuring machine (Fig. 7, the subfigures) illustrate different parts of one tooth flank. In these figures the difference in the surface structure is highlighted. The surface lay (undulation direction) turns continuously from parallel to the face width at the root to almost perpendicular at the tip. Subfigures close to the root resemble ground surfaces, consisting of undulations only. Changes due to measuring locations in surface amplitude parameters, obtained from these measurements, are shown in Figure 6b. The Rq and the Ra value increased significantly by more than 40% from tip to root (x-direction) of the tooth, but these values did not indicate significant changes when they were compared to the face width direction (y-direction). The significance level for these parameters was estimated at 10%. The estimation was based on measurements on different teeth, but on the same location along the involute. Moreover, it was worth mentioning that all other surface amplitude parameters follow the trends of the surface Rq value (see also Figure 6b) and are therefore not considered in the diagram.

Fig. 8, using the spectral analysis, characterizes the profile undulation of the gears produced. The curves indicate an undulation wavelength (λa) in the range of 0.25 to 0.3 mm—these numbers refer to the location of the highest peak of the curves along the x-axis. The solid line represents the surface produced by grain size 180 at a running speed of 140 rpm. The dashed line analyzes the surface 120/560 (the lowest right one in Figure 5). A reduction of the undulation amplitude (*f*wa) and a shortening of wavelength (λa) was observed. The main reason for the reduction of (*f*wa) was the increasing tool speed. For the sake of clarity, only two curves are plotted. Spectral curves for the other surfaces are not included since their wavelength content and magnitude are within the two curves presented.

Discussions

The reason this article discusses the undulations is that they negatively influence the functional properties of the gear. The undulations increase the noise activity of the gear and influence the noise quality, the way the noise is perceived by the human ear. Harmonics of the mesh frequency increase significantly when undulations like those shown in Figure 2 were present on the surfaces (Ref. 2). The undulations on the surface shown in Figure 2 was two times higher and wider than those made by the power honing. It is known that the harmonics of a frequency influence the way it sounds. Therefore undulations are of great importance for the functional performance of the gear.

The results presented in this paper, surfaces obtained by power honing, are consistently in agreement with the results reported for other gear finishing operations, i.e. the results presented for spheric honing and threaded grinding operations (Ref. 1, 3). The three most important results are:

- That a rise in the tool speed reduces the amplitude parameters of the surface produced;
- That while tool grain size is of minor significance due to gear surface topography, it does have an indirect influence. The grain size can shorten the wavelength of the surface undulations and this, in turn, can offer a better condition for accomplishing lower amplitude levels. In other words, the problem is that in order to produce lower *f*wa, shorter λa are required:
- That undulations are unavoidable on gear surfaces and that they have different wavelengths and amplitudes for different operations.

Figure 7 bears strong evidence of the serious problems connected with evaluation of gear surface topography based only on a minor part of the surface. This is because gear surfaces are not uniform. For example, if the evaluation range of the flank were based on the area close to the root, the surface would be classed as a ground surface although it was honed. And, if the evaluation range were based on the near-tip area, the measurement would not show the existence of the undulations. In both cases a 40% error would occur. Furthermore, 2D measurements would also lead to a wrong assessment of the surfaces. None of the measurements would show the real surface features.

Conclusions

- The power honing process stands between conventional gear honing and threaded gear grinding operations. Since the wavelength and the amplitude level of the undulations on these surfaces is less than a half of that for undulations occurring in gear grinding operations, it is expected that this kind of surface reduces noise in the gearbox.

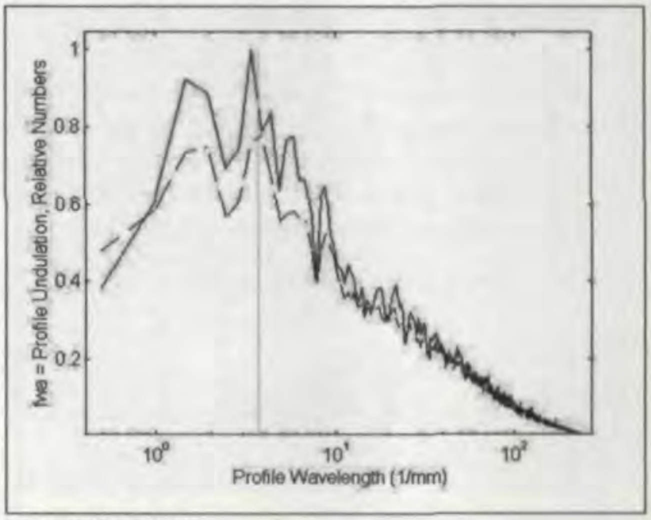

Fig. 8—Profile undulation.

- Increasing tool speed reduces the level of amplitude parameters on the surface.
- Grain size of the tool is of minor significance for the surface topography.
- Surfaces are not uniform from the root through the tip, and surface amplitude values may differ by as much as 40%. Evaluation of surfaces of this kind must be cautiously performed.
- Undulations with a wavelength of 0.3 mm occurred on surfaces, although it was expected that gear honing operations create a favorable surface lay with no grinding scratches on the surface. These parameters could not be significantly affected by running conditions; however they were slightly affected by the grain size of the tool.
- The surface lay was the same as that found in conventional gear honing processes. ○

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