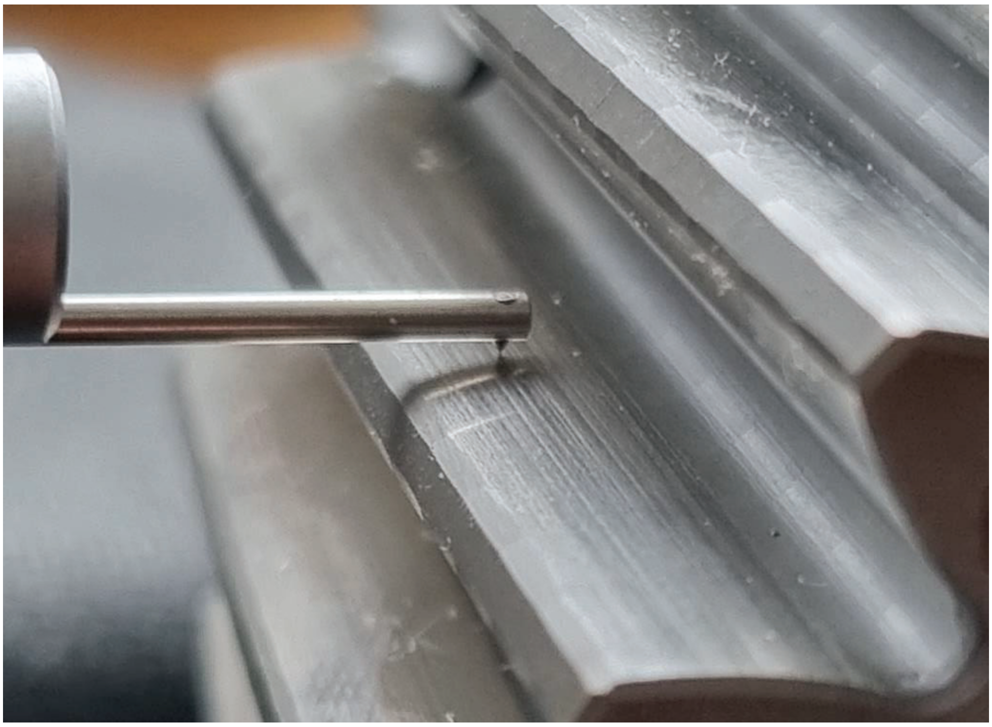
SURGE

Publik rapport



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Projekt inom Sustainable Production

FFI Fordonsstrategisk Forskning och Innovation

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1 Sammanfattning

Projektet Surge har haft som fokus att studera trender och normal praxis vad gäller mätning och kontroll av ytor samt vilka ökade krav som uppkommit på senare tid som en följd framför allt av elektrifieringen av fordonsparken. Detta har gjorts genom frågeformulär till och intervjuer med personer verksamma inom produktion och mätning av komponenter till drivlinor i fordon och genom studie av litteraturen. Dessutom gjordes stickprov i produktionen på nya och gamla produkter där ytjämnheten mättes mekaniskt med nål och med ett optiskt instrument. Bäst information om ytans tillstånd erhölls med nålinstrument och SEM fotografi.

2 Executive Summary

The Surge project is generated from questions concerning present and future demands on surfaces in drive trains for electric vehicles. Many components in these drive trains will be lighter and subjected to higher loads, increased rotational speeds and number of load cycles. The trend is going for finer surfaces with more narrow tolerances with the goal of reaching improvements in gear efficiency and life and reduction of noise from the gear box and other parts which will be more obvious without the sound of the internal combustion engine. This work shows that for quick evaluation of surface roughness the stylus instruments are still the most common and best solution. There exists an increasing number of optical shape measurement equipments that can be set up in or close by the production machine in order to measure and detect geometric errors. For roughness in the ranges required for gears, no equipment was found here.

Normal roughness parameters are used also for the finer surfaces. In addition to the common Ra, Rz, Rp etc. from the mean line family, parameters derived from the bearing curve (Rpk, Rmr, Rvk etc.) are also used. These standard values are combined with specific amplitude tolerances for a defined range of wavelengths. The special requirements can come both from the producer and the customer.

The main problem lies not in measuring the surface parameters but in producing them consistently and knowing how they interact with surface properties such as geometric accuracy and surface integrity to influence fatigue life, fretting, lubrication properties and noise. That task is too big for this project but some information can be gained from literature. However the levels of the parameters are very hard to find and more general recommendations for a smoother surface is mostly given. This is also due to the many different components and differing situations and demands that they are subjected to. Most valuable would be to find the good enough level where the specific requirements for each part is met.

Recently there has been an increase in surface requirements leading to more articles requiring a final polishing step. This can be done by using a dual grinding worm with a final polishing step. As shown here to achieve the best results there is still a lot of work in setting up the process involving among other things cutting data and the correct dressing of the grinding wheel. The final result is also depending on the surface coming in from previous machining steps.
Polishing with a grinding wheel and hard skiving was found here to give similar effects on the measured surface parameters and hard skiving is one process that is used as a final step for the component.

3 Introduction

3.1 Background

The automotive industry is undergoing a modern revolution driven by environmental laws and a fast-paced transition to E-mobility (Electromobility). With the 2030 Climate Target Plan, the European commission has an ambition to reduce net EU greenhouse gas emissions to 55% below 1990 levels by 2030 [1]. Other crucial automotive markets such as China, USA and Japan have also faced significantly stricter CO_2–emission limitations by the year of 2025 and 2030 [2]. These demands can no longer be accomplished by merely optimizing the internal combustion engine (ICE) drivetrain and this has further accelerated the development of electrified vehicles.
In the on-going advancement of E-mobility powertrains, gears and elements close to electric motors will decrease in number and size while each component will have to accommodate higher rotational speeds. Furthermore, the lack of a combustion engine in electric vehicles puts more emphasis on the noise and vibration (NVH) emitted from the driveline [3]. As a result, increased demands regarding NVH, gear efficiency and fatigue resistance are created which impact the manufacturing process of the E-mobility driveline components. All these aspects are dependent on the finishing machining step where the final surface is generated.
Gears are the elements in the electrified powertrain that have some of the strictest requirements for surface finish and geometrical accuracy [4]. Although there are several recognized gear finishing processes, the increasing demand for high-performance gears necessitates in-depth investigations in how to specify and machine the required surface quality needed in future electric vehicles. This involves examining what surface quality is possible to achieve, how to measure the surface and how to properly define the surface integrity in a requirement specification.

This pre-study will focus on the connection between the finishing machining process and the generated surface integrity of gears in electrified drivelines. Since E-mobility and electric powertrains are a relatively recent topic most research involve surface optimization of gears in traditional internal combustion engine drivelines. Although some research has been done regarding surface integrity parameters for driveline components connected to manufacturing finishing methods, there is still a lot more research to be done concerning the E-mobility topic.

3.2 Objective and research questions

The project aim is to highlight questions regarding surface roughness demands on gears and their validity, how to create these surfaces consistently and how to measure and control that the demands are met. Knowledge on how to define, machine and control the required surface can result in an increased gear performance and improved sustainability throughout the product life cycle.

4 Methods

A literature review was made focusing on surface requirement trends for gears, surface roughness measuring equipment and their limits, factors influencing the result of roughness measurements and which roughness parameters that can give relevant information regarding the performance of the gears. Furthermore, the ability of different machining operations to give fine surfaces and the characteristics of these surfaces was included. The effect of fine surfaces on gear life and performance with regard to surface fatigue was also added. A questionnaire was sent out to members of the industry highlighting the trends in surface demands from customers.

Finally three sets of demonstrators were picked out as examples of common current operations on gears and these articles were measured using stylus instruments and infinite focus equipment. The surfaces were also documented in SEM.

5 Results

5.1 Questionnaire, manufacturers point of view

A set of questions were sent out to manufacturers of gears. A summary of the answers is shown below. Some companies were a bit more reluctant to answer more specific questions.

The finishing processes most commonly used are grinding, polishing, hard skiving and to a lesser degree the slower and more costly honing. Recently there has been an increase in surface requirements leading to more articles requiring a polishing step. The polishing can be added in grinding by adding a polishing part to the grinding wheel for extra smoothness. More costly is adding some vibratory polishing process such as Isotropic super finishing, ISF. The roughness tolerances are tighter in general and it is getting more common to specify both upper and lower limits.

The increased demands can have several goals, most commonly to reduce effect losses in the gears and to reduce noise and vibrations but also to increase the gear life and reduce surface damages. There are strong indications in some cases that the increased smoothness can be detrimental to performance and also that the gears can become more sensitive to edge contacts. For some surfaces where an oil film is required a too fine surface cannot hold the oil film.

In production control the standard instrument for roughness measurement and control is still a 2D stylus instrument, with or without skids (more common). Coordinate Measuring Machines CMM are used for longer wavelengths. In R&D situations, 3D measuring optical equipments such as Alicona Infinite focus or stylus based mechanical 3D equipments are also used but then often requires sectioning of the gears.

The surface parameters used for production control are 2D profile based and are the familiar Ra, Rz, Rmr, Rp and Rpk but also Rsk, Rvk, Rmr, Rmax and Wt and Pt. These standard values are combined with specific amplitude tolerances for a defined range of wavelengths. The special requirements can be set both by the producer and the customer.

Producers are of course reluctant to add costly extra steps to reach certain surface parameter values and if there are problems will first modify tool and blank conditions and process data. Components that have a design that restricts the manufacturing flexibility most often cause problems with surfaces.

The problems that will occur when measuring the surfaces of the gears are to some degree all of access, measurement uncertainty, accuracy, repeatability and variation. The involute form can be difficult to remove completely from the roughness calculations.

The roughness and waviness in production is intensely monitored during setting-up of a new production batch. After that the process should be stable enough to give similar results and measurements are made with longer intervals. How long depends on the variation in results.

The complex shape of gear teeth and drive train components will give special problems with access for measurements. When standardized measuring data are impossible to use it is common to reduce the standardized number of sampling lengths from five to three or reduce the cut-off filter λc according to customer internal standards. In some cases the raw profile is used with external data handling software.

The manufacturers in this inquiry measures both along and across the feed pattern on the teeth and on several teeth around the wheel. It is also deemed necessary to adapt the measuring position on the individual teeth to the area that is the “best” in terms of performing reliable measurements. Several measurements are made to reduce human error. Both the driving and the braking side of the gear tooth is measured as their roughness may vary substantially.

Companies are themselves quite active in assessing what is possible in terms of surface finish with different processes and which surface parameters that are most relevant for different applications.

5.2 Literature survey / State of the art

Measuring surface roughness

Surface roughness is quantified by the deviations in the direction of the normal vector of a real surface from its ideal form. In surface metrology, roughness is typically considered to be the high-frequency, short-wavelength component of a measured surface. In practice it is often necessary to know both the amplitude and frequency to ensure that a surface is fit for a purpose. There are parameters defined both for the amplitude and the wavelength domains with the former being most frequently used.

There are some basic requirements for surface parameters intended for use in a product specification. They should be relevant to the current production method, to the intended use of the part and the critical failure mechanism of the gear. They should also be possible to measure without having to invest considerable resources in money and time. Equipments used should not be too costly and should be useable outside advanced lab environments.

It is also important that the parameter values are consistent for a “good” or a “bad” surface. Some of the more exotic surface parameters can have very varying values between different gear teeth on a wheel or different positions on the tooth and it will be very difficult to find a level or limit that signals an approved or a discarded product.

The most simple, easy to operate and most widely accepted roughness measuring equipments are still the 2D stylus instruments. They give fast measurements on surfaces that do not have to be super clean. The pickup exists in a variety of designs to access both internal and external surfaces with complicated geometries. Stylus instruments do not have many sources of error and the height resolution can be very high. The lower wavelength limit is set by the radius of the stylus which gives a natural filtering.

The downside of 2D stylus measurements is that they do not always give a fair view of what the normal surface looks like and you are more likely to miss some surface features than you would be with a 3D system.

It is very important to measure the 2D profiles in the right direction with regard to the machining operation used on the work piece, normally perpendicular to the lay of the surface. In grinding this is perpendicular to the grinding marks, most often along the rotating direction of the gear.

Roughness measurements are described in various standards for instance ISO 4287:1997, ISO4288:1996. The standard is based on the ″M″ (mean line) system. There are many different roughness parameters in use, but Ra is by far the most common. Other common parameters include Rz, Rq and Rsk. These will be defined in the next chapter.

Some parameters are used only in certain industries or within certain countries. For example, the Rk parameters is used mainly for cylinder bore linings, and the Motif parameters are used primarily in the French automotive industry. The MOTIF method provides a graphical evaluation of a surface profile without filtering waviness from roughness. A motif consists of the portion of a profile between two peaks and the final combinations of these motifs eliminate ″insignificant″ peaks and retains ″significant″ ones.

Producers of measuring equipment often provide guidelines of R-value definitions as well as recommendations on what parameter to use. Mitutoyo recommends some preferred parameters in different situations. The maximum surface roughness Rz1max is recommended for surfaces where individual deviations heavily affect the function of the surface, e.g. sealing surfaces. For guide surfaces and sealing surfaces, Rmr(c), the material portion of the profile at a certain distance from the highest peak is suggested and for all other surfaces Rz, the surface roughness depth is recommended.
Companies involved in gear producing can also use modified R-value specifications with specific limitations and settings. It can be relevant to set both upper and lower limits of for example Rz to ensure both gear wear resistance and lubrication properties.

Surface parameter definitions

Central in the evaluation of roughness parameters is the filtering process where a decision is made on what wavelengths to consider. In general a form is first removed by deducting the longest wavelengths from the raw profile or for example a cylindrical shape if the shape is given. In the next step a filter, usually a gaussian phase corrected filter, is used to separate the profile into a waviness profile and a roughness profile. The length of the filter decides where this divide is set. There are recommendations in the standards for which filter length Lc to use based on within what region the final Ra and Rz values will be. The Lc values 0.25 mm, 0.8 mm, 2.5 mm and so on in the standards were chosen without any real theoretical meaning but serves the purpose of making measurements performed at different sites and times possible to compare. It is crucial that the filter length Lc is stated whenever an R-value of any kind is presented. If there is a known periodicity in the surface that is considered uninteresting but would dominate the R-values, the wavelength of this feature could instead govern which Lc to use in order to remove it from the roughness profile.

Some restrictions in wavelengths are imposed by the measuring equipment. On a stylus the smallest wavelengths are cut away by the radius of the tip. At the other end the maximum wavelength is restricted by the total measuring length which in turn is restricted by the maximum travel length of the stylus.

When setting specific roughness requirements, they should be focused on the wavelengths most critical for the functionality of the component, be it resistance to pitting or other fatigue related phenomena or creation of noise. The problem is that this critical wavelength range is not always known. The same is true for picking the most relevant R-parameter connected to the current failure type.

Amplitude parameters.

Rz is a surface parameter that have at least three different definitions in different standards. Most commonly it is defined as the mean of the maximum peak to valley value of each cut-off length within the total evaluation length. If the absolute max should be used, this has to be specified in the drawing.

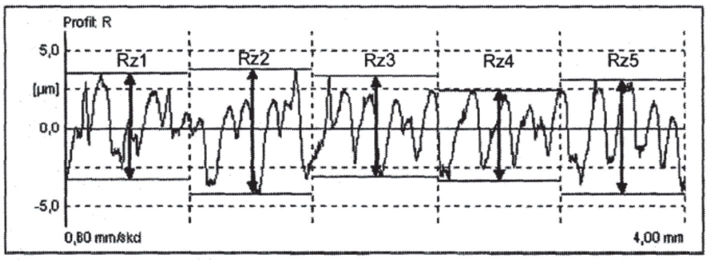


Figure 1 Definition of Rz

Rp and **Rv** have similar definitions being the mean of the highest peak or valley from the mean line in the 5 cut-off length areas.

One other commonly used parameter is Rsk - **skewness** that gives information about the distribution of amplitudes in the surface, Figure 2. A positive skewness means that there are a lot of peaks in the profile, a situation that should be detrimental to surface fatigue life due to local stress concentrations. Polishing or ISF treatment should lower the skewness value substantially. However, the scatter in results from tooth to tooth is often too great for this value to be used.

A summary of some definitions of amplitude R-values is shown in Table 1.

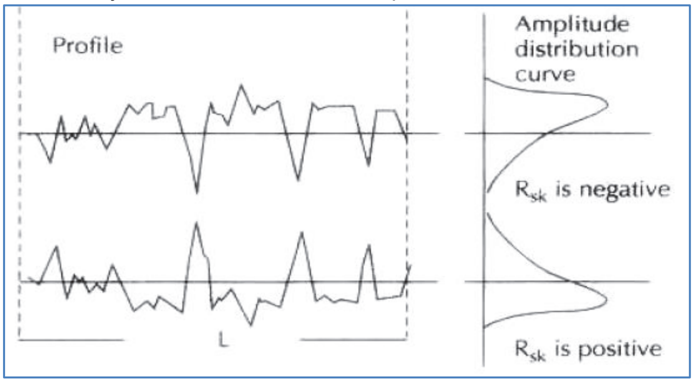


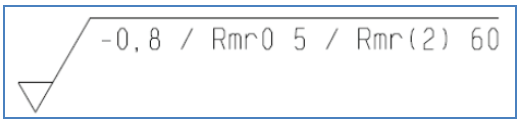
Figure 2 Explanation of the meaning of the skewness parameter Rsk.

Table 1 Summary of common amplitude parameters

Parameter	Description	Formula
Ra,[8] Raa, Ryni	Average, or arithmetic average of profile height deviations from the mean line.[9]	$Ra = \frac{1}{l_r}\int_0^{l_r} \lvert z(x)\rvert \, dx$[4][5]
Rq, Rms[8]	Quadratic mean, or root mean square average of profile height deviations from the mean line.[9]	$Rq = \sqrt{\frac{1}{l_r}\int_0^{l_r} z(x)^2 \, dx}$[4][5]
Rv_i; Rv	Maximum valley depth below the mean line, within a single sampling length; Average Rv value over assessment length [4]	$Rv_i = \lvert \min z(x) \rvert$; $Rv = \frac{\sum_{i=1}^{n} Rv_i}{n}$[4]
Rp_i; Rp	Maximum peak height above the mean line, within a single sampling length; Average Rp value over assessment length[4]	$Rp_i = \max z(x)$; $Rp = \frac{\sum_{i=1}^{n} Rp_i}{n}$[4]
Rz_i; Rz	Maximum peak to valley height of the profile, within a single sampling length; Average Rz value over assessment length[4]	$Rz_i = Rp_i + Rv_i$;[4] $Rz = \frac{\sum_{i=1}^{n} Rz_i}{n}$
Rsk	Skewness, or measure of asymmetry of the profile about the mean line.[9]	$Rsk = \frac{1}{Rq^3}\left[\frac{1}{l_r}\int_0^{l_r} Z^3(x)dx\right]$[5]
Rku	Kurtosis, or measure of peakedness (or tailedness) of the profile about the mean line.[9]	$Rku = \frac{1}{{R_q}^4}\left[\frac{1}{l_r}\int_0^{l_r} Z^4(x)dx\right]$[5]
RzDIN, Rtm	Average distance between the highest peak and lowest valley in each sampling length, ASME Y14.36M - 1996 Surface Texture Symbols	$RzDIN = \frac{1}{s}\sum_{i=1}^{s} Rt_i$, where s is the number of sampling lengths, and Rt_i is Rt for the i^{th} sampling length.

Bearing ratio parameters

The roughness curve can be transformed into a bearing curve from which several parameters can be calculated. **Rmr** is one interesting parameter that describes the bearing ratio of the material at a certain depth. The blueprint notation below specifies a minimum level of 60% material at 2 µm depth from the start line. The start line is set at 5% material fraction to counteract that a few sharp peaks have a too big influence on the value.



Another way of annotating this limit would be Rmr(-2.00,5.0) 60. Without the number 60 it would specify the measured percentage of material at that depth.

Rvk and **Rpk** are calculated from the bearing curve, Figure 3, and are values derived from the valleys and peaks of the profile. A big Rvk for instance means that there are a lot of deep valleys in the profile and a big Rpk that there are a lot of high peaks. A polishing process should lead to a lower Rpk, Rz and Rp value while the Rvk and Rv values should be affected to a much lower degree.

The Rk, Rpk and Rvk values are calculated according to Figure 3.
A line is drawn in the center region of the bearing curve where the inclination is lowest. The line should be based on a length of at least 40% of the x axis. This line is extrapolated to 0 and 100 percent material and the difference between these two points defines Rk, the core roughness. Mr1 is defined as the material ratio at the intersection between the upper limit of the core roughness L1 and the bearing curve. The area between L1 and the bearing curve is calculated. A triangle having the same area is constructed with Mr1 as the base and Rpk as the height. This will remove the influence of a few very big peaks. An analogous calculation is made at the other end of the curve to get Rvk using Mr2.

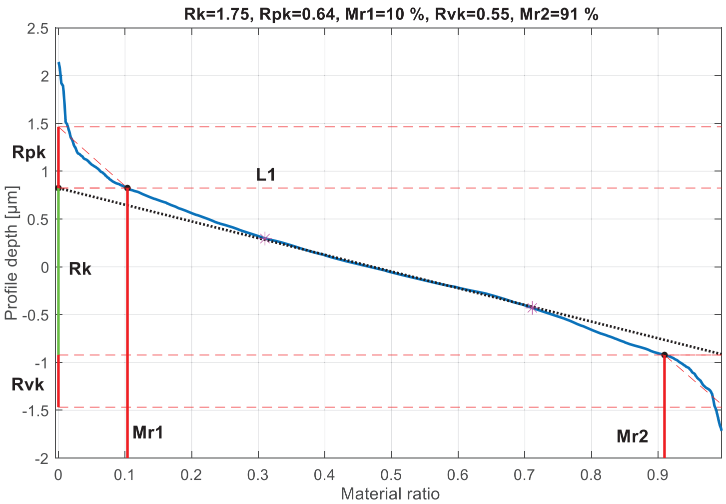


Figure 3 Definition of Rk, Rpk and Rvk values and Mr1 and Mr2.

Areal parameters

Areal roughness parameters are defined in the ISO 25178 series. The resulting values are Sa, Sq, Sz etc. that are similarly defined as the 2D R-values. Many optical measurement instruments are able to measure the surface roughness over an area. Area measurements are also possible with contact measurement systems. In this case multiple, closely spaced 2D scans are taken of the target area. These are then digitally stitched together with special software, resulting in a 3D image and accompanying areal roughness parameters.

The main advantages of areal measurements are that they provide a better overview of the gear surface. In addition to the color coded areal diagram, most often the 3D images are reduced down to a single S-value as for the 2D case.

There are some issues with optical 3D technique on the hard to reach surfaces on gears where special fixturing and stitching often is required to give good measurements. In the case where one pixel generates one xyz value there is also a need for large magnifications to get good lateral resolution leading to extensive stitching due to small individual measuring areas and long measuring and evaluation times. Thus areal measurements are probably mostly performed in a research lab environment for R&D and more seldom used in production control situations even though there are manufacturers offering equipment for fast 3D measurements.

Surface roughness levels and production methods

Some general facts on surface roughness levels attainable with different production methods and offered on-line by various companies are shown in Figure 4 below. For gear surfaces where increased performance with regard to increased loads, load cycles to failure and resistance to surface fatigue is wanted, the different grinding/polishing/super finishing processes can get down to Ra levels from 0.1 to 0.0125µm.

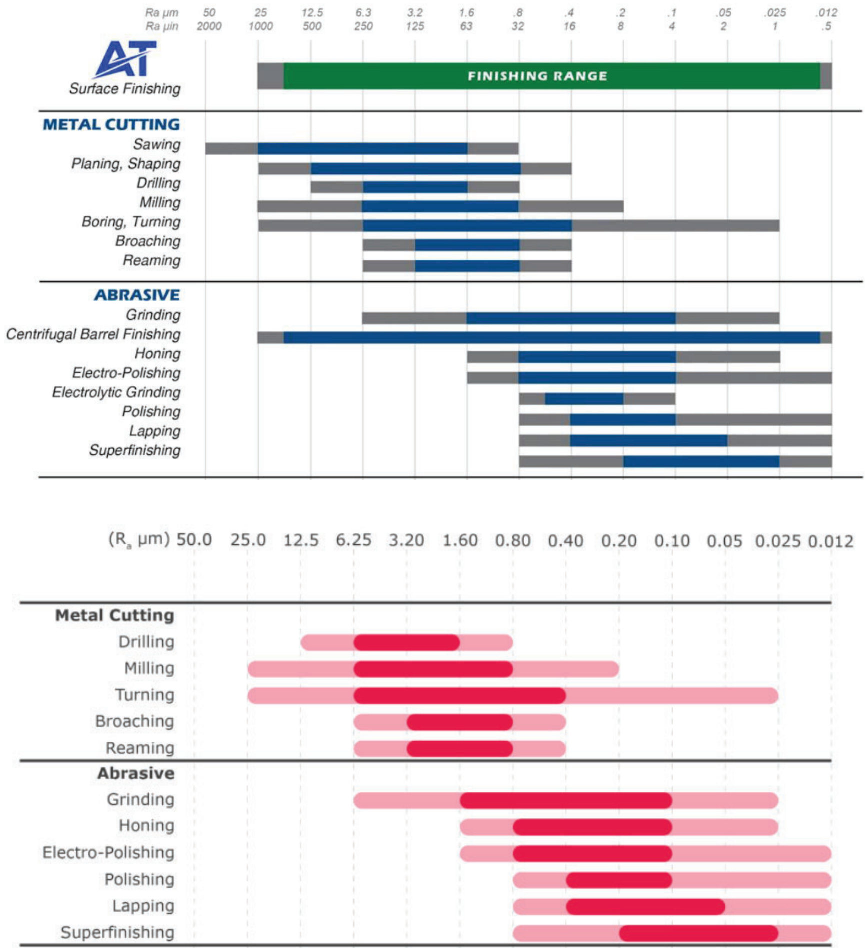


Figure 4 Surface roughness levels expressed as Ra for different processes, [5], [6]

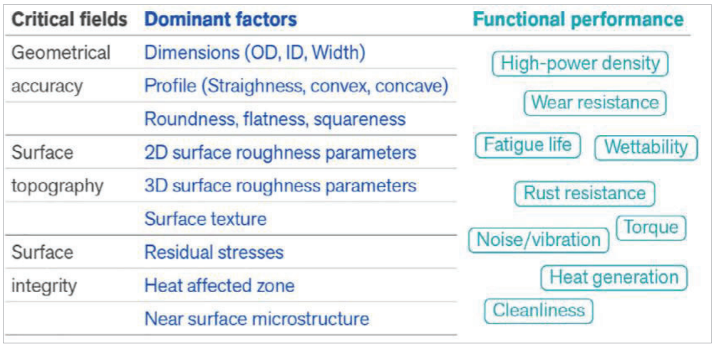
Effects of surface roughness on gear performance

The current increase in surface requirements seems to be driven by a hunt for increased gear efficiency, increased (micro)pitting resistance and increased tool life.

The noise problem seems to be more related to meshing errors, longwave variations and assembly related problems. Zecchino [7] points out the importance of waviness along the gear tooth for noise generation where the middle frequency waviness on gear teeth were correlated to gear noise in the audible range. These wavelengths are in the order of 2 to 3 undulations along one gear tooth flank and often go undetected and are typically much smaller than the overall form tolerance limits for the gear. He suggests Wtc and Stc as good indicators, the maximum Waviness depth and height in the measured area when the outside extreme values are removed.

Testing of gear efficiency and wear and all factors that can influence them is notoriously difficult and time consuming and there are few conclusive studies made on the effects of different surface states, treatments and roughness parameter values on gear efficiency, wear resistance and noise elimination, especially when it comes to electrified drive lines.

The different critical fields and dominant factors that have to be managed to achieve a certain performance of the gear is listed by Krajnik [4] in Figure 5. The choice of machining steps in the production will affect all these surface properties. Even if the focus is on surface roughness it must be seen in the context of all other surface properties.



Critical fields	Dominant factors
Geometrical accuracy	Dimensions (OD, ID, Width)
	Profile (Straighness, convex, concave)
	Roundness, flatness, squareness
Surface topography	2D surface roughness parameters
	3D surface roughness parameters
	Surface texture
Surface integrity	Residual stresses
	Heat affected zone
	Near surface microstructure

Figure 5 Factors influencing gear performance [7]

Finishing method and surface texture

The surface texture of a component depends on the finishing method. A ground surface consists of directional scratches, whereas a hard-turned surface exhibits regular feed marks [4]. A superfinished surface, in contrast, features characteristic cross-hatch grooves, whereas an isotropic finished surface exhibits no directionality in the marks.

These surfaces yield different coefficients of friction when in sliding contact [8]. In terms of residual stresses, superfinishing generates the highest compressive residual stress, followed by grinding.

By the adjustment of the pre and final machining, involving both a milling and a honing process [9], a more favorable surface structure compared to a ground structure can be attained, consisting of grooves along the sliding direction, shortening the running-in phase and lowering the friction. Processes should be adjusted not only for their own efficiency but in regard to the preconditions for the subsequent machining step.

The surface roughness can be pushed down to very low values with different polishing techniques but the cost for potentially quite small improvements must also be taken into consideration [10]. There are also reports of finer surfaces getting impaired lubrication properties.

Micropitting in gears and correlations to surface roughness

The transition to electrical drivelines means that some gears will be engaged all the time that the engine is running and at quite high speeds. In combination with high loads this puts increased demands on resistance to micro pitting damage and contact fatigue phenomena. One possible way to increase gear life is by using cleaner steel to reduce the risk of inclusions initiating fatigue cracks. Once that is accomplished the next step is to look at the state of the surface, among other things the roughness.

Kahraman describes the micro pitting in the following way in a comprehensive study [11]:
Micro-pitting is a progressive rolling contact fatigue wear phenomenon occurring on the micro-scale induced by severe localized stress concentrations at or very near the contact surfaces. As two contacting rough surfaces slide against each other, the roughness profiles often interact to produce instantaneous peaks of normal pressure and surface shear. These time-varying surface tractions result in large multi-axial stress amplitudes for the material points within a very shallow layer of material (typically less than 2μm in depth). The localized cyclic loading, which can be several times higher than the corresponding Hertzian pressure, dictates the fatigue failure in the form of micron size pits. These small pits can either be clustered together or scattered over the surface, depending on the surface roughness texture. As the number of contact cycles increases, the amount of micro-pits grows. The scattered light reflections from the numerous micro-pits lead to a grey-colored appearance and has often been referred to as grey staining or frosting. Under the condition that the two surfaces are well separated by a layer of fluid film, the hydrodynamic pressure and viscous shear can still be raised to relatively high levels when the surfaces are relatively rough, leading to the occurrence of micro-pitting.

In gearing applications, the wear of micro-pitting can largely increase the transmission error and lead to undesirable noise and vibration. The dynamic response also amplifies the tooth contact force, further accelerating the rate of micro-pitting. Under certain operating conditions, the amount of micro-pits stabilizes after the surface wear redistributes and relieves the contact pressure. However, the continued cyclic contact can result in failure from macro-pitting which initiates from the micro-pit cracks. In order to avoid such failures, extensive experimental studies have been conducted in literature, investigating the influences of various potential factors on micro-pitting.

In one study of the roughness influence on micropitting, Kahraman [11] uses a two roller contact fatigue testing machine where the lay of the grinded rolls is perpendicular to the sliding/rolling direction so that not only the amplitudes but the directionality of the gear contact surface roughness can be simulated.

Table 2 below lists the test matrix Kahraman constructed using the Design of Experiment (DOE) approach. To study the influence of run-in on micro-pitting occurrence, a run-in stage was implemented before each normal test stage. During each test, the machine was paused periodically for inspection of the specimens, including circumferential surface roughness measurements and a micro-pitting area measurement using a digital microscope. During the test, the inspection was carried out every 2 million roller contact cycles.

The sliding direction was not included in the test matrix but was found to have a big impact on micro pitting so that the roller which has negative sliding gets a lot of micro pitting and the slider that experiences positive sliding has none.

Table 2 Rolling contact fatigue test matrix

Test #	p'_h [GPa]	v'_r [m/s]	p_h [GPa]	v_r [m/s]	SR	R_q [µm]	$\bar{\Phi}$ [%]
1	0.6	5.85	1	3.9	-0.2	0.4	0.02
2	1.2	1.95	1.5	3.9	-0.2	0.4	0.07
3	0.8	1.95	1	3.9	-0.65	0.7	0.41
4	0.6	3.9	1	7.8	-0.2	0.7	3.06
5	0.9	5.85	1.5	3.9	-0.65	0.7	28.10
6	0.8	11.7	1	7.8	-0.65	0.4	0.00
7	0.9	3.9	1.5	7.8	-0.65	0.4	0.00
8	1.2	11.7	1.5	7.8	-0.2	0.7	2.71

P'h - Hertzian pressure at run-in stage*, v'r* - rolling velocity at run-in stage,

Ph - Hertzian pressure of the test stage*, vr* - rolling velocity at the test stage,

SR - slide-to-roll ratio of the test and run-in,

Rq - the root of the sum of the squares of Rq1 and Rq2, the Rq values for roller and disk.

Φ - micro pitting parameter = ratio micro pitted area/ total inspected area (max 28.1%)

It is seen in Figure 6 that a high level of hertzian pressure, low rolling velocity, high slide to roll ratio and high roughness amplitude Rq lead to a greater micro-pitted area.

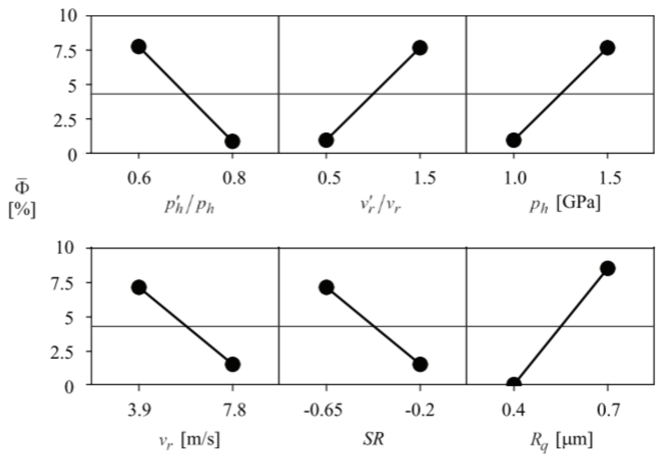


Figure 6 Detrimental effect of high Rq, pressure and slide/roll ratio and low speed.

It is shown here that a run-in stage with relatively high contact pressure and relatively low rolling velocity can effectively reduce the amount of micro-pits, benefitting the contact surface in many ways, for instance by: (i) gently flatten the roughness peaks and relieve the surface stress concentrations induced by local roughness interactions before the normal test stage; (ii) more effectively generate a protective low-friction tribo-film owing to the relatively large frictional heat; and (iii) raise the local surface hardness through work hardening.

The development of the surface profiles during run-in and test is shown in Figure 7. The effect of the run-in looks very much like the effect of an ISF process, the peaks are smoothed out while the valleys remain unaffected. During the test the Rq value again rises for the roller due to micro pitting. It was observed that a high pressure and low speed during the run-in could have a positive effect on the pitting resistance due to this smoothing effect. (Even in this very detailed test the only roughness value that was considered was Rq. It should also be noted that the levels of Rq are not indicating super fine surfaces.)

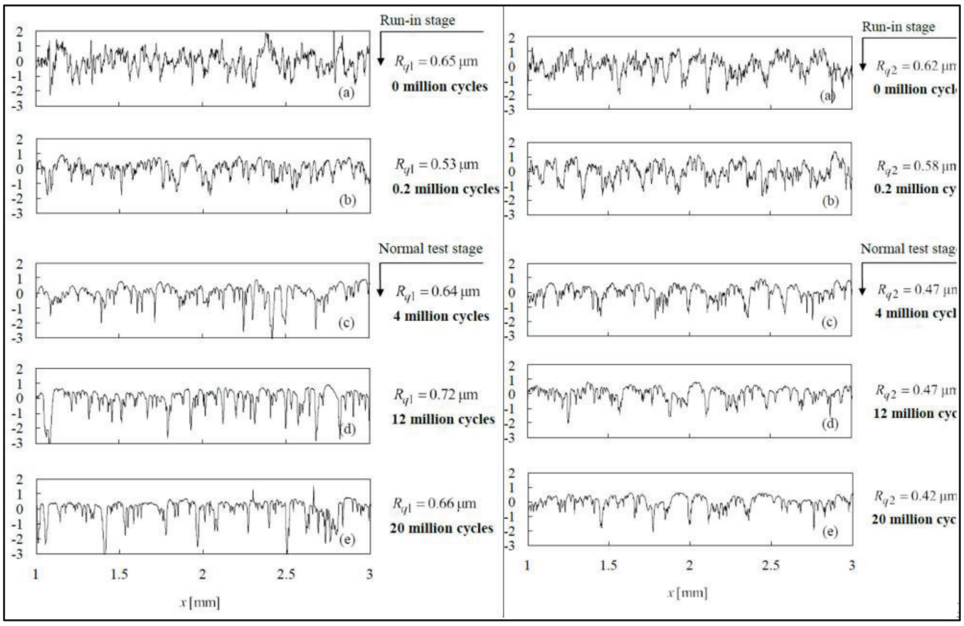


Figure 7 Development of surface roughness for roller (left) and disk (right)

In the absence of an established criterion, the Λ-ratio (the ratio of lubricant film thickness to surface roughness) is often used as a simple way to assess the risk of micropitting. In a study Wainwright et al. decouples the roughness from the film thickness [12] and shows that higher Λ ratio at fixed roughness produces less micropitting and, more interestingly, that at a fixed Λ ratio, the amount of micropitting damage is extremely sensitive to the actual surface roughness, with lower roughness both lengthening the micropitting incubation phase and decreasing the rate of material loss in the micropitting wear phase. In relative terms micropitting was more sensitive to surface roughness than to Λ and Wainwright claims that there exists a sufficiently low surface roughness below which micropitting is unlikely to occur even at extremely low Λ ratios. In Figure 8 this value is ~0.25µm for these tests. This of course supports increasing the demands on low roughness for improved surface fatigue resistance.

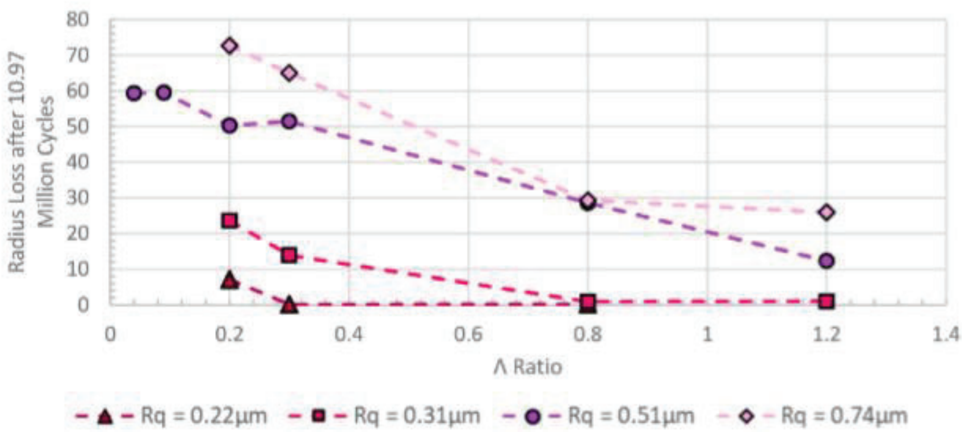


Figure 8 Influence of the Λ ratio on micropitting at a fixed Rq roughness value

Webster and Norbart [13] also showed that micro-pits tended to appear on the surface with negative sliding. Through the reduction of slide-to-roll ratio, they successfully eliminated micro-pitting. It was also found that increasing the lambda-ratio (the ratio of film thickness to the roughness amplitude) via reducing the roughness amplitude effectively eliminated the micro-pitting failure.

Oila states that the most significant factor that influences micropitting *initiation* is the contact pressure. At high contact pressure, the number of cycles necessary for micropitting to initiate is almost independent by the other factors. This he means implies the existence of a load threshold above which the means to avoid rnicropitting occurrence are limited.[14]

Regarding the main effects on micropitting *propagation*, Oila states that they are speed and slide-to-roll ratio[14]. At high speed micro pitting propagates with high rate regardless of the values of other factors. This implies that little can be done to stop the progression of micropitting when the operating speed is high (as it could be in certain electrical drive chain parts).

The link between the surface roughness and the resultant micro-pitting performance has been well established experimentally but it is hard if not impossible to find any actual roughness values in the articles or which surface parameters that are most interesting to reduce and control.

Ariura [15] shows that the initial surface roughness has a significant effect on the contact fatigue and creation of micro pitting in a two roller type fatigue testing machine. The surface failure “gray-staining” in gear testing was also mostly influenced by the initial surface roughness. These gears were grinded and the surface roughness was measured as Rz and ranged from 0.3 to 3. The lower end of this range is interesting for high performance gears.

Wei et al [16] have published one of the few articles that give any actual R values and find that the surface pressure becomes two to three times the Herzian stress at the convex roughness peaks for a combination of Ra=0.4 and an oil film thickness of less than 0.5 µm. This promoted micro pitting.

Isotropic super finished surfaces have been studied by a few researchers. The work often focuses on noise generation, fuel consumption and friction as well as efficiency ie small power loss in the gear transmission.

Andersson et al [17] studied the difference between ISF surfaces and ground surfaces with respect to running in. They found that the ISF surfaces improved very little by running in while there were big differences for the grinded surfaces. The efficiency of the ISF surfaces was good directly after production. Not surprising since ISF should have a very similar effect as running in.

A study from Krantz et al shows one more example of the super finishing process improving the pitting resistance [18]The gears were superfinished by the "Abral" process. It was found that typically the surface finish improved from about 0.4 µm roughness average (Ra) to 0.05 - 0.1µm Ra. It was concluded that approximately 2.5 µm had been removed from the tooth surfaces. This appeared to be the minimum required to remove all traces of the initial grinding marks for gears with an initial nominal finish of 0.4 µm Ra.

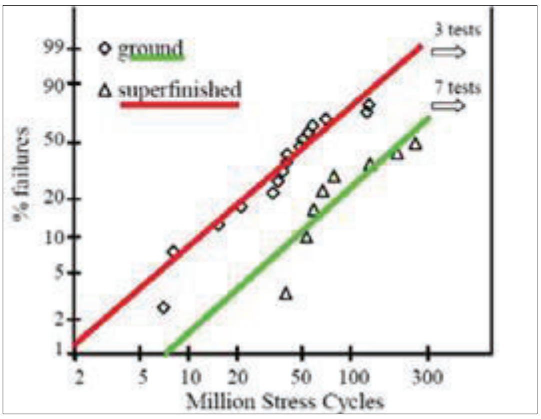


Figure 9 Big improvements in pitting resistance and fatigue life recorded after ISF treatment

Malipeddi investigated the influence on micropitting of roughness, residual stresses and material microstructure. He used preground gears (Ra0.32µm) that were honed to Ra 0.18µm or IF treated to Ra 0.08µm. Besides the roughness differences the honed surfaces exhibited a specific lay and irregular surface asperities which the IF surface did not have. The compressive residual stresses increased in the order ground<IF<honed which correlated to a reduction in retained austenite. At efficiency testing deformation of surface asperities led to micropitting of the honed surfaces, not for the IF surface. IF thus seems to be more efficient in preventing micropitting than honing.

Summing up some of the statements made from different references in this chapter it was found that:
negative sliding promotes micro pitting (rolling fatigue tests)
high hertzian pressure, low rolling velocity, high slide to roll ratio and high roughness amplitude Rq promotes micro pitting in rolling fatigue tests but a run-in stage with slightly lower contact pressure and relatively low rolling velocity can effectively reduce the amount of micro-pits by acting as a fine polishing step but also by increasing surface hardness and creating a tribo film
there may exist a surface roughness level below which micropitting is unlikely to occur even at extremely low Λ ratios, ~0.22 in the cases investigated.
increasing the lambda-ratio (the ratio of film thickness to the roughness amplitude) via reducing the roughness amplitude effectively eliminated the micro-pitting failure at Ra~0.4.
There exists a load threshold above which the means to avoid rnicropit *formation* are limited and little can be done to stop the *progression* of micropitting when the operating speed is high.
ISF surfaces were found to be beneficial for gear surface durability.

From the literature there is thus support for a drive towards improved surface finish from about 0.3 to 0.4 µm downwards through fine finishing steps to improve resistance to surface fatigue damages. It was not possible to find out how far down it is necessary to go or which surface parameters to monitor to get these improvements but a step from 0.3-0.4µm down to around Ra=0.1µm was reported beneficial in several cases.

Advances in grinding and measuring techniques

A few recent studies have touched on the specifics of machining of gear surfaces intended for electrified transmissions. A state-of-the-art review regarding grinding and fine finishing technologies was made by Krajnik et al. [4] with a focus on the current electrification trend. In the study recent advancements of different grinding and finishing processes are included with a comparative analysis on the advantages and disadvantages of each process. Evidently there is a huge driving force for new more productive finishing processes delivering gears with improved capabilities.

There are a lot of fine finishing processes for gears as diverse as wire EDM, lapping of bevel or hypoid gears using an abrasive slurry, vibratory finishing, and magnetic-abrasive finishing. Novel techniques, such as fluid-jet polishing, magnetic polishing and magnetorheological finishing may be feasible as well. Isotropic finishing (IF) of gears employs chemically accelerated vibratory finishing. More widely used operations include gear honing, which can be used for fine finishing of internal and external gears (e.g. planetary and sun-gear rings) [4].

Gear honing can give good gear surface properties but is mostly used only when the requirements are very high due to low productivity and cost.

Recent measurement techniques

There is ongoing work in different approaches to use image analysis and machine learning to measure the form and roughness of gear surfaces. While there seem to be some success in measuring the shape and form deviations as well as detecting defects and thermal damages, the author has however not found anything that goes beyond estimating Ra values when it comes to roughness and it is unlikely that this approach will be used for inspection of gear surfaces in the near future.

Different measurement techniques are on offer from different companies. The example text below is from a promotion paper and the technique has not been tested in this project.

A new *inspection* concept developed by Gleason called "GRSL" (*Gear* Rolling System with Integrated Laser *Technology*) features the possible combination of double flank roll testing and laser scanning. With this completely new approach *inspection* can now be performed in parallel at the same speed to the time required for the hard *finishing* operation. As a result, 100% in-process *inspection* has become a reality, eliminating the need for statistical process evaluation. In addition, the measured data can be further evaluated concerning waviness in profile, lead and/or line of contact direction which allows the evaluation of the noise behavior. Hence, this new system allows to do an up to 100% in-process noise analysis prediction of the finished *gear*. And even more, the measured *gear* deviations can be fed back into the design software to run a loaded tooth contact analysis under real conditions including the *gear* geometry with manufacturing errors superimposed. This new revolutionary *inspection* concept has been integrated with a modern threaded wheel grinding machine and a fast and flexible automation system to create the HFC (Hard *Finishing* Cell) which features an automated Closed Loop correction system.
This looks promising but is more intended for shape and form deviations of longer wavelengths and can most likely not do roughness evaluation.

5.3 Demonstrators

The surface of three components from the industrial partners were investigated using stylus instruments, optical instruments and SEM. The final methods for two of the components are grinding and polishing while the third one is produced by hard skiving. The object of the studies was to find the level of surface finish relatively easily attainable without using additional slow and costly processes and to compare measuring methods and results and see effects of polishing and whether any such effects can be detected using normal measuring procedures or more elaborate methods. Reaching maximum surface smoothness and investigating all aspects of them is a task that would require very large efforts in time and money to investigate thoroughly so the work here is a mere indication of what is possible.

Case 1 - Generating grinding plus polishing – outside cog ring wheel

The first demonstrator component is a ring with outside cogs which is produced by generating grinding, fine grinding and polishing. Four different test samples were produced for the measurements after a quick set-up procedure involving two grinding wheels from two different producers, Saint Gobain and 3M. Both grinding wheels have a polishing part at one end, one with a hard binder (SG) and the other with a softer one (3M). For each grinding wheel one component was taken out before, SGS and 3MS, and one after the polishing step, SGP and 3MP. The process with the dual grinding worm is also called grind-finishing.

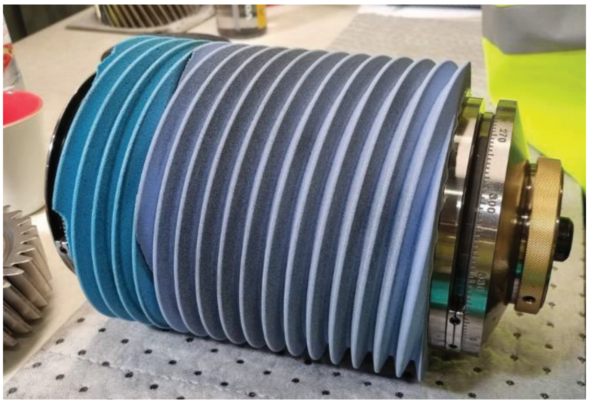


Figure 10 Grinding worm from 3M with polishing step.

Stylus measurements

The components were measured in the normal production control unit at Leax on a Mahr stylus instrument. The limit values for this specific component were defined in Ra, Rz, Rp, RMr(-1,5) and Rpk according to Table 3 and are shown with typical measurements made on the actual components. The actual values here are after fine grinding, before the polishing step. Thus, in this case the requirements were met without the use of the polishing step. The components were also measured at Swerim using a free bearing Mitutyo instrument for comparison.

Table 3   Roughness limits and results after grinding step from wheel SG

parameter	Low limit	High limit	Typical (grinded N)
Ra	-	0.3	0.177
Rz	-	2.5	1.182
Rp	-	0.7	0.462
R Mr (-1.00, 5.0)	90%	100%	99.5%
Rpk	-	0.4	0.197

Measurements in Alicona IF-SL

The grinding wheel N was examined in the Alicona IF-SL using three lenses giving 5, 10 and 20 times magnification. The 5 times is only used for general visual information as it is not recommended to use this low magnification for surface roughness measurements.
The 10x lens gives a 2x2 mm observation area in one image. If a greater area is needed, stitching of multiple images must be performed. One single image was used here and the image was cropped to 1.8x1.8 mm to remove edges and to enable comparisons with the 20x lens.
The 20x lens was used with stitching of 4 images. For comparison the area was cropped down to a 1.8x1.8 mm area for the surface roughness studies.
The components had to be cut into smaller pieces to enable studies of the flank surfaces. It would have been impossible to handle the whole component without investing in new fixtures and instrument stands.

Figure 11 Piece cut out from component 1.

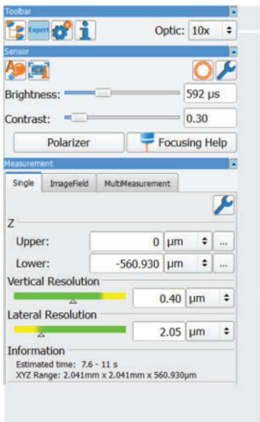
With the curved surfaces and complicated geometry of the part it was quite difficult to get good reflections to make dense measurements with high lateral resolution (Lr) without getting holes in the image where no values were recorded. With the 10x lens, a Lr of 2 µm was used and a vertical resolution (Vr) of 0.4 µm. This is unsatisfactory for surfaces with Ra-values below 0.3µm and where the width of grinding marks could be in the order of 2 µm.

There are some guidelines from the manufacturer that are useful to follow. If we put in the actual product limits from Table 3 we can see what is required of the measurement equipment. For a random structure the Vr should be around Rz/(15 to 30). With the limit and the typical value from the stylus measurements we get a Vr requirement of 83-167 nm for the limit and 39-79 nm for the typical values. So the lens needed for these values is the 20x one or possibly the 10x. For an Rz of 0.6µm a longer measuring length is recommended. There are some conflicting values stated but the best possible values for the lenses is shown in Table 4.

Table 4 Overview of lenses and their limits

		5x	10x	20x	50x	100x
Best Lr	µm	3.52	1.76	0.88	0.64	0.44
Best Vr	nm	410	100	50	20	10

For a fine surface with Ra between 0.1 and 2 µm the ISO standard recommends an Lc of 0.8 mm which leads to a measuring length of 4 mm. With the 20x lens this means at least a 5x5 frame measurement with max Vr and a step of 1µm. This would give long measuring times and create very large files, at least 64MB, which would make the system very sluggish. In our measurements a cut off Lc of 0.25 mm was used with a square side of 1.8 mm.
Figure 12 shows an example of the setup and some of the Rvalues available in the Alicona IFSL instrument. As we can see these values are considerably higher than the ones recorded from the stylus measurements in Table 3.



Name	Value (µm)
Ra	0.814
Rq	1.028
Rt	6.212
Rz	5.325
Rmax	5.911
Rp	3.104
Rv	3.107
Rc	3.175
Rsm	33.83
Rsk	0.129
Rku	3.036
Rdq	0.312
Rt/Rz	1.167
Meas.length	1.799 mm
Lc	250µm

Figure 12   Setup with the Alicona IFSL. Measurement of SGP variant.

The vertical resolution is 0.4 µm and the lateral resolution is 2 µm close to what is needed for a reasonable roughness evaluation. In addition to the R values we get and can compare the S area measurements with the Alicona IFSL.

In the next section we compare the grinded surface with the polished one with respect to appearance, S- and R values and compare the stylus measurements with the optical ones.

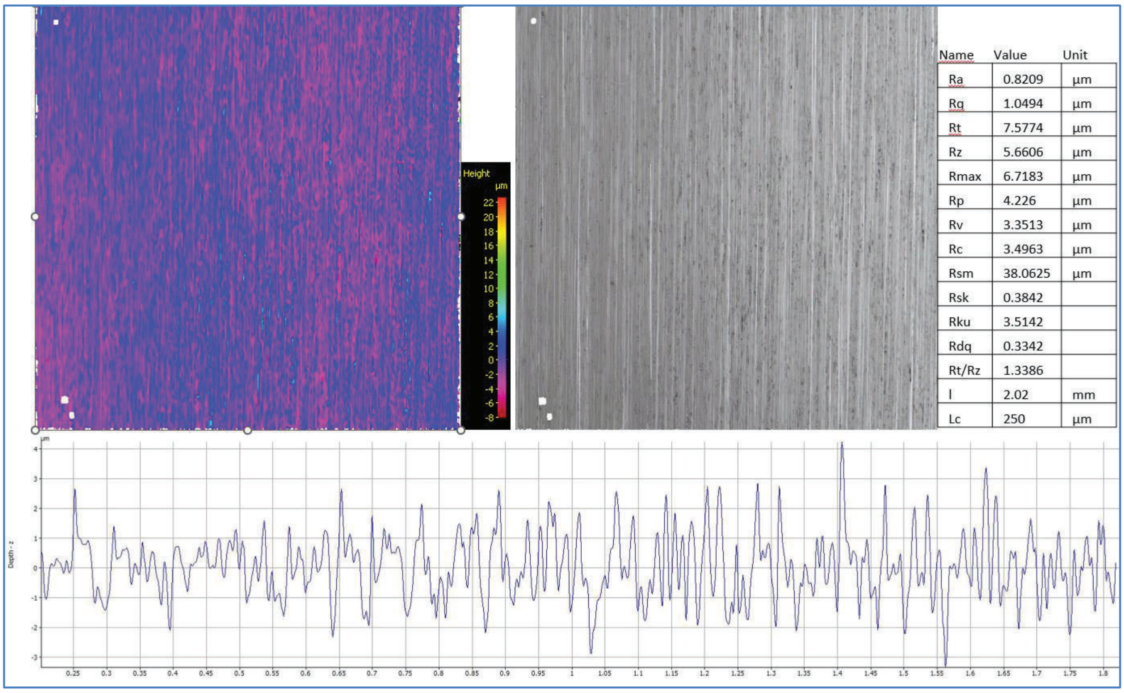


Figure 13 Alicona IFSL greyscale image and colorcoded topography map, roughness profile and Rvalues

Figure 13shows the Alicona measurement of the polished SG case. The greyscale image at this magnification still shows a lot of scratches. The color coded height image does not yield very much more information. With a more elaborate height scale setting the scratches disappear and only separate pits remain. The R values here are quite high and clearly above the limits.

A comparison between R values from the Mahr production lab equipment, the small Mitutoyo at the Swerim lab and Alicona measurements at 10x magnification (on profiles) is shown in Table 5. The differences are big between the measurements and the Alicona even suggests that the roughness is greater for the polished SGP variant than the purely grinded SGS. Clearly the Alicona measurements are not reliable for this type of surface at all. The measurements were repeated with 20x magnification which just confirmed these results. The instrument is best for shape and wear measurements but less reliable for roughness, especially for fine surfaces with a complex shape. Also for really fine surfaces not much additional information can be gained from a color coded height map than from a standard photo.

Table 5 The SG wheel component R values after grinding (S) and polishing (P)

	SGS			SGP		
	production	Lab	Alicona	production	Lab	Alicona
Ra	0.289	0.428	0.929	0.162	0.330	0.958
Rz	2.063	2.443	5.735	1.162	1.417	6.655
Rp	0.994	1.406	2.989	0.412	0.790	3.670
R Mr(-1.0,5)	88.69	79.08	20.40	98.84	98.47	15.25
Rpk	0.309	0.350	1.188	0.127	0.142	1.570
Rv	-	1.038			0.627	

No Alicona studies were made for the 3M wheels but comparisons between the two stylus instruments again showed much greater values for the Mitutoyo instrument. These measurements were repeated with 3 different stylii all giving results in the same range. This can only be explained by a difference in the filtering process, probably the Lc value.
As for the trends in the surface roughness as shown by the R values they are clear. The polishing step on the grinding worm reduces Ra, Rz, Rp and Rpk between 40 and 60%, most for the Rpk value which is logical in view of the peaks being removed by the polishing.

Table 6 The 3M wheel component R values after grinding (S) and polishing (P)

	3MS	3MS	3MS	3MP	3MP
	production	Lab	Lab 0.025	production	Lab
Ra	0.182	0.438	0.190	0.113	0.398
Rz	1.180	2.622	1.689	0.548	2.104
Rp	0.572	1.475	0.720	0.273	1.238
R Mr(-1.0,5)	99.62	76.33	98.84	100.00	87.01
Rpk	0.223	0.403	0.217	0.064	0.314
Rv	-	1.147			0.867

The efficiency of the polishing step can also be seen in the bearing curves.

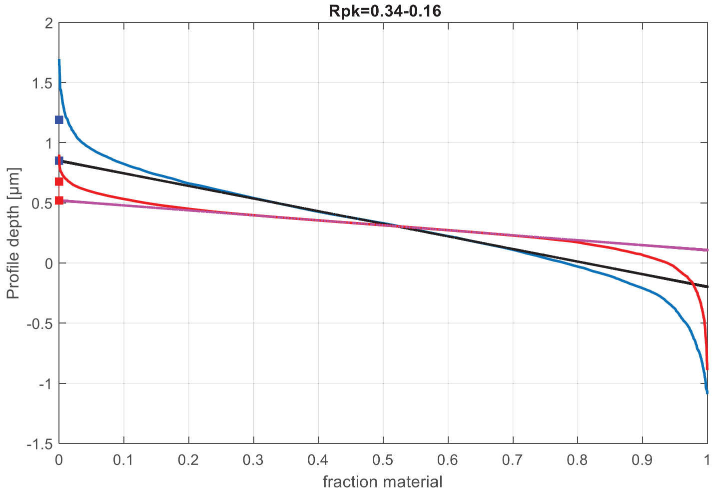


Figure 14 Abbot curve for Rpk evaluation for a grinded and for a grinded & polished surface

In Figure 14 the blue line is the grinded SG component. The curve is tilted down and the Rpk value is much reduced for the polished component, red line.
The surfaces of the SGS and SGP samples were examined in SEM, Figure 15. By the naked eye the polished samples are more shiny but still with some scratchmarks. Clearly the finishing step has not been able to remove all traces of the prior grinding step.

This is clearly shown in the SEM images. There are only very small differences in the surfaces and it requires a magnification of around 2000 to 5000 to detect them.
The scratchmarks are a little bit more clearly defined for the ground surface, bottom row, and the ground surface show more areas of smeared material at the edges of the scratches, which are removed in the polished surface. The process is not fully optimized at this point.

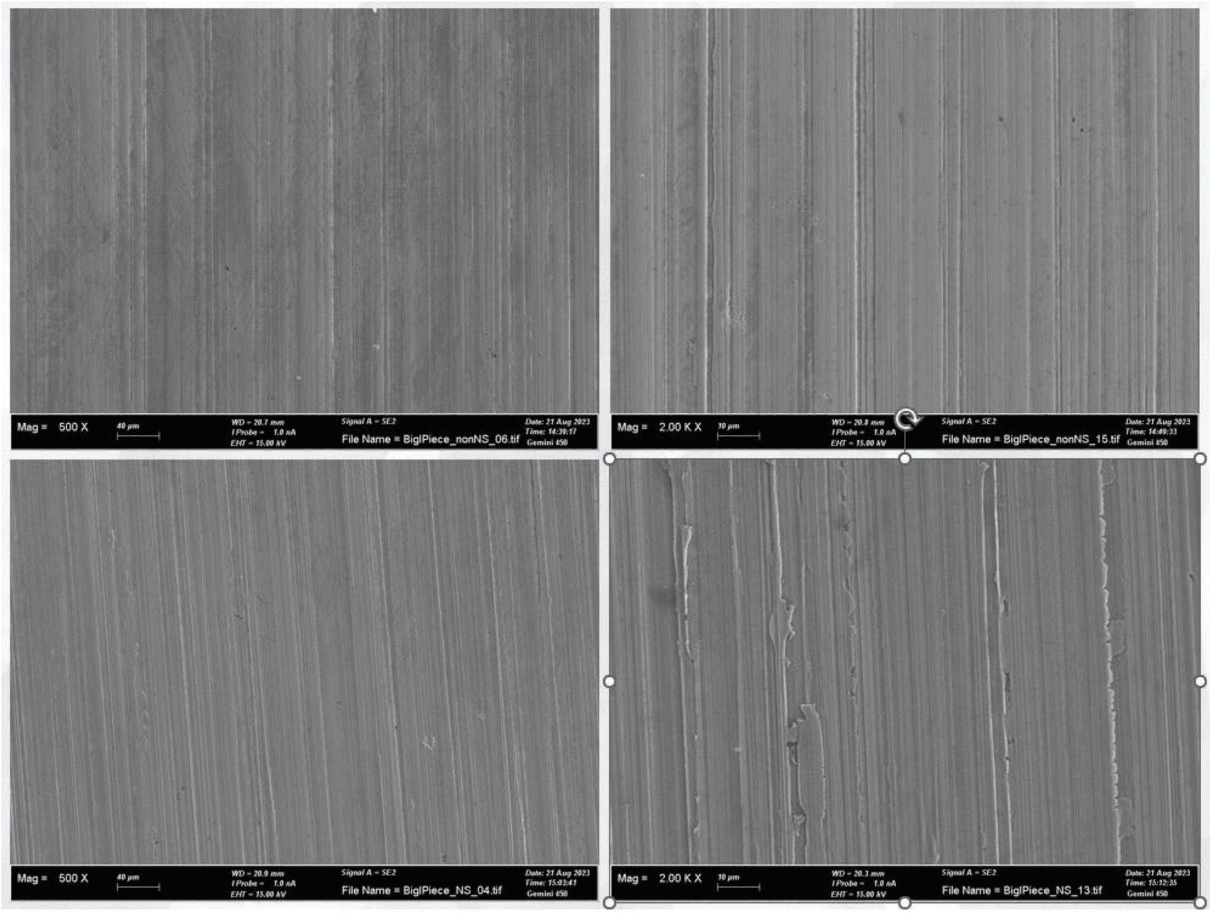


Figure 15 SEM images of polished sample, top row, and grinded sample bottom row. Worm SG.

It seems the profile measuring stylus instruments are competitive in giving valid information about topography compared both to more advanced optical instruments and SEM studies.

Case 1b - Generating grinding plus polishing – outside cog ring wheel

In the abovementioned example the setup work was not finished at the time of the project end and the finishing and polishing was not optimized. In a parallel second trial, hybrid grinding worm wheels delivered by Hermes were tested on the same product. The roughing part had a grit size of 120 with vitrified bond and the polishing stage a grit size of 800 with a resin bonding agent. The aim here was to reach Ra<0.2µm and a profile form deviation $ff\alpha$<10 µm.

The usual setup required two strokes for the roughing part, one finishing stroke and 2 polishing steps.
By varying dressing data and speed and feed levels at roughing and finishing, after several tests the required quality parameters were achieved while reducing the cutting time.

In the first solution using a two stroke roughing step and one finishing and one polishing stroke setup, Ra values were as low as 0.075 and 0.088 µm for the left and right flank respectively with $ff\alpha$ of 2 and 3µm.
In the second solution productivity was prioritized by doing the roughing step in one stroke and increasing the material removal ae in the finishing step. The Ra values was increased slightly to 0.13 and 0.18 but still better than the set quality level.

Finishing continuous grinding can thus give really good results but require a lot of setup and expertise to reach its full potential. Further work will be made to improve these results even further.

Case 2 Cogwheel Scania

In this case there are samples of the component removed at three different stages of the manufacturing. They will be labeled G, SP and P which stands for
G: Generating grinding,
SP: G+ shot peening and
P: SP+ polished with grinding worm.
The shot peening is not intended to lower the roughness but is used to improve the residual stresses in the surface area. No overall images can be shown of these components for confidentiality reasons.

The surface is quite rough after generating grinding G, Figure 16.

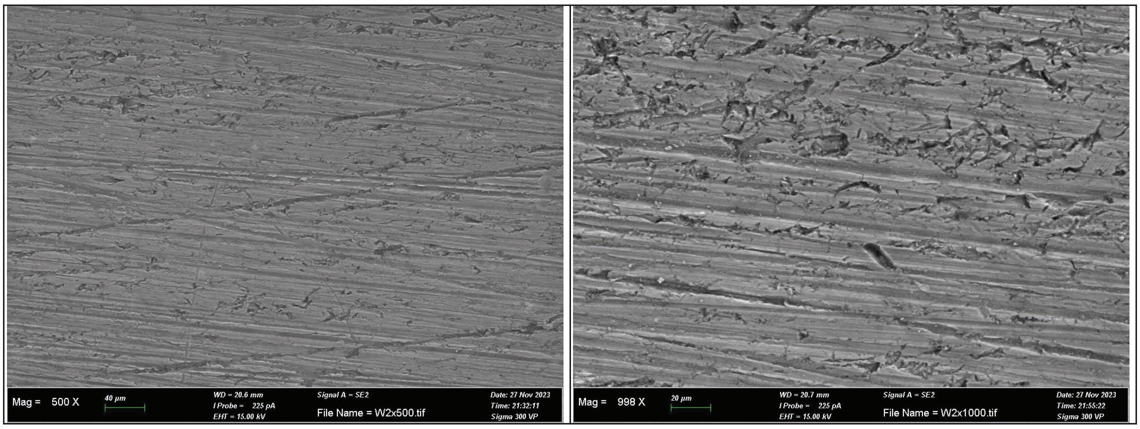


Figure 16 SEM images of sample G, 500x and 1000x, after generating grinding.

The Alicona measurements made on these samples showed the difficulties inherent in measuring shiny surfaces with complex shapes and large inclinations with this technique. Neither the imagery nor the surface values seemed reliable. Comparisons with SEM images such as in Figure 16 failed to show the same complex pattern of scratches and other features. The S value determination from the Alicona measurement varied a lot from measurement to measurement and with magnification and size of measured area on the tested cogwheel.

All three variants were measured with Swerims' stylus instrument, Mitutoyo SJ-400. An average of these measurements is shown for some relevant parameters in Table 7.

Table 7 Evolution of roughness parameters at different production steps.

parameter	G	SP	P
Ra	0.709	0.904	0.718
Rz	3.141	4.786	2.425
Rp	2.103	3.122	1.868
Rv	1.038	1.664	0.557
R Mr (-1,5)	61.4	28.4	65.8
Rpk	0.521	0.920	0.331
Rsk	1.350	1.370	1.336
Rku	2.217	2.830	1.997

The shot peening SP increases all R values substantially from the grinding step. The polishing step then lowers all values again but they do not reach the low values that could be expected, compare case 1b above. The Rvalues show different sensibility to the changes in the surface. The skewness is almost constant for the three operations with values above zero (indicating a large proportion of high peaks in the roughness profile). The RMr value is sensitive to the change in surface roughness and is halved. Rpk and Rku also show great changes.

The polishing step here was not optimized and the prior steps may also create surface features that are hard to remove by polishing. The test geometry is very new in production and the test pieces are taken from the set up process and has not undergone an optimized and complete polishing. There is thus room for improvement of the roughness and it is a good case to see which R values to use to specify the desired surface. The differences become clear for a closer look at the Abbot curves. Whereas repeated measurements of the shot peened and the grinded surfaces show curves that are nearly identical, the polished gear shows a lot of differences between different positions P5, P2 and P3 on the teeth, Figure 17.

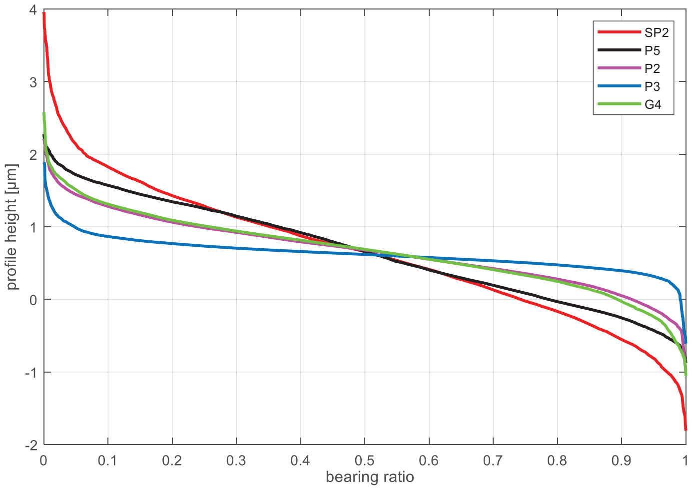


Figure 17   Abbot curves for all three variants with 3 polished cases that show big differences.

The green G4 line shows the state after grinding. After shot peening (orange line) the curve is tilted up. The polishing step tilts it back down but the results vary from only small improvements (black line) to good results (blue line).

A look at the profiles themselves shows clear differences, Figure 18. If we look at the roughness values for measurement P5, P2 and P3 the greatest differences (best indicators of differences in the surface) is shown for Rz, Rv, Rk, Mr1 and RMr(-1,5).

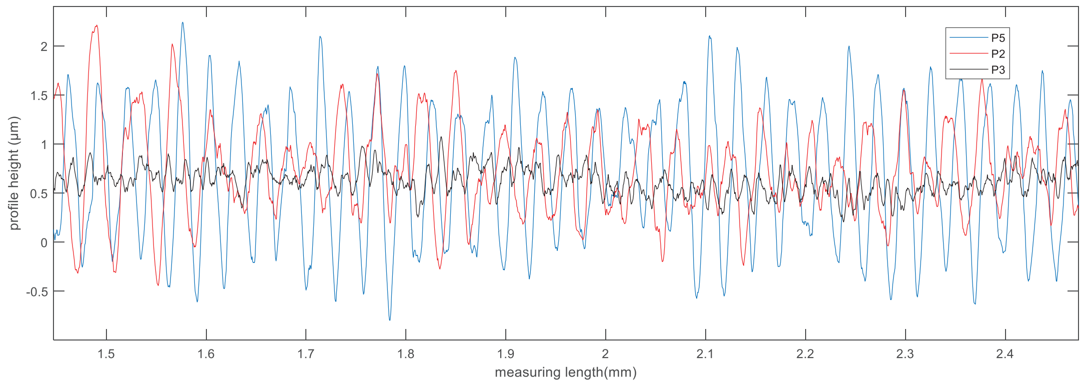


Figure 18 The tree polished measurements from Figure 17

The differences on the polished gear teeth are so big that almost all normally used R parameters are effective. It is important to measure at least 3 positions on three teeth to pick up such differences, maybe more so for a polishing step.

Case 3 Hard skived internal cog ring wheel (Leax)

Skiving is often used for hard to reach geometries such as in this case where internal cogs are made on a ring wheel. This component was first soft skived to generate the basic shape of the gear teeth. After heat treating and possibly straightening it is put through the final operation which for this component is hard skiving. The hard skiving tool is made of massive sintered carbide. Only a very small amount of material is removed in the final step where the component surface is formed mainly by the flanks of the tool in a quite complicated contact situation as opposed to the soft skiving process where the big loads and material removal take place at the tool nose. No correction step is made on the surfaces after the hard skiving.
A comparison in SEM between the surfaces after soft skiving and hard skiving, Figure 19 shows that the surface is much "cleaner" for the hard skived piece which does not exhibit the small tears and smeared areas that can be seen in the soft piece. There is a clear lay in the surface with scratches and feed marks from the skiving tool in the direction of cutting, axially from the inside of the wheel to the outside. This is an example when not only the topography but also the surface integrity is changed by the final step.

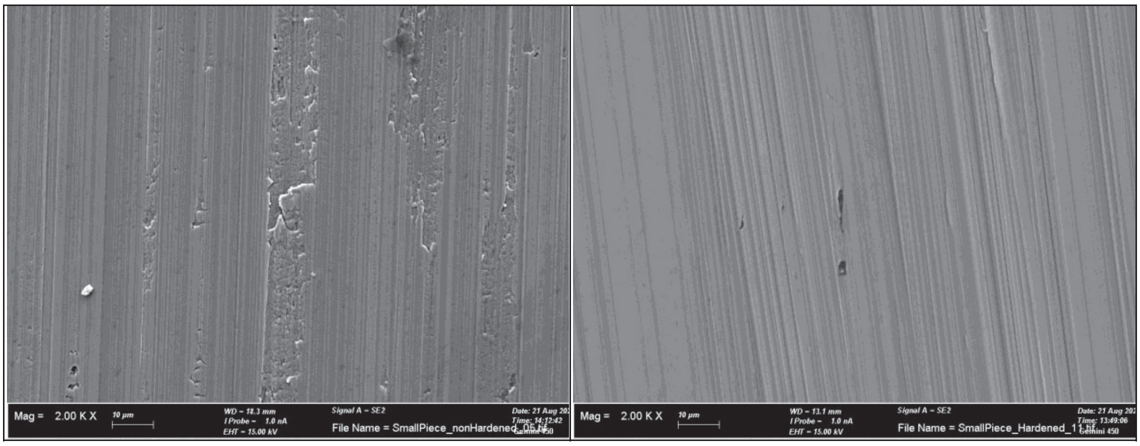


Figure 19 Soft skived tooth flank (left) and hard skived one (right).

A stylus was used to record the roughness after soft and hard skiving. The profiles are shown in Figure 20.

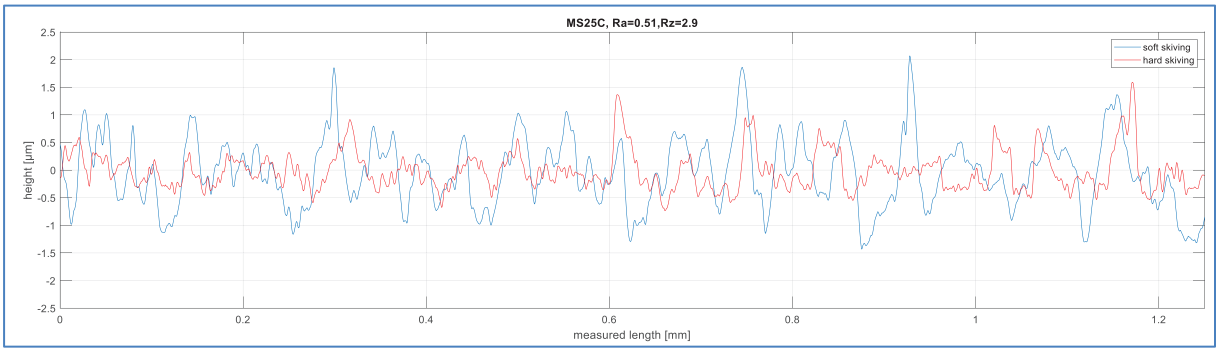


Figure 20 Surface stylus profiles for the component after soft and hard skiving.

The hard skived surface contains much fewer high peaks. A number of parameters are used to control this surface, the least common one being the material percentage at 1.0 μm below the surface, R Mr (-1,5). The R-values are almost halved after hard skiving and the RMr(-1.5) value goes from 48 to 91%, Table 8.

Table 8 R values evaluated from four profiles of each hard and soft skiving.

state	Ra	Rz	Rp	Rv	R Mr (-1.0,5)	Rpk
soft	0.49	2.69	1.41	1.28	47.69	0.62
hard	0.26	1.57	0.92	0.65	90.67	0.45

The differences in the bearing curve between soft and hard skiving is shown in Figure 21. The number of big peaks and valleys is lowered and the curve inclination is much reduced after hard skiving in a similar way to the polishing step in grinding.

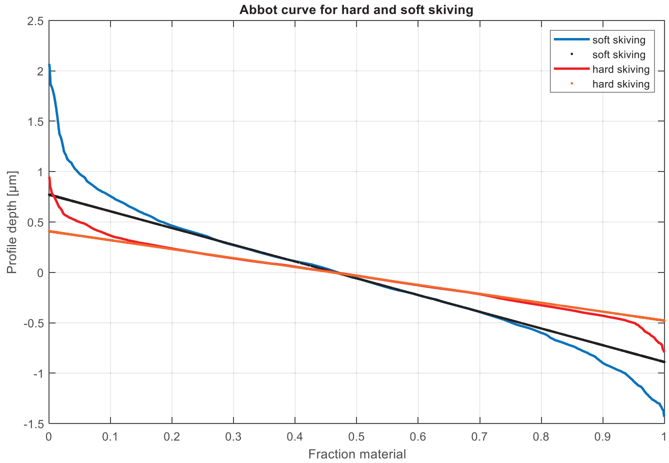


Figure 21 Comparison of Abbot curve for hard and soft skiving.

6 Discussion

The subject of surface roughness and surface integrity in gear manufacturing is very big and there are a lot of factors influencing the final result of the gear manufacturing process, Figure 5. The switch to electrified vehicles will influence the demands on the gear surfaces with higher loads, faster rotational speeds and more load cycles in the normal expected life span of the transmission and also require the additional demand of lower emitted sound. There seems to be unity in the belief that finer surfaces will be needed to increase resistance to surface induced fatigue cracks which will most probably be one of the critical mechanisms in limiting the gear life.

The aim of this project was to investigate how surfaces are specified with regard to surface roughness today and what should be reasonable levels of relevant R parameters for future electrified drive lines tomorrow. This work has only touched on the answers to questions regarding the proper demands to set on future gears. Big efforts with a lot of difficult and time consuming testing is required to properly analyse the long term effects on gear life and performance of different surface roughness levels in combination with textures and residual stresses. This project has at least highlighted the difficulties and lack of information.

7 Dissemination and Publications

How will the project result be used and disseminated?	Mark with X	Comment
Increase our knowledge in the area	x	
Be transferred to other technical research projects	x	Will be used for future work in the area of surfaces and gear performance
Be transferred to other product development projects.	x	Is currently incorporated in surface improvement work at companies

8 Conclusions and Future Work

This study has been focused on the increased requirements on surface roughness of gears, with the increased performance demands brought on by the current electrification of vehicles. There is an increased awareness in industry of the need to make finer surfaces and also that surface roughness must be put in context with other important factors such as surface texture, lubrication properties, residual stresses and sound generation from gear meashing errors, waviness and building errors.

It is certainly possible to reach very low surface roughness values using different modern finishing techniques but it requires time and money. What is interesting to know is where the good enough point is, when further polishing is unnecessary or even detrimental. Future work should be aimed at trying to find this point, not only for roughness but also for different geometrical errors of the gear tooth. Knowing where this level is for reducing noise, improving efficiency and extending gear life would lead to big cost savings by removing unnescessarily high tolerances and surface roughness demands on the products.

There is in principal no sensational new developments in the gear production but there is an ongoing improvement of the existing processes and our demonstrators showed the need for optimizing every step in the production chain.

As for measuring surface roughness, the stylus instruments dominate the production control lines and the traditional amplitude R values are most common but few rely only on Ra anymore. A trend is to specify roughness parameter requirements for a certain limited range of wavelengths. Also the bearing curve related parameter Rpk, Rk and RMr are being widely used. For noise reduction, control of the longer wavelengths is vital.

Three dimensional measurements are becoming more common but mostly in research situations and in the setup stage of a new product.

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