THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Characterisation of Functional Pressing Die Surfaces

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Abstract

The manufacture of dies and moulds is a critical aspect of many production systems since the manufacturing and try-out of new dies and moulds often is essential in determining the lead-time and quality of a new production system. In the automotive industry, many new car models are introduced each year and for each of these models, a new set of pressing dies has to be designed and manufactured. The manufacturing of pressing dies consists of several different process steps of which machining and manual polishing contribute largely to the time and cost. To be able to improve the manufacturing processes rationally, for example by optimising the machining to reduce or eliminate the subsequent manual work, an appropriate specification of the required surface quality, using a relevant parametric description of the surface, is needed.

In pressing dies, the effects of manufacturing processes on functional performance are not fully understood. One of the reasons for this is the lack of effective methods for characterisation. In the work described in this thesis, research is conducted to evaluate and establish such methods.

It was found that surface roughness measurement of dies, with the purpose of manufacturing process development, requires 3D data. Replication often needs to be used in these cases since dies usually are too large to bring into a lab measurement equipment. The replication techniques tested in this thesis work adequately. For quality control in production 2D measurements from a handheld instrument are good enough if an appropriate measuring strategy is used and limits for the evaluated parameters are defined.

Using a multi-scale approach when analysing roughness data it may be possible to find so called functional bandwidths. With the analysis focused on the functional bandwidth the characterisation is more effective and it is easier to identify roughness parameters which correlate to the functional property or the process parameter of interest. Such a method for functional filtering of roughness data is developed and presented in the thesis.

Surface texture anisotropy has been found to be important for the function of a die surface. It has also been observed that texture anisotropy can vary depending on the scale of observation. The method developed in this work to analyse and visualise texture anisotropy as a function of scale can be a helpful tool when evaluating die surfaces, especially when analysing surfaces produced with different manufacturing methods to make sure that the manufactured surface has the required texture properties in the relevant scales.

Keywords: *pressing die, surface topography, characterisation, functional surface, functional filtration, functional correlation, finish milling, polishing, multi-scale analysis, texture anisotropy*

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Appended papers

The results presented in this thesis are based on the work in the following appended papers:

Paper 1: J. Berglund, P. Jonsson, S. Rebeggiani, B.-G. Rosén: *Measuring strategies for smooth tool steel surfaces.* Proceedings of the XII. International Colloquium on Surfaces, pp. 110-119 (2008).

Paper 2: J. Berglund, B.-G. Rosén: *Robust and Easy to Use Quality Control of Roughness on Milled Tool Steel Surfaces.* Proceedings of the 18th International Conference on Flexible Automation and Intelligent Manufacturing, pp. 284-289 (2008).

Paper 3: J. Berglund, C. Agunwamba, B. Powers, C. A. Brown, B.-G. Rosén: *On discovering relevant scales in surface roughness measurement – An evaluation of a band-pass method.* Scanning, vol. 32, pp. 244-249 (2010).

Paper 4: J. Berglund, C. A. Brown, B.-G. Rosén, N. Bay: *Milled die steel surface roughness correlation with steel sheet friction.* CIRP Annals – Manufacturing Technology, vol. 59, pp. 577-580 (2010).

Paper 5: J. Berglund, B.-G. Rosén: *A Method development for correlation of surface finish appearance of die surfaces and roughness measurement data.* Tribology Letters, vol. 36, pp. 157-164 (2009).

Paper 6: J. Berglund, D. Wiklund, B.-G. Rosén: *A Method for Visualisation of Surface Texture Anisotropy in Different Scales of Observation.* Submitted for publication in Scanning.

Additional publications

Additional publications with contributions from the author:

- J. Berglund, B.-G. Rosén: *Surface Finish and Roughness Measurement in Die and Mould Manufacturing.* Proceedings of the 2nd Swedish Production Symposium, pp. 385-391, Stockholm (2008).
- J. Berglund: *Methods for Characterisation of Pressing Die Surfaces.* Licentiate thesis, Chalmers University of Technology, Göteborg (2008).
- J. Berglund, M. Liljengren, B.-G. Rosén: *Machine Hammer Peening – A Substitute for Polishing of Pressing Die Surfaces?* Proceedings of the International 3rd Swedish Production Symposium, pp. 184-189, Göteborg, (2009).
- P. Jonsson, J. Berglund, K. Kjellsson, B.-G. Rosén: *Surface topography on trimming dies and the influence of wear.* Proceedings of IDDRG International Conference, pp. 345-354, Graz (2010).
- D. Wiklund, M. Liljengren, J. Berglund, N. Bay, K. Kjellsson, B.-G. Rosén: *Friction in Sheet Metal Forming - A Comparison Between Milled and Manually Polished Die Surfaces.* Proceedings of 4th International Conference on Tribology in Manufacturing Processes ICTMP, pp. 613-622, Nice (2010).
- J. Berglund, M. Liljengren, B.-G. Rosén: *On finishing of pressing die surfaces using machine hammer peening.* The International Journal of Advanced Manufacturing Technology, vol. 52, pp. 115-121 (2011).
- Medvedeva, J. Berglund, J. Wied, S. Gunnarsson: *Surface characteristics of different tool steels and cast iron after machine hammer peening.* Accepted for presentation at the 4th Swedish Production Symposium, held in Lund May 3-5 2011.

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1. Introduction

1.1. Background

Industrial production often involves manufacturing of separate parts that are assembled into complete products. Most mass produced parts are manufactured in processes using dies and moulds such as plastic injection moulding, casting, forging or stamping. Therefore, the manufacture and functional performance of dies and moulds are important links in many production chains. Manufacture and try-out of new dies and moulds is often essential in determining the lead-time and quality of a new production system [1]. Pressing dies often constitute a small investment compared to the total value of a production system. Still, they are crucial in determining lead times, costs and quality of manufactured parts [1].

In the automotive industry, many new car models are introduced every year. For each of these models, a new set of pressing dies has to be designed and manufactured. The manufacturing of pressing dies consists of several different stages of which machining and manual polishing contribute largely to the time and cost. Up to 65% of the total manufacturing time can be spent in machining and doing manual post-machining work, for example polishing [2].

The resulting surface roughness after the finish milling stage is greatly influential for the amount of manual work that is subsequently needed [3]. Employing a good strategy when finish milling makes it possible to improve the surface roughness and thereby significantly reduce, or even completely eliminate, the amount of time needed for manual work [2]. Consequently, the surface roughness after finish milling is important in manufacturing of pressing dies. The technique commonly used on the die shop floor to evaluate surface finish after milling is visual and tactile inspection by an experienced machine operator [3]. At present however, there are no general standards with quantifiable measures of what a good surface quality is in manufacturing of pressing dies. The judgements are made on the basis of experience [4].

To be able to improve the manufacturing processes rationally, for example by optimising the machining to reduce or eliminate the needed manual work, an appropriate specification of the required surface quality is needed. An understanding of the surface function is required to define such specifications, otherwise the specifications will not be meaningful [5].

The surface engineering control loop was presented by Stout and Davis in 1984 [6], see Figure 1. It illustrates a surface engineering process where the manufacture of a surface is linked to the functional performance through characterisation by some relevant parameters. The loop is closed by the link back to manufacturing. The manufacturing process can then be adjusted to obtain a different functional performance. If the effects of manufacturing process on the functional performance of a surface are completely understood, the characterisation step would not be necessary. One would be able to directly know how to change the manufacturing process to get a surface with a specific functional performance.

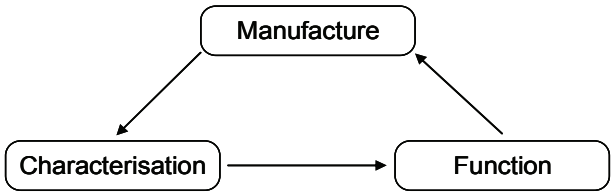


Figure 1:The surface engineering control loop, adapted from Stout and Davis [6].

For pressing dies however, the effects of manufacturing processes on functional performance are not fully understood. The reasons for this are the complex nature of both the manufacturing processes and the functional performance in combination with the lack of effective methods for characterisation.

The general objective of characterisation is to measure and analyse the surface topography to get an understanding of how the topography has been influenced by previous events, for example manufacture or wear and how the surface topography influences its function [7].

There are several methods available for characterisation of surfaces using roughness measurements. Topographical data in a surface measurement contains information on a wide range of scales, from the smallest features detectable by the instrument used to larger features which are limited by the measurement area. A major difficulty, in general, when characterising surfaces is the lack of information on the scale of surface topography responsible for different functions or effects [8, 9].

1.2. Research objectives

The research presented in this thesis is part of a more comprehensive effort towards dealing with some of the issues presented in section 1.1 above. The long term aim is to improve and streamline the process of manufacturing dies and moulds which will hopefully result in shorter lead times and higher quality. The development of effective methods for characterisation of pressing die surfaces would enable such process improvements.

The objective of this thesis is to develop methods for characterisation of functional pressing die surfaces to enable future manufacturing process development. The methods for characterisation should be used to relate functional performance of die surfaces to their respective surface topographies as well as to relate the surface topographies to the processes used to manufacture the die surfaces.

A successful method for characterisation would consist of several steps. First surface roughness data needs to be acquired. Then the data is to be manipulated to separate the relevant data from the irrelevant data. Finally the data has to be evaluated and results presented in a meaningful way. These general process steps of surface roughness characterisation are described in more detail in chapter 3.

Specifically, the objective is to give answers to the research questions (RQs) presented below.

RQ1: *How can pressing die surface roughness be measured in a suitable way in the context of:*
  a. *manufacturing process development?*
  b. *quality control in production?*

RQ2: *What approach is suitable for data manipulation and finding parameters with high relevance?*

RQ3: *How should the surface roughness data be evaluated and results presented in a relevant way?*

1.3. Delimitations

The scope of this thesis is limited to surfaces of pressing dies for stamping of body parts in the automotive industry, more precisely, dies for cold forming of steel sheet. The scope is also limited to surface characterisation. Manufacturing processes and functional performance are treated as background information and are not in the scope of the research in this thesis.

1.4. Outline of the thesis

Chapter 1 is an introduction to the thesis. The background is described and the research objectives as well as the delimitations are stated.

Chapter 2 describes both the process of manufacturing pressing dies, with some parts of the process described in more detail, and the function of pressing dies with focus on the pressing die surface.

Chapter 3 explains the concept of surface roughness and give details on roughness measurement and characterisation techniques.

Chapter 4 contains a description of the research approach and summaries of the results found in the appended papers. The summaries are made in reference to the research questions stated chapter 1.2. Following each summary there is a discussion where the results are discussed in terms of generality and limitations of the specific studies.

Chapter 5 contains the synthesis and discussion of the results in relation to the research questions as well as a description of future research aims.

Chapter 6 gives the conclusions.

Chapter 7 is a list of references used in the thesis.

1.5. Author's contribution to the appended papers

Paper 1: J. Berglund, P. Jonsson, S. Rebeggiani, B.-G. Rosén: *Measuring strategies for smooth tool steel surfaces.* Berglund planned, performed and evaluated the experiments regarding milled tool steel for pressing dies, took part in writing the paper and presented the paper.

Paper 2: J. Berglund, B.-G. Rosén: *Robust and Easy to Use Quality Control of Roughness on Milled Tool Steel Surfaces.* Berglund initiated the study, planned, performed and evaluated the experiments, wrote and presented the paper.

Paper 3: J. Berglund, C. Agunwamba, B. Powers, C. A. Brown, B.-G. Rosén: *On discovering relevant scales in surface roughness measurement – An evaluation of a band-pass method.* Berglund took part in the friction experiments, made and evaluated the surface roughness measurements and took part in writing the paper.

Paper 4: J. Berglund, C. A. Brown, B.-G. Rosén, N. Bay: *Milled die steel surface roughness correlation with steel sheet friction.* Berglund took part in the friction experiments, made and evaluated the surface roughness measurements, made the analysis and took part in writing the paper.

Paper 5: J. Berglund, B.-G. Rosén: *A Method development for correlation of surface finish appearance of die surfaces and roughness measurement data.* Berglund initiated the study, planned, performed and evaluated the experiments and wrote the paper.

Paper 6: J. Berglund, D. Wiklund, B.-G. Rosén: *A Method for Visualisation of Surface Texture Anisotropy in Different Scales of Observation.* Berglund initiated the study, planned, performed and evaluated the experiments and wrote the paper.

2. Pressing dies

Pressing dies include tools for blanking, forming, trimming and flanging. Parts with complicated shapes, different radii and cavities often have to be manufactured to close tolerances when producing car body components in the automotive industry. To accomplish this, the sheet material has to be pressed in several press tools where a small change in the shape is made each time. A chain process with several steps can often be needed to reach the final component geometry [10].

The focus of this thesis is on pressing dies for forming of steel sheet. Therefore the descriptions below regarding manufacture and function of dies are limited to this scope.

2.1. Die manufacturing process

Forming dies are usually made in two different ways depending on the load they are expected to be subjected to during use. They can be made from a casting, usually made of nodular cast iron and cast to near net shape, or they can be made of tool steel inserts screwed to a matrix of cast iron [1]. The two different types of dies require two slightly different processes for manufacture. The difference is mostly in when and how the hardening is done. The type with steel inserts also requires some added work regarding mounting and dismounting of the inserts [10].

After designing, process planning and so on, the die machining processes starts with a non-hardened die blank and can be divided into the steps roughing, semi-finishing and finishing [10-12], see Figure 2.

- Roughing. The workpiece material is removed as fast as possible. A semi-finishing allowance is left for the subsequent milling stage. The focus is not on workpiece geometrical accuracy or surface roughness but on material removal.
- Semi-finishing. The surface profile, often containing large steps from the roughing step, is reduced and a finishing allowance of uniform thickness is left. Rest milling (removal of residual stock) is included in the semi-finishing step. It is an important operation where excessive material in some parts of the machined geometry, especially in inner radii and corners left by the larger cutting tools used in the roughing operations, is removed. The aim of the semi-finishing is to minimise cutter deflection and tool wear during the finishing stage.
- Finishing. The final shape of the part is produced. In this stage, focus is on the resulting surface roughness and geometrical accuracy. The finish milling stage often requires the largest amount of machining time. The finishing process is described further in chapter 2.1.1.

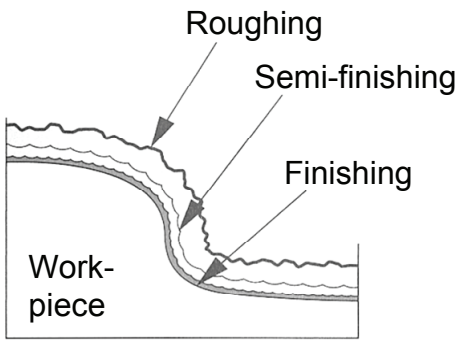


Figure 2: Machining steps [12].

For several reasons, it is desired to do all the machining in one single set up. Therefore, deep cavities and other hard to reach sections are machined as much as possible by milling with long and slender cutting tools. However, in some cases, an extra process step using Electrical Discharge Machining (EDM) may be required to remove material from parts of the die cavities which cannot be reached with a cutting tool. These are typically sections of deep cavities or where small internal radii are required. This is mostly common with die casting dies and also with geometrically complex plastic injection moulds [1, 10].

After machining, grinding and polishing is often performed to achieve the required surface finish. This is generally performed manually [11, 13]. The manual post-machining work, including the try-out process, is described further in chapter 2.1.2.

2.1.1. Finish milling

Pressing die surfaces are usually finish milled using ball-nose end-mills [10, 12]. To machine the surfaces, the cutting tool follows sequential paths separated by a distance, the radial step-over or path pick. Because of the geometrical shape and the rotation of the cutting tool, path-interval scallop, also called cusp, and feed-interval scallop are generated on the machined surface. The path-interval scallop is determined by the radial step-over between the successive cutting paths and the feed-interval scallop is determined by the movement between the successive tooth feeds [12, 14].

A model commonly used to describe the resulting surface texture after milling with a ball-nose end-mill is presented, for example, in [10]. This model makes use of the process parameters feed per tooth (f_z), radial step-over (a_e) and tool diameter to calculate the resulting topography. No consideration is taken to the fact that the tool is rotating and moving simultaneously. This model is commonly used in CAM systems to calculate the process parameters above to achieve a certain maximum cusp height. It is recommended to set $f_z = a_e$ for finish milling to get a symmetrical surface [12], see Figure 3.

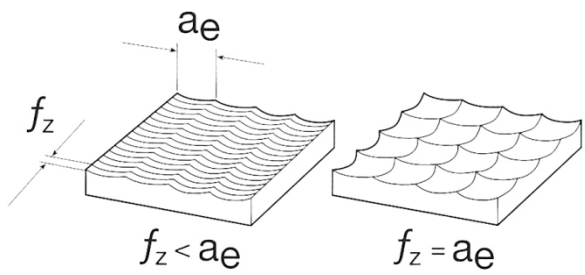


Figure 3: Theoretical surface geometry after ball-nose finish milling [10].

A more complex model, taking simultaneous tool rotation and movement and tool angle into account, is presented in [14]. It is shown that, for finishing, the feed-interval scallop height can be of much greater importance than the pick-interval scallop height when the tool angle is 0 degrees. At a tool angle of 10 degrees the difference is smaller [14].

Another factor influencing the surface texture in finish milling is radial run-out. Well-known effects of radial run-out include premature cutting edge failure as well as increased surface roughness [15]. See Figure 4 for an illustrative example.

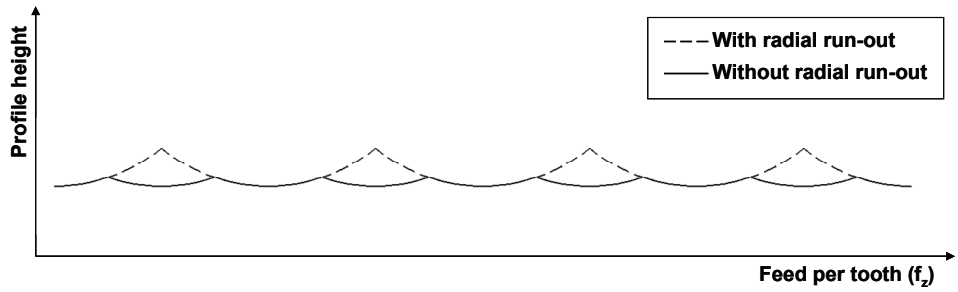


Figure 4: Surface profile after cutting with and without radial run-out. Adapted from ref. [10].

2.1.2. Manual post-machining work

After machining, grinding and polishing is often performed to achieve the required surface finish. This is generally performed manually [11, 13]. Die polishing is labour intensive and time consuming [10, 13]. For example, the normal time to manually polish a die for a large car body part can be 350 to 400 hours [10]. However, this time can often be reduced with the optimal use of finish milling operations [1, 2]. When the required surface finish is achieved a try-out process is started during which additional manual work is performed.

When the pressing die is thought to be finished the try-out process starts where the two halves must be fitted together. This is done by spotting where the surface of one of the halves is covered with ink, and then a component is test pressed in the tool. The die has to be corrected by additional grinding and polishing until the result is satisfactory [10].

If the previous manual polishing can be reduced it not only reduces the cost, but also enhances the geometrical accuracy of the tool which in turn leads to shorter try-out times [10].

2.2. Die function

In the forming process, the metal sheet is pressed and through a plastic material flow the shape of the sheet is permanently changed. The pressing die will obviously also be exposed to the high forces needed to accomplish this. However, the die has to be of such material and have surface finish so that it is only elastically deformed [7].

Higher strength sheet materials are increasingly used in automotive structures to decrease weight but still keep the same rigidity. The increased use of higher strength sheet materials leads to higher forces in forming operations and requires more wear resistant tool materials [16]. This applies to forming tools made with tool steel inserts as well as cast iron [16, 17].

2.2.1. Die surface function

The surface of a forming die is involved in the forming operation in several ways. It carries the forces of the deformation of the sheet which means it has to be though enough not to crack or plastically deform [7]. It is also in contact with sliding sheet metal under high pressure which means it has to withstand adhesive and abrasive wear [18, 19]. The die surface texture influences the material flow of the sheet metal and the lubricant pressure build up which affects quality of the produced parts as well as wear of the die [20-23].

The surface roughness of both the pressing die and the sheet metal is an important parameter influencing the frictional response in the contact. The friction affects both deformation of the sheet metal and wear of the pressing die [3]. In addition to surface roughness or texture there are several other factors influencing the tribological contact in a forming operation such as normal pressure, sliding length, sliding speed, and tool-workpiece interface temperature. It is not possible to evaluate the influence of these parameters in a real forming tool since they are

interrelated. However, simulative tests can be constructed where the parameters can be varied independently [24].

The conditions in the critical entry zone of a forming tool can be simulated in a bending under tension test rig (BUT). In this test a metal sheet strip is bent around a non-rotating tool while it is clamped in two claws. The strip is pulled with the front claw while breaking the back claw with a controlled force. This ensures sliding of the strip around the pin under controlled back tension. The different process parameters can be varied and the frictional response is measured directly as the torque on the tool [24]. An illustration of the BUT test is presented in Figure 5.

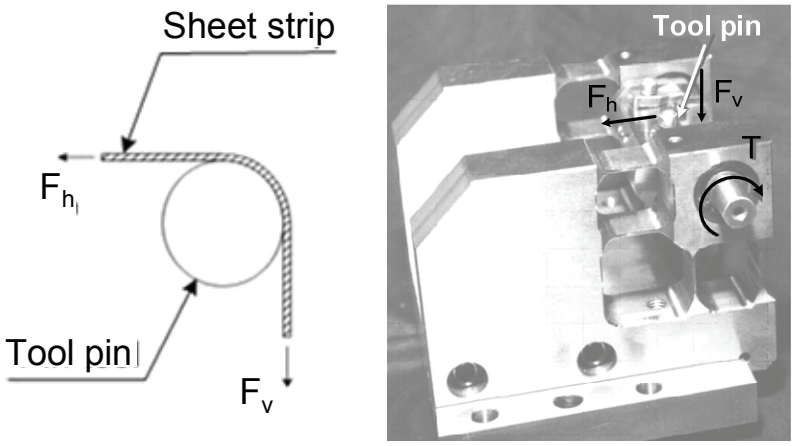


Figure 5: Bending Under Tension (BUT) test. Schematic outline of BUT test (left) and forces and torque acting on the tool-pin during testing (right). Fh = breaking force, Fv = pulling force, T = torque. Adapted from ref. [24].

2.2.2. Die wear

Typical failure mechanisms in press tools are abrasive wear, plastic deformation, chipping or cracking and adhesive wear [10], see Figure 6.

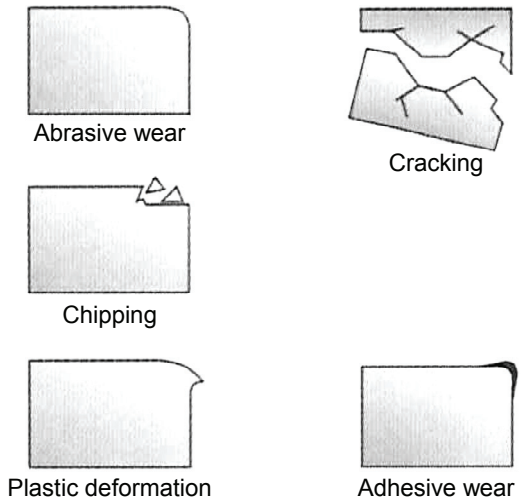


Figure 6: Typical failure mechanism in press tools [10].

The most common problems are with excessive abrasive wear and adhesive wear [10]. Since surface roughness of pressing dies decreases with use, as in a running-in process [3], some abrasive wear is expected, but wear particles can be problematic and excessive wear can change the tool geometry too much. The major cause for tool failure is transfer of sheet material to tool surfaces. This adhesive wear process is usually referred to as galling. The transferred sheet material generates unstable frictional conditions and affects the surface quality on the formed part as well as wear on the tool surfaces [18, 19].

3. Surface roughness characterisation

The general objective of characterisation is to measure and analyse the surface topography to get an understanding of how the topography has been influenced by previous events, for example manufacture or wear and how the surface topography influences its function [7]. More specifically, the objective is to create a parametric description of the surface topography to be able to relate this to the surface function or manufacturing process [6, 9].

To achieve this parametric description of the surface topography some process steps have to be completed. First the surface needs to be measured, then the data has to be manipulated to facilitate an effective evaluation, lastly the data is to be evaluated and described using relevant parameters. These different steps of the characterisation process can be performed using various techniques, many of which are described in the following chapters. First, the concept of surface roughness is presented.

3.1. Surface roughness

The geometric form of a surface is traditionally divided into the components roughness, waviness and form, see Figure 7. The differentiation of these components is done by examining their wavelengths. The points at which roughness becomes waviness and waviness becomes form are arbitrary and must be related to the manufacturing process, function or size of the object [8]. Usually, topography features created by the normal interaction between for example a tool and a workpiece belong to roughness. Features belonging to waviness are usually effects of some problem with the machine tool and are often periodic. Form errors are errors on the general geometry of an object. These can be effects of thermal deformation, weight deflection of the workpiece or tool deflection. Features with longer wavelengths than the ones belonging to waviness belong to this category [25].

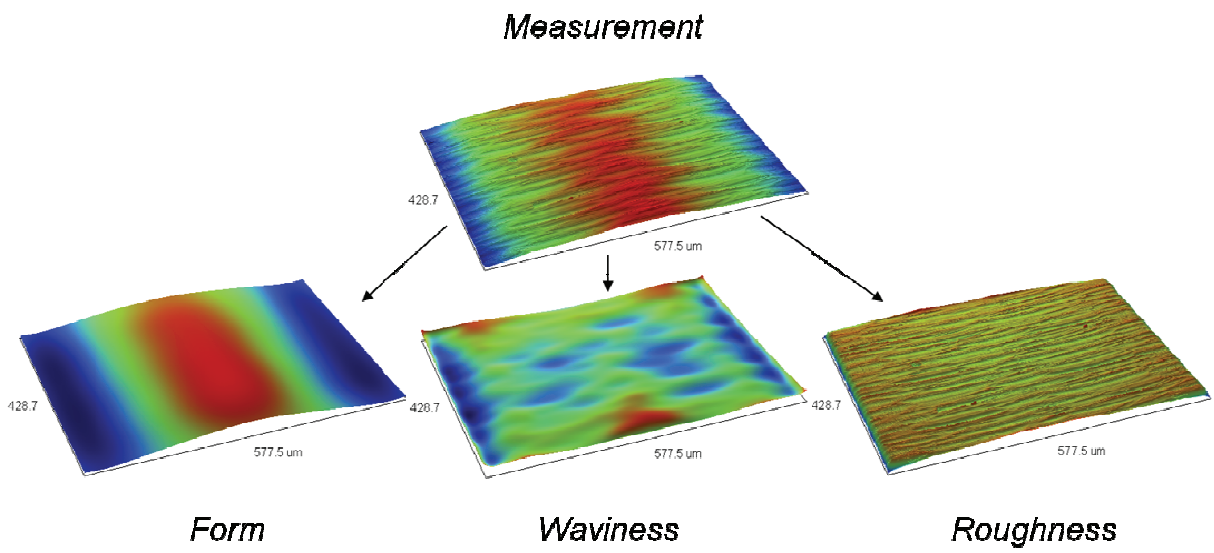


Figure 7: Geometric components of a surface measurement: roughness, waviness, and form.

Much of the natural world appears to follow what is called fractal geometry rather than Euclidian geometry. Euclidian geometry is made up of things such as straight lines, circles and planes. However, it is only over a small range of dimensions, from sub-millimetres to some metres, where man has influenced nature and created relatively flat planes and straight lines [26].

A quote that summarises this is found in the beginning of Mandelbrot's famous book 'The Fractal Geometry of Nature' [27]:

"Clouds are not spheres, mountains are not cones, coastlines are not circles, and bark is not smooth, nor does lightning travel in a straight line"

In the quote above, coastlines are given as an example and a coastline is a good example to demonstrate fractal geometry as shown in Mandelbrot's paper 'How long is the coast of Britain?' [28], the principles of which are explained below.

When measuring the length of an irregular boundary line, such as a coastline, the result will vary depending on the scale of the map. As the scale increases, the measurement is made at higher resolution and the boundary length becomes longer.

If the approximated boundary lengths, made at different resolutions, are plotted against the value of the step length (resolution) using logarithmic scales the results will be a straight line. The straight line on a log-log plot means that the amount of increase in observed boundary length is the same in every scale. This property is called self-similarity. The slope of the line is different for different boundaries. The more irregular the boundary line is the higher the slope will be. An artificial straight line would produce a horizontal line on this plot [26]. The dimension of an Euclidian line is 1 and the fractal dimension of the profile is the sum of 1 and the magnitude of the slope and is always a number between 1 and 2. The dimension of an Euclidian plane is 2 and the fractal dimension of a surface is between 2 and 3.

The linear part of such a plot is limited to some range of scales. For natural geometries this range can be large [29]. For manufactured surfaces this range is usually shorter and some times several linear ranges can be found having different slopes. These can be related to different manufacturing steps leaving different traces on the surface. Surfaces like these are called multi-fractal surfaces [8, 26].

3.2. Data acquisition

Surface roughness can be measured using many different techniques which all have their respective advantages and disadvantages. These instruments will give information on the surface texture in 2D in the form of a profile or in 3D in the form of a surface map [30, 31]. Currently, there is a shift of paradigms in the use of characterisation techniques, from profile to areal characterisation, from 2D to 3D [30, 32]. See Figure 8 for a comparison between a 2D roughness measurement and a 3D roughness measurement.

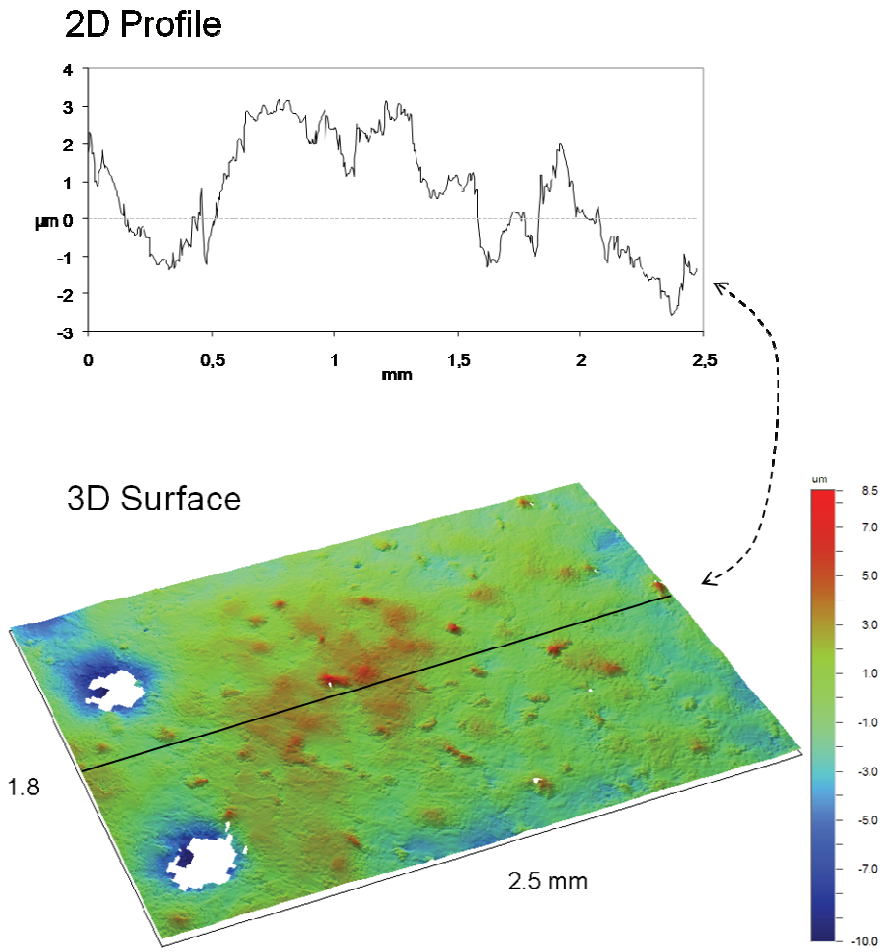


Figure 8: Example measurements, 2D profile (above) and 3D surface (below).

3.2.1. Measurement technologies

The most common types of measuring instruments can be divided into two categories, contacting and non-contacting instruments, typically stylus instruments and optical instruments respectively. In Figure 9 an overview is given of commonly used techniques for surface measurements. The different techniques are based on different physical principles to do the measurements and have different limitations. There are excellent reviews of the different technologies available in for example refs. [8, 25, 33, 34].

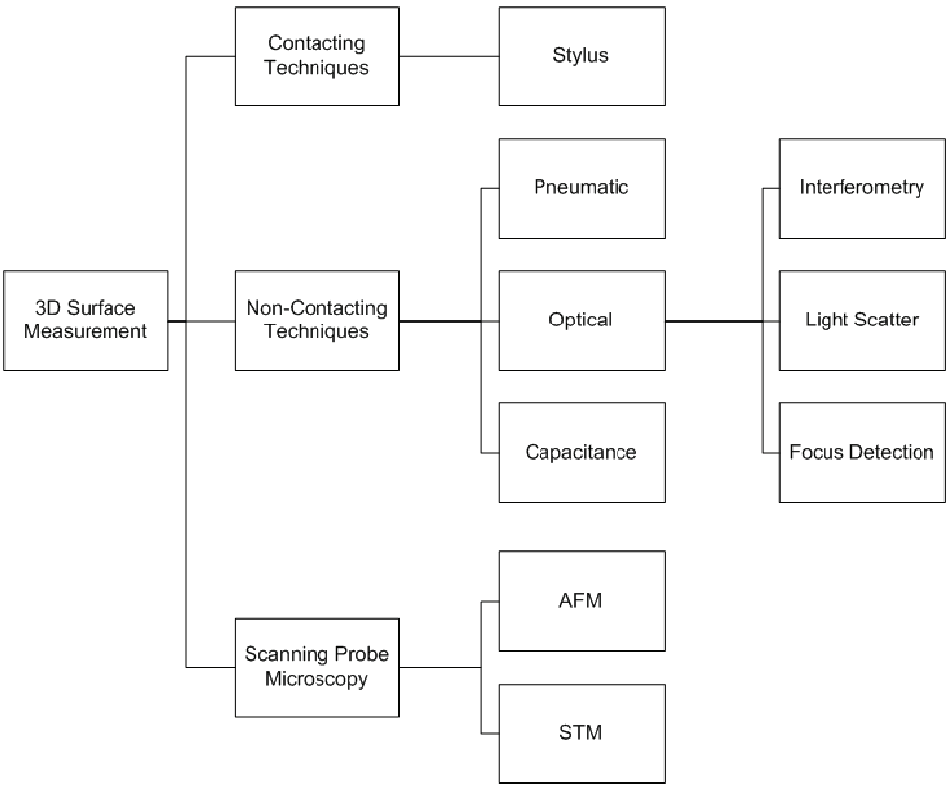


Figure 9: Overview of commonly used measurement technologies. Adapted from ref. [31].

All instruments have limitations regarding vertical and horizontal range and resolution as well as steepest slope and sharpest curvature that can be measured. The envelope in which an instrument can operate can be shown in a Stedman diagram [35]. As an example, see Figure 10 (left), for a general Stedman diagram where vertical range and resolution is on the y-axis and lateral range and resolution is on the x-axis. The Stedman diagram is a useful tool for describing and comparing different instruments' capabilities and limitations. In Figure 10 (right) several instruments' working envelopes are plotted in the same diagram.

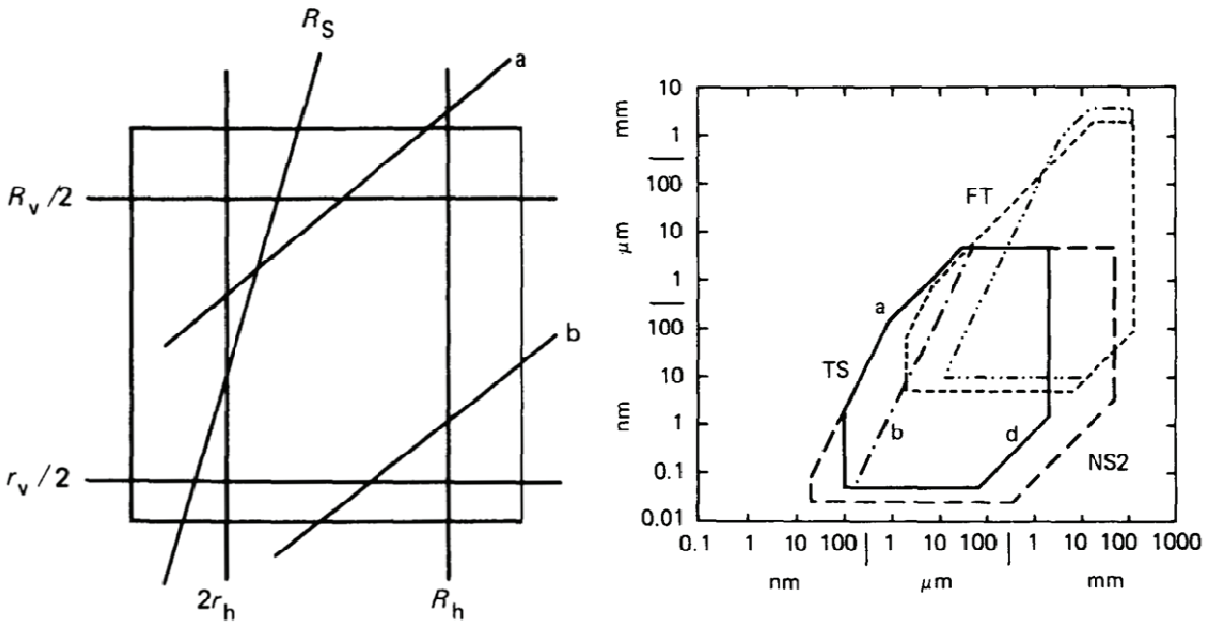


Figure 10: General Stedman diagram for stylus instrument (left), Rv = vertical range, rv = vertical resolution, Rh = lateral (horizontal) range, rh = lateral resolution, Rs = radius of stylus tip, a = stylus slope angle, b= slope limit. Several instruments' working envelopes (right) From ref. [35].

3.2.2. Replication

Replication usually implies making an imprint of the surface that is to be measured using some kind of specialised product. The replica is ideally a negative copy of the original surface, a mirror image [8]. This is useful since sometimes it is not practical to make measurements directly on original objects as they can be large and heavy, or the surface that is to measured may be hard to reach with an instrument. Most instruments for roughness measurement are also limited in terms of sample sizes and sample weights, often around a few kilograms. In these cases there is a possibility to make the measurement on a replica. Additionally, using replicas, it is possible to 'save' a surface as it was at a specific time, for example in wear processes, for future studies [36]. Studies regarding the accuracy of replicas of a number of different surfaces, including cylinder liners and cam shafts, have been conducted and are presented in for example refs. [36-38]. See Figure 11 for an example. In conclusion, the error usually is smaller than 10%, and under some circumstances only a few percent, depending on the replica material used, the surface replicated and the parameters evaluated.

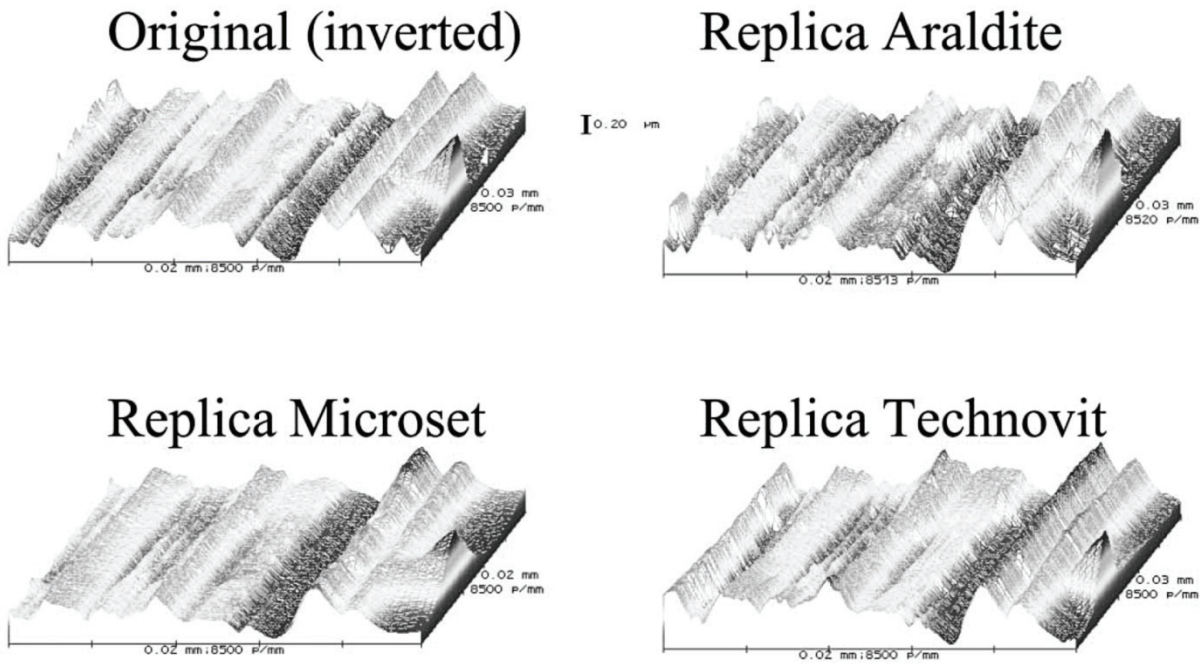


Figure 11: Relocated measurements on an original surface and three replicas. From ref. [36].

3.3. Data manipulation

Most often, the use of a measurement instrument will produce too much information compared to what is needed for a specific application. Consequently, to effectively perform a characterisation, the useful information has to be extracted. In electrical engineering, the useful information is called the signal and the irrelevant information is the noise. The process of separating the signal from the noise is called filtering [8]. In surface engineering, in analogy with the terminology used in electrical engineering, the object of filtering is to remove components of the surface topography which are not required for evaluation and to emphasise those components that are [31].

3.3.1. Filters

Traditionally, filters are used to decompose the measured geometric form of a surface into the components roughness, waviness and form. For this task, a high-pass filter has typically been used. A high-pass filter lets the shortest wavelengths (roughness) pass and removes the longer wavelengths. However, the new ISO standard (ISO 25178) prescribes a new procedure and partly a new nomenclature for this [39]. See Figure 12 for a graphical presentation. An S-filter removes the short wavelengths (measurement noise). An L-filter removes the long wavelengths (waviness). An F-operator removes the form. A filtered surface is called a 'scale limited surface' and can for example be an SF-surface (noise and form removed) or an SL-surface (noise, waviness and form removed). Some of the more popular filters are presented below.

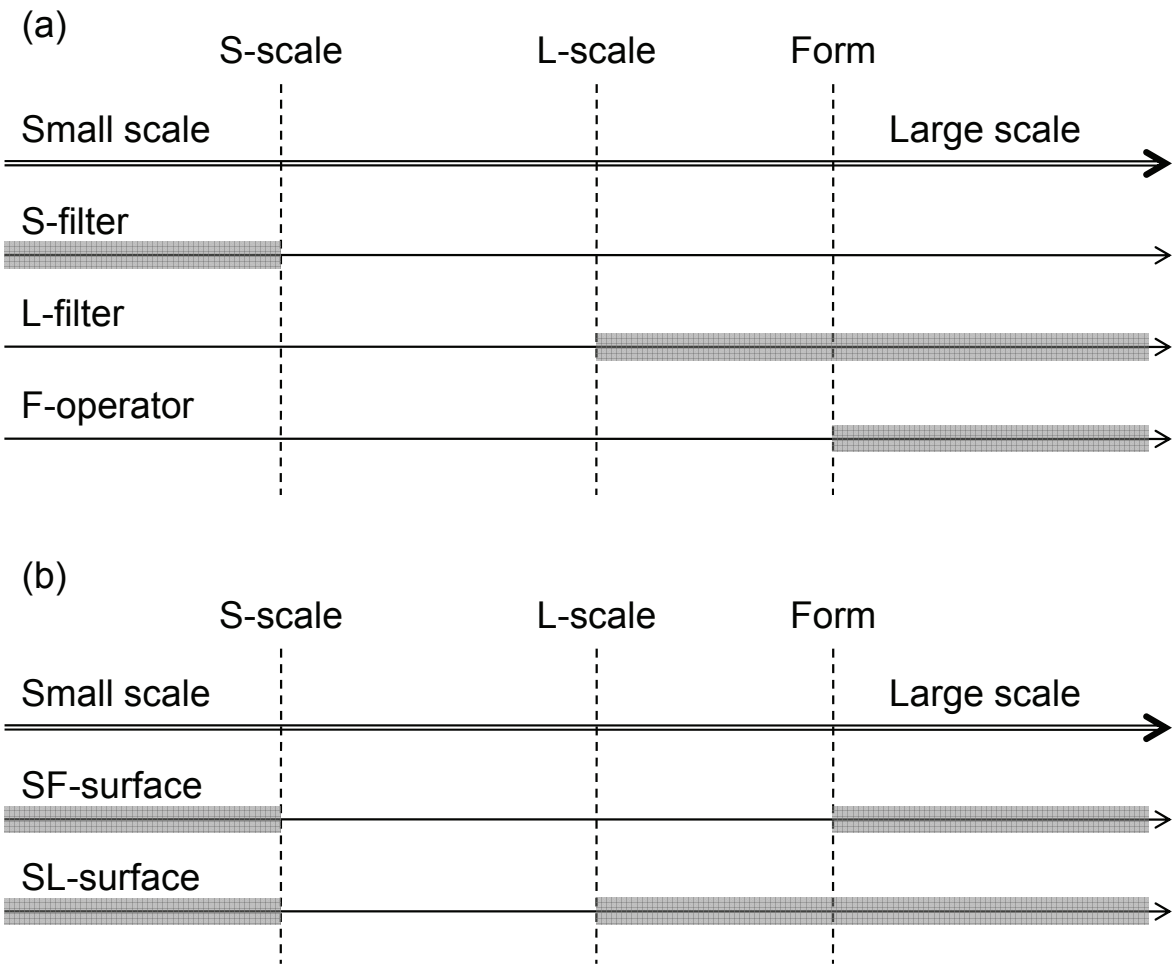


Figure 12: (a) Filters (S-filter or L-filter) and operator (F-operator), (b) scale-limited surfaces (SF or SL surface) used in surface texture. The gray areas on the scale continuums show which scales that are removed.

Gaussian and robust Gaussian filters

The Gaussian filter [40] is a widely used filter to separate surface measurement data into roughness, waviness and form [41]. The Gaussian filter does not have a sharp fall-off of transmission ratio at the cut-off, instead, it has a gradual fall-off which helps avoiding the ringing effect associated with sharp cut-offs [31]. However, there are running in and running out sections of the filter which shorten the filter mean line, as a consequence, the filtered data is somewhat cropped [41].

As stated above, the Gaussian filter is widely used and in many cases it works adequately. However, the regular Gaussian filter is sensitive to outliers. For example, surface features like deep pores or scratches will influence the mean line significantly, and in consequence, the filtered surface and its calculated parameters as well. As a result, there is a lack of robustness when using the regular Gaussian filter with surfaces created by some modern manufacturing processes like honing or laser texturing. For this reason new filtering methods have been developed, one being the robust Gaussian filter [41], see Figure 13 for an example. The robust algorithm applies a regression filter iteratively until the mean line is satisfactory. A statistic function is used to decide when to stop the iteration [42]. To get good results using the robust Gaussian filter it is suggested to use a feature oriented choice of cut-off wavelength. It is appropriate to use a cut-off length three times longer than the length of the largest feature of interest when high-pass filtering [41].

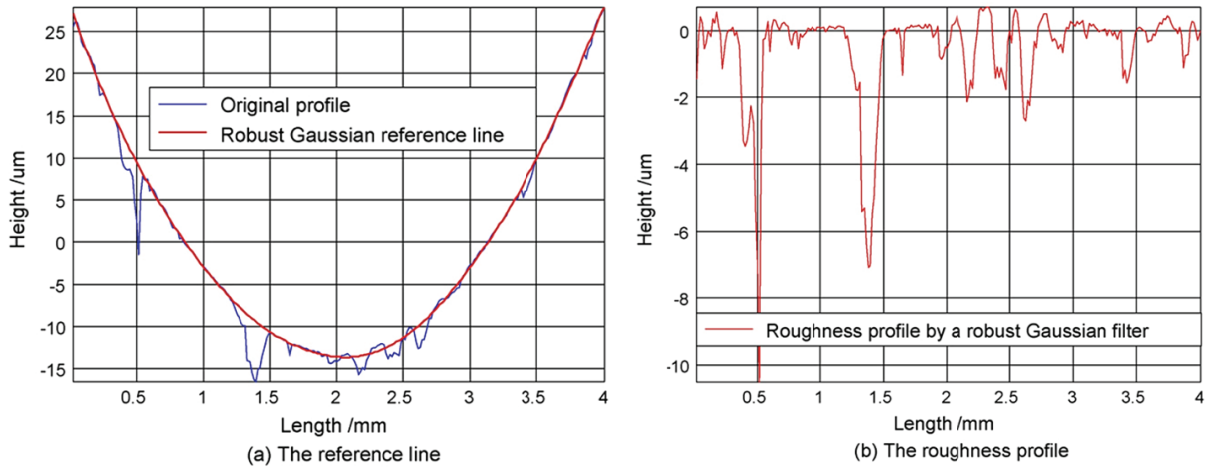


Figure 13: Roughness profile from a robust Gaussian filter. Original profile and reference line (left), filtered roughness profile (right). Adapted from ref. [43].

Wavelet filters

Gaussian filters have relatively poor transmission characteristics compared to wavelet transforms. Wavelets transforms are mathematical functions that can be used to separate data into different scale components which then can be analyzed separately [44]. The fundamental idea behind wavelet analysis is to analyse signal according to scale. Wavelet analysis provides a flexible time-scale window localised on a time-scale plane. Large features appear when evaluating a signal with a large window and small features appear when the signal is examined with a small window [42].

When applying the wavelet transform to roughness data two new sets of data are created, a smoother version of the original data and a data set which represents the difference between the original data set and the new smoother data set. The wavelet transform is then applied again to the smoother set and two new sets are created, and so on, creating different levels, each level representing a different scale [30, 45]. This filtration technique is becoming increasingly popular and there are many examples with more details and applications available in for example refs. [46-50].

Other filters

The spline filter was introduced to overcome some of the issues with the original Gaussian filter such as end effects and over sensitivity to outliers before the robust Gaussian filter was developed. Spline filters can be periodic or non-periodic and the filter characteristics can not be described using weighting functions, instead equations are used [42, 51].

Morphological filters are a mathematical approach to the mechanical envelope filters [51]. With these filters a structuring element is used, typically a disc or line in case of 2D or a sphere in case of 3D, to expand or shrink (dilation and erosion respectively) the surface profile. A closing filter is obtained by a dilation followed by an erosion and an opening filter is obtained by an erosion followed by a dilation [42].

Segmentation filters have become increasingly important as a result of the current shift from stochastic to structured surfaces. These filters facilitate the identification and separation of individual features of the surface topography such as hills and dales (peaks and pits). This partition follows specific rules and can be tweaked to fit the purpose [30]. The motif approach belongs to this class of filters [51].

3.4. Data evaluation

As stated previously, the goal of the characterisation process is to create a relevant parametric description of the surface. This is typically accomplished by evaluating the measured and filtered topography data and calculating roughness parameters [6]. In the following sections, a summary of some available roughness parameters are given then the subject of texture anisotropy is treated in more depth with details on methods for evaluation. Lastly, the concept of multi-scale analysis is explained and some methods for evaluation are described.

3.4.1. Roughness parameters

A common question is what parameter to use to relate surface roughness to surface function [5]. With the previous rise of available computing power the number of roughness parameters developed greatly. Many companies developed their own parameters for quality control of manufacturing processes and when the processes were changed new parameters were developed yet again [52]. The most commonly used parameter is Ra, the arithmetic mean value of the magnitude of the deviation of the profile from the mean line [4, 25].

Surface roughness parameters are described at length, with a focus on 2D parameters [53], in works by for example Thomas [8] and Whitehouse [25]. Comprehensive reviews on the application of roughness parameters in engineering fields are given in refs. [9, 21, 34, 54].

The new ISO standard (ISO 25178) includes parameters for areal (3D) characterisation [39]. In the new standard the parameters are grouped into field and feature parameters. The field parameters consist of S-parameters and V-parameters. The S-parameters depend on height amplitude and space frequency to describe amplitude and spatial information. The V-parameters give volumetric information based on the material ratio curve. The feature parameters are based on segmentation [30]. See Figures 14 to 16 below for an overview of the roughness parameters available in ISO 25178.

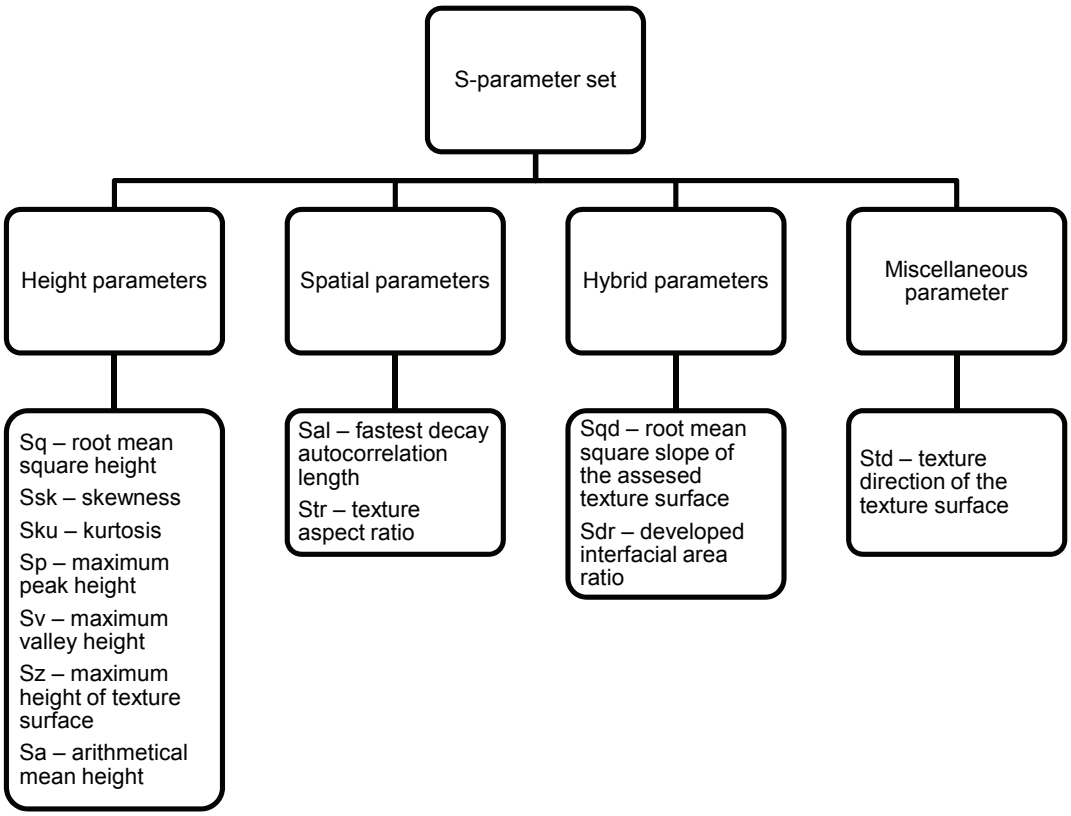


Figure 14: S-parameter set. Adapted from ref. [30].

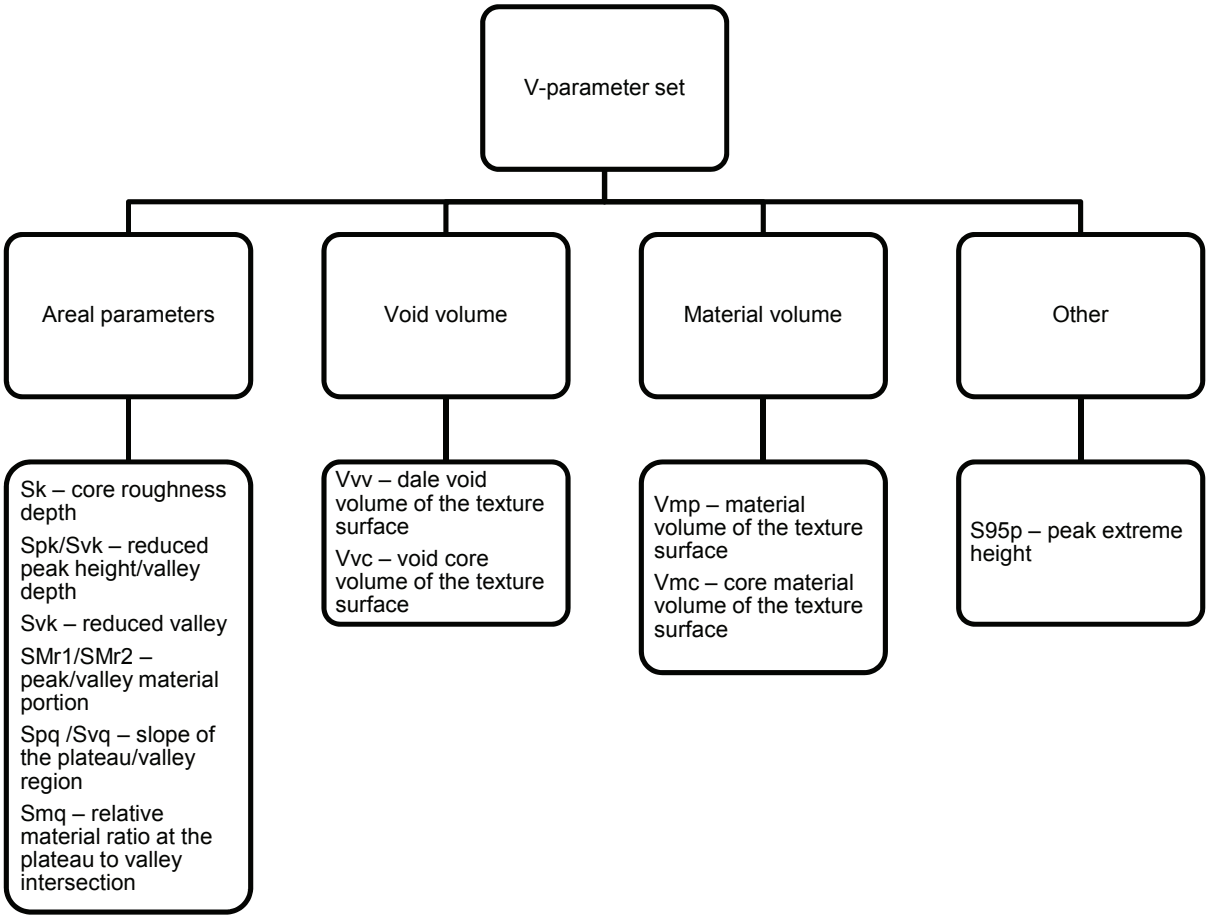


Figure 15: V-parameter set. Adapted from ref. [30].

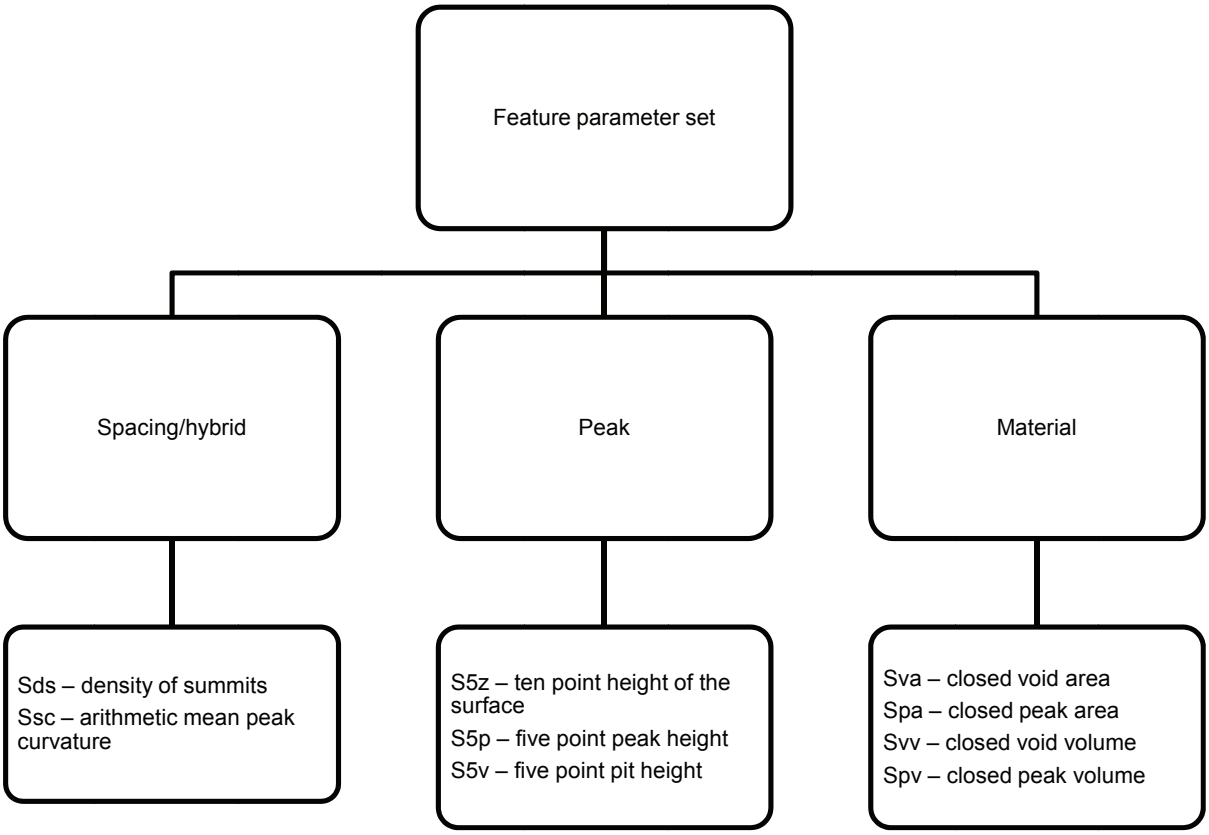


Figure 16: Feature parameter set. Adapted from ref. [30].

3.4.2. Surface texture anisotropy

Surface texture can be isotropic or anisotropic. An isotropic surface has the same properties in any direction. An anisotropic surface has different properties depending on direction. In engineering, an anisotropic surface is said to have a lay with a certain direction [8].See Figure 17 for an example.

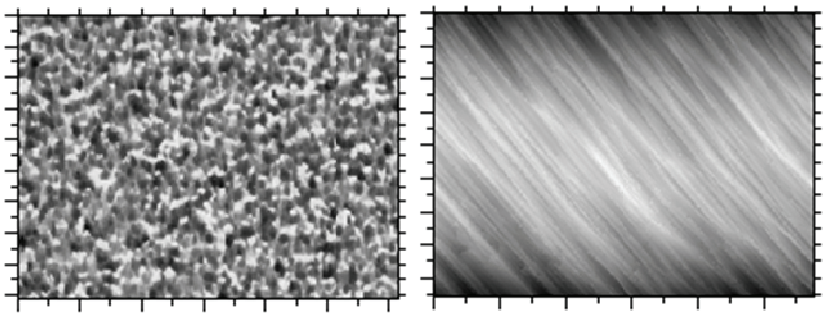


Figure 17: Isotropic surface (left), anisotropic surface (right).

There are a few parameters in the ISO standard dealing with texture anisotropy. These are Str (texture aspect ratio of the surface) and Std (texture direction of the surface) [39]. Str can vary from 0 to 1 where Str = 1 is isotropic (similar in all directions) and Str = 0 is anisotropic (strong lay). Std is the dominant texture direction and can vary from 0° to 180°. When evaluated these parameters will be calculated using all available wavelengths in the scale-limited surface.

With length-scale anisotropy analysis the anisotropy of a surface is evaluated at a particular length scale. At this scale, relative lengths of profiles are measured across the surface at different directions. Compare with the length of boundary lines measured using a certain step size discussed in chapter 3.1. A longer relative length means a rougher profile. Longer relative lengths are found perpendicular to the direction of the lay. This technique is demonstrated in refs. [55, 56]. See Figure 18 for an example of a surface measurement and the relative lengths calculated at the scale 1.8 µm.

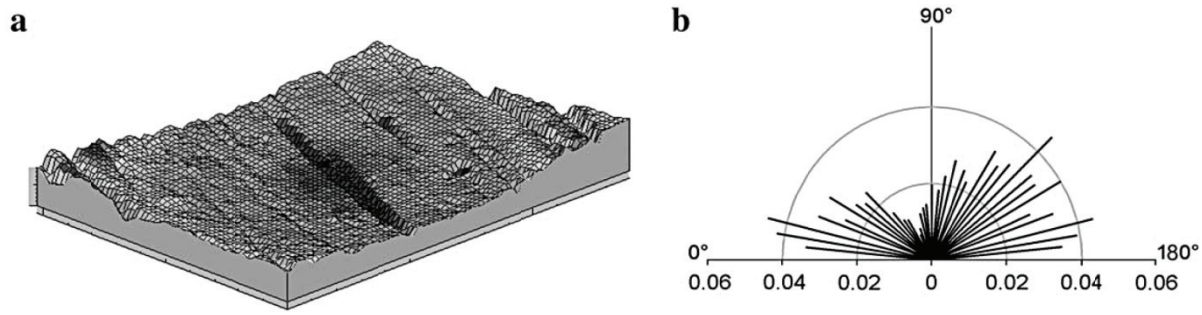


Figure 18: Surface measurement (a) and relative lengths calculated at the scale 1.8 µm (b). From ref. [56].

With the morphological tree approach the concept is to decompose the surface roughness into a combination of motifs which are defined by amplitude, wavelength as well as local and overall direction of various components [57]. The anisotropy can be evaluated at different height levels, see Figure 19. Using this method a so called morphological tree can be constructed displaying various properties of the surface roughness as a function of the level of motifs [58], see Figure 20.

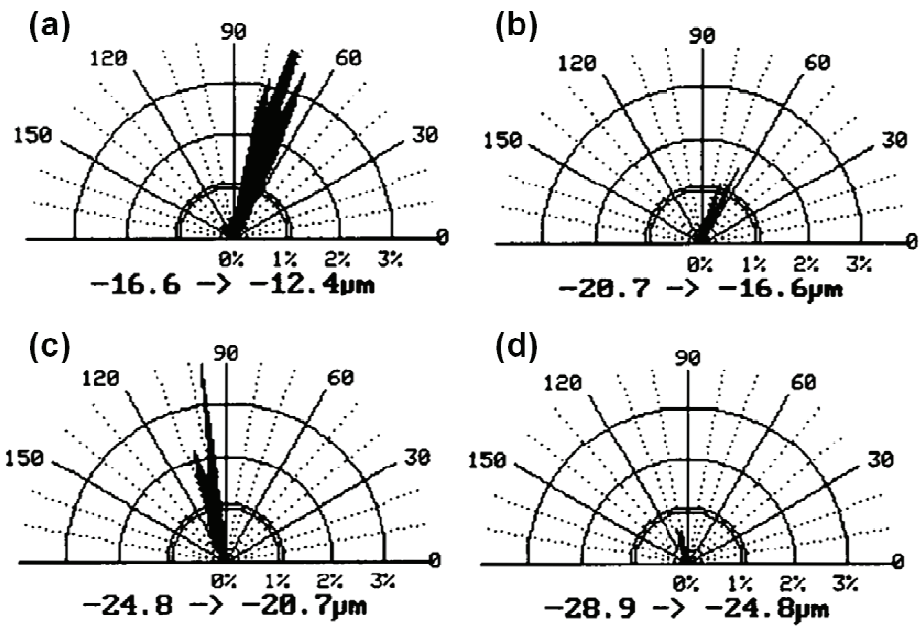


Figure 19: Anisotropy of a surface at four height levels. From ref. [57].

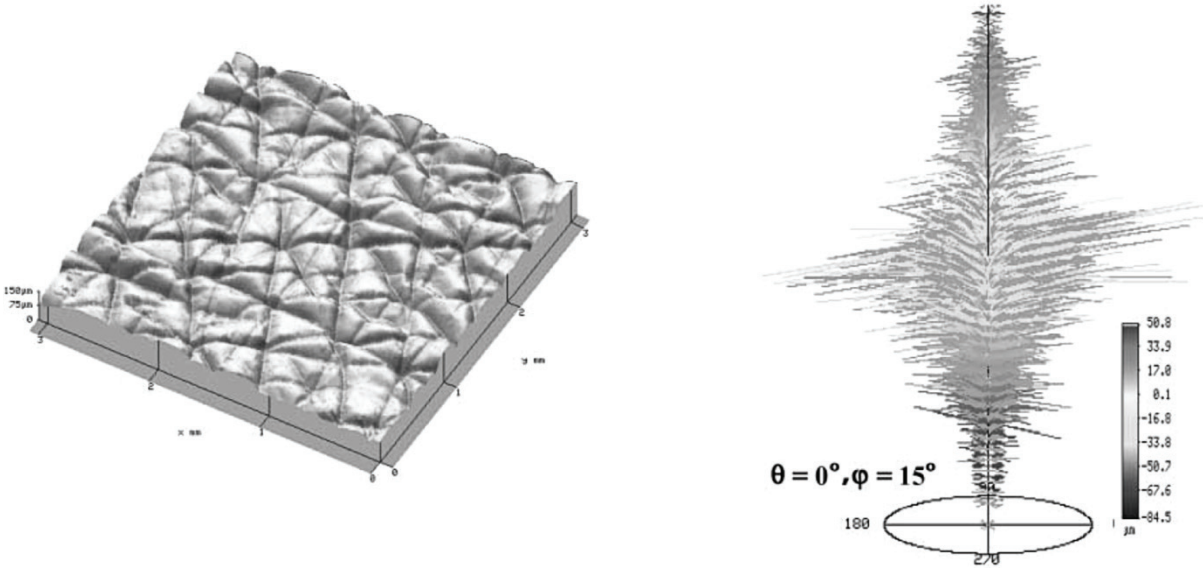


Figure 20: The 3D morphological tree of motifs of bio-material texture. From ref. [58].

3.4.3. Multi-scale analysis

Engineering surfaces are composed of a large number of scales of roughness superimposed on each other [44]. There are several approaches available for multi-scale analysis, or multi-resolution analysis, of surfaces where properties of the surface can be studied separately at different scales of observation.

A commonly used technique is the Fourier transform with which the wavelength contents of a surface data set can be studied. With this analysis no localisation of surface wavelengths or features can be assessed [44].

With wavelet decomposition of the wavelength components multi-scale approximations can be achieved of the surface roughness data [42, 44, 47, 49]. Similar multi-scale approximations can be achieved using morphological filters with different size structuring elements [42].

Multi-scale properties of surfaces can also be described using fractal analysis. The structure function can be used to calculate the fractal parameters fractal dimension and topothesy. Fractal dimension is a measure of how intricate a profile is and was described in chapter 3.1. Topothesy is a scaling factor with dimensions of length which is needed to keep the appearance of self-similarity when the scale of observation changes [8]. See Figure 21 for an example of structure functions calculated for a cylinder liner surface.

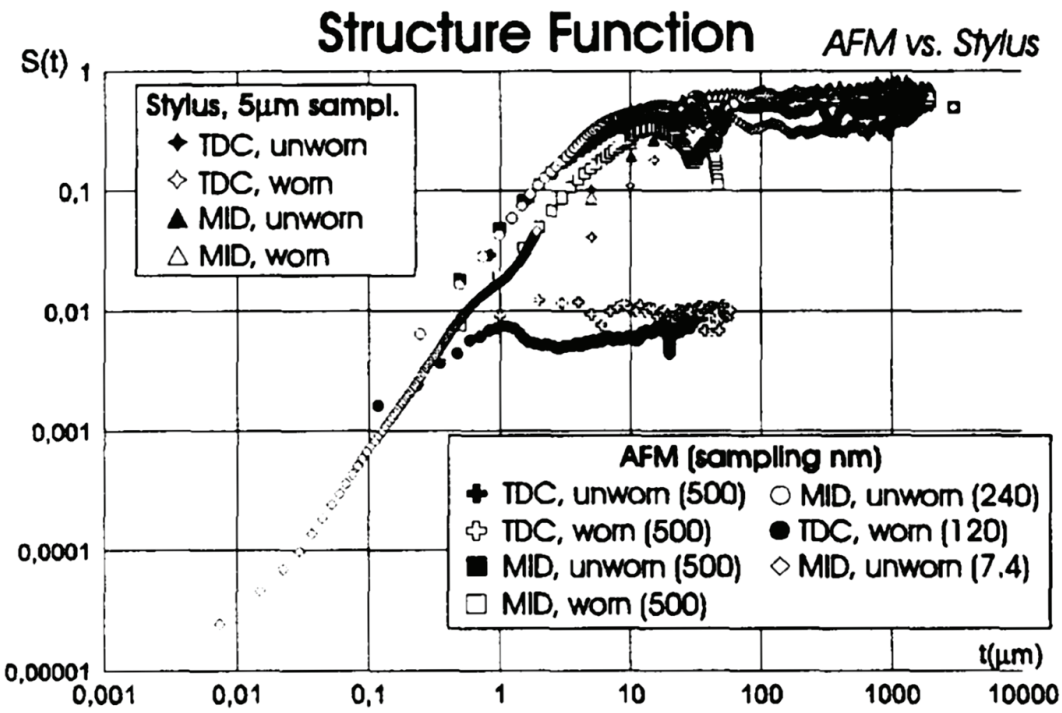


Figure 21: Structure functions of regions of the same cylinder liner in worn and unworn conditions, measured with AFM and stylus instrument. From ref. [59].

Scale-sensitive fractal analysis [60, 61] is another type of analysis using the fractal approach. With this type of analysis several parameters can be calculated, for example relative area and complexity. Relative area is calculated using a tiling algorithm where the topography of the surface measurement is modelled using triangular tiles. At each scale all tiles have the same area, but not necessarily the same shape. The relative area at each scale is the calculated area at that scale divided by the nominal area. The calculated area at each scale is found by multiplying the number of tiles by the area of the tile at that scale. The area of the tile is also used to represent the scale. Complexity is the slope of the relative area plot at each scale calculated over one order of magnitude in scale [60].

A complete account of scale-sensitive fractal analysis is given in the standards [39, 60] and illustrative demonstrations of the method are available in refs. [55, 62, 63]. See Figure 22 for an example of tiling exercises at three different scales and the calculated relative areas plotted versus the scale of observation.

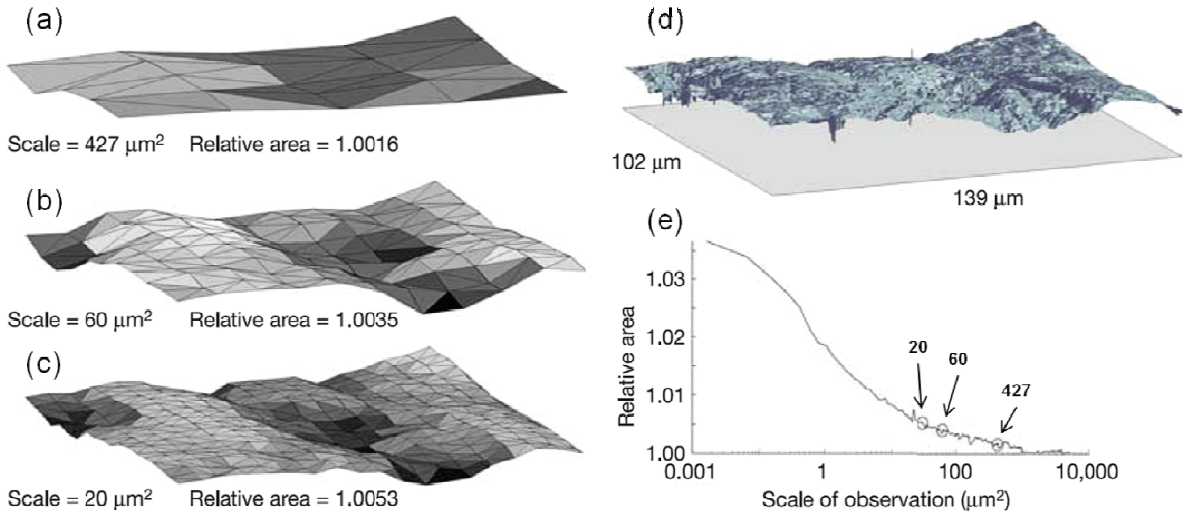


Figure 22: Scale-sensitive fractal analysis, example of tiling exercises at three scales. Surface represented at three different scales using triangular tiles of different sizes (a)-(c). Surface measurement with projected nominal area (d). Relative areas plotted against scale (e). Adapted from ref. [55].

4. Characterisation of functional pressing die surfaces

The objective of this thesis is to develop methods for characterisation of functional pressing die surfaces to enable future manufacturing process development. A successful method for characterisation would consist of several steps. First surface roughness data needs to be acquired. Then the data is to be manipulated to separate the relevant data from the irrelevant data. Finally the data has to be evaluated and results presented in a meaningful way.

Specifically, what needs to be found are suitable methods for:

1. Making measurements for manufacturing process development.
2. Making measurements for process control.
3. Identifying and filtering relevant surface roughness data.
4. Data evaluation and presentation.

There are many methods and technologies available to do surface roughness measurements. The suitability of measurement methods in the application scope of this thesis is a matter of choice of measurement strategy and instrument handling rather than the choice of instrumentation since the surface textures that are to be measured are well within the range of many commercially available instruments. To ensure a high industrial applicability the choice was made to use interferometry instruments for 3D measurements and stylus instruments for 2D since these technologies are well established and widespread.

For identifying relevant surface data two approaches were tested. One using traditional filters in a non-traditional way for identifying a functional bandwidth. The other using the more exotic method of scale-sensitive fractal analysis. The approach with traditional filters was interesting to test since it is possible to use with the filtering capabilities already implemented in many available software packages. Scale-sensitive fractal analysis was interesting to test since it has previously been successfully used to identify functional bandwidths in other applications, for examples see refs. [62, 63].

For data evaluation and presentation it was preferable to use parameters in the ISO standard [39] to ensure high industrial applicability since these parameters are already implemented in many available software packages.

In this chapter, results from the appended papers are summarised in reference to the research questions stated in chapter 1.2. In the summaries, emphasis is put on the results in the papers since the introductory parts as well as the parts covering methodology and frame of reference are covered in previous sections of this thesis. More details can be found in the appended papers. In the discussions directly following the summaries, the results are discussed in terms of generality and limitations of the specific studies. A fuller discussion on the synthesis and applicability of the results follows in chapter 5.

4.1. Acquiring surface roughness data

Below follows a summary of the results from two appended papers. Both studies deal with acquiring surface roughness data, e.g. making measurements, however, in two different contexts. The first study, presented in paper 1, is on making roughness measurements with the purpose of process development. The second study, presented in paper 2, is on making measurements in a production environment with the purpose of quality control.

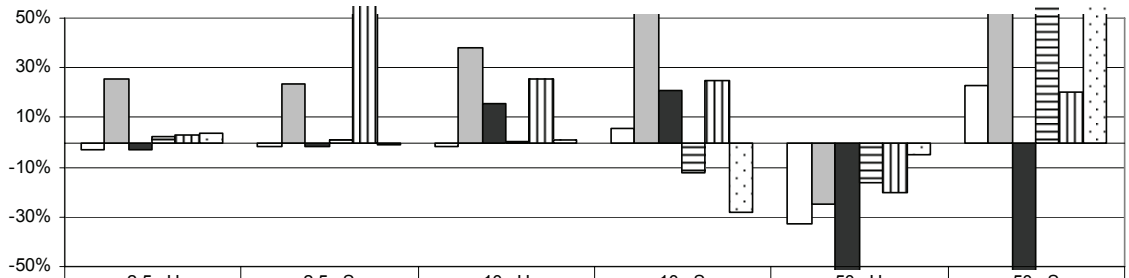
4.1.1. Manufacturing process development

In paper 1 a study including three different applications is presented. In this thesis the focus is on the parts of paper 1 covering the application ‘Milled tool steels for pressing dies’. The

objective of the study was to evaluate different surface topography measuring strategies to establish reliable metrology methods in the evaluated applications.

Two types of surfaces were tested, called HSM and HSMP in the paper. Both were finish milled using a ball-nose end mill. HSMP was manually polished with diamond paste, grain size 9 µm, after the machining. Two replica materials were tested, one soft and one hard. Surface measurements were made using an interferometer instrument at three different levels of magnification: 2.5x, 10x and 50x. The specimens were relocated visually, using scotch tape on the original surface which was imprinted in the replicas, between the measurements so the measurements were made in approximately the same location on the replicas as on the original surfaces. More details are found in the appended paper.

Figure 23 shows the deviation in per cent between the parameter values calculated from the replicas and the original surfaces (HSM and HSMP) measured at different levels of magnification. The results show that both the soft as well as the hard replica technique give good results at 2.5x magnification for the parameters Sq and Sk but not for the extreme amplitude parameter Sz (ten point height). At 10x magnification there are larger differences and at 50x magnification there are large differences in all the calculated surface roughness parameter values.



	2.5x H	2.5x S	10x H	10x S	50x H	50x S
Sq HSM	-3%	-2%	-2%	5%	-33%	23%
Sz HSM	26%	23%	38%	55%	-25%	189%
Sk HSM	-3%	-2%	16%	21%	-56%	-56%
Sq HSMP	2%	1%	0%	-12%	-16%	91%
Sz HSMP	3%	54%	25%	25%	-20%	20%
Sk HSMP	4%	-1%	1%	-28%	-5%	87%

Figure 23: Deviation in per cent between the parameter values calculated from the replicas and the original surfaces (H = Hard replica, S = Soft replica) at different levels of magnification. Note that the scale is cut off at +-50%.

At 50x magnification the measurement area is too small to see an entire feed mark from the milling. At 10x magnification it is possible to distinguish the texture created by the milling process and at 2.5x magnification the measurement area is large enough to get a comprehensive view of surface texture, see Figure 24. It is also possible to identify patterns with longer wavelengths at this magnification. This is true for the milled as well as the polished surfaces.

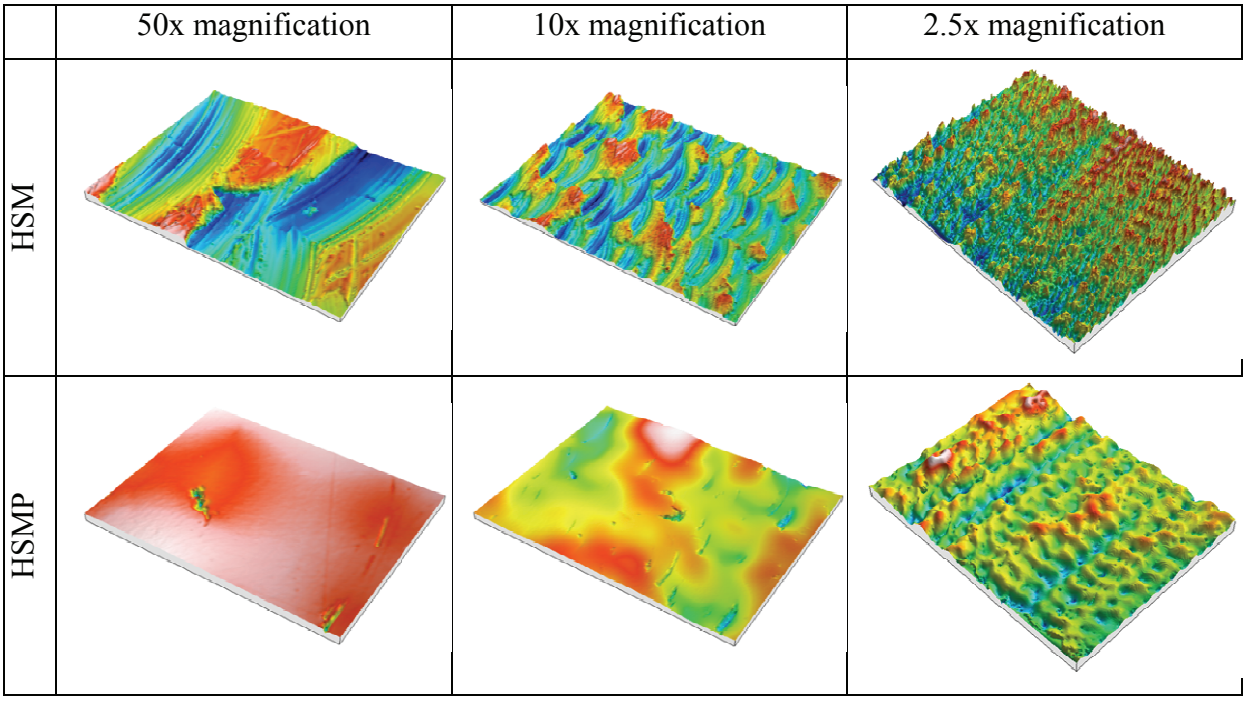


Figure 24: Materials HSM above & HSMP below at 50x, 10x and 2.5x magnification.

4.1.2. Quality control in production

The objective of the study presented in paper 2 was to establish a practical, robust measuring strategy that was possible to use with a 2D profiler in a tool and die workshop and to study to what extent a handheld 2D profiler could give reliable results in this type of application.

Two different tool steels were used in the study. They were finish milled using a selection of different ball-nose end mills. After each level was cut the machine operator made an optical inspection of the surface finish to decide whether to keep on using the same tool to cut another level or to change tools. Measurements and images of the surface were made on three faces of the machined workpiece at two times for each cutting tool, after the first level was cut and after the last. The 2D measurements were made using a handheld stylus type instrument with a 2µm diamond tip. For reference, 3D measurements were made on replicas of the milled surfaces using an interferometer instrument. More details are found in the appended paper.

A large number (100) of 2D measurements were made at one time, randomly spaced over one of the faces, to evaluate the distribution of the measured values. These measurements were made at approximately mid-life of one of the tools. There was a detectable wear on the tool but the surface finish was still considered to be good. Mean values and standard deviations for the evaluated roughness parameters were calculated, see Table 1.

Table 1: Summary of roughness parameters calculated from 100 2D measurements.

	Ra (µm)	**Rz (µm)**	**Rp (µm)**
Mean	0.512	2.430	1.384
StDev	0.154	0.555	0.410
StDev/Mean	30%	22%	30%

From the collection of 100 measurements different sets of values were randomly picked to simulate different measuring strategies. The different strategies were: 3, 5, 5-2, 7, 7-2, 7-4, 10, 10-2, 10-4 and 10-6 (where "5" means: one set consists of five randomly picked values, and "5-2" means: one set consists of five randomly picked values with the highest and lowest values excluded). A large number of sets using each strategy were collected and mean values and standard deviations were calculated for each new set. These mean values were compared to the mean value for all 100 measurements. The average deviations of the mean values and the average standard deviations for each strategy are shown in Figure 25. Strategy "5-2" was considered to be a good compromise between reliability and ease of use.

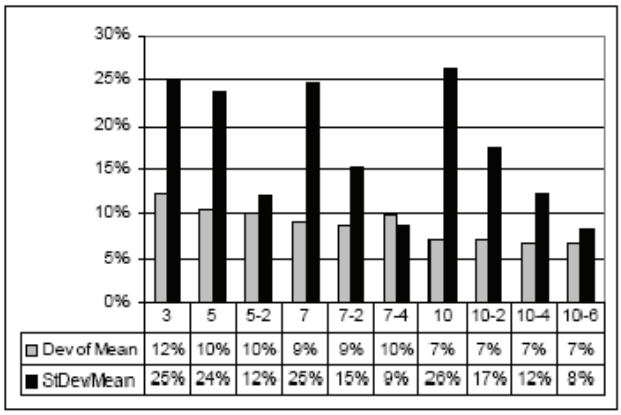


Figure 25: Average deviations of the mean values and average standard deviations for the different measuring strategies.

In all three measurement locations there was generally a considerable increase in the evaluated 2D roughness parameters. This was also the case in the 3D measurements made for reference with only a few exceptions. A summary of the average difference in the 2D parameters is presented in Figure 26.

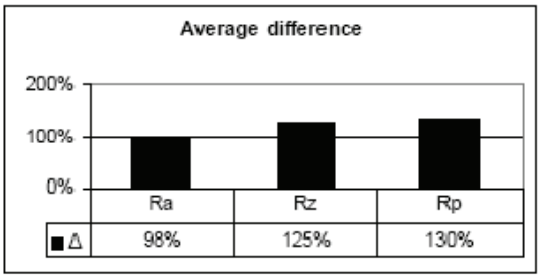


Figure 26: Average difference in 2D roughness parameters from surfaces cut with new tool and surfaces cut with a worn tool.

Although there was an increase of the average value of Ra, in some cases the Ra value did not change much at all during tool wear. This indicates that the Ra parameter might not be a very good parameter to use for evaluation of surfaces in cases like this. Instead Rz or Rp is suggested to be used since an increase of those parameters showed a more consistent relation to the deterioration of surface finish appearance as the cutting tools were worn.

4.1.3. Discussion

Roughness measurement on large dies requires the use of replica. Therefore, it is interesting to know what works and what does not work. In the study presented in paper 1 the relocation process did not work well at 50x magnification probably because too few significant features were included in each measurement to ensure a good relocation. At this level of magnification

a single groove made by the cutting tool can cover most of the measured area. If this groove is moved in the measurement, it has an impact on the calculated parameters.

At the preferred level of magnification 2.5x the parameters Sq and Sk seem to be usable when comparing the values calculated for the original surfaces to the replicas, see Figure 23. However, the parameter Sz did not work so well with replicas. Sz is an extreme value parameter and is therefore very sensitive to errors in single measurement points. Thus, it is not surprising that the evaluation of Sz gave bad results.

Instruments for 3D measurements are typically more expensive than 2D instruments. In addition, they are usually not very suitable to use in a workshop for quality control since they often are comparatively large and more difficult to handle. The measurement method has to be simple and easy to use but give good enough results. Consequently, portable and inexpensive 2D instruments are more commonly used for quality control.

The handheld profiler used in the study presented in paper 2 showed a large variation in the results, see Table 1. There are several factors which could explain this. First of all, since the 2D profiler was handheld the operator probably was responsible for some measurement errors through accidental movement of the profiler during the measurement or by not being able to position the device accurately. Secondly, the 100 measurements were made on a surface which hade been milled with one tool. It is possible that the wear of the tool during this milling pass created a surface with a non homogenous texture.

In the study, it was confirmed that using a single Ra value to determine if a surface is good or bad is very uncertain. First of all, it was observed that a surface judged as good by an experienced machine operator can have the same Ra value as a surface judged as bad. Secondly, using a handheld profiler, as the one used in this study, a set of several measurements has to be made to reduce the impact of measurement error and to get a more reliable result.

4.2. Finding functional bandwidths and relevant parameters

Below follows a summary of the results from three appended papers. In two studies, presented in detail in papers 3 and 4, two different multi-scale approaches were tested for finding functional bandwidths and roughness parameters with correlation to function. In the first approach sets of band-pass filters with different bandwidths and centre wavelengths were tested. In the second approach scale-sensitive fractal analysis was tested. In a third study, presented in detail in paper 5, a methodology for functional filtering was evaluated.

4.2.1. Functional bandwidth and relevant parameters

In the two studies, presented in papers 3 and 4, the objective was to evaluate two methods for finding correlations between surface roughness data and a functional property of interest at the most appropriate scale or range of scales. The same set of surface roughness measurements and the same test results from friction testing were used.

Milled surfaces of three different tool materials were used for the experiments. Cutting parameters variations were used to produce two variants of surface textures with different levels of roughness. A DP600 sheet metal was used in the testing with a surface roughness of Ra 1 µm and thickness 1.2 mm. The amount of lubrication was measured on every sheet strip to be approximately 0.8 g/m^2. Three surface roughness measurements were made on each tool surface using an interferometer instrument. Friction data from BUT testing was used as a measure of functional performance. The BUT test method is further explained in chapter 2.2.1 as well as in the appended papers and ref. [24].

To have a reference, surface roughness parameters were calculated and correlated with the friction data using linear regression. All parameters from the new standard, ISO 25178, available in the software were used. The cylindrical form had been removed from the roughness data and it had been levelled. The correlation coefficients, R^2, are presented in Table 2 below. As can be seen, two fairly strong correlations were found with the parameters Sdr ($R^2 = 0.72$) and Sdq ($R^2 = 0.70$). These results were used as a reference in both studies.

Table 2: Correlation coefficients, R^2, for correlations between surface roughness parameters and friction.

Parameter	R^2	Parameter	R^2	Parameter	R^2
Sdr	0.72	Vvc	0.15	S5v	0.01
Sdq	0.70	Spc	0.12	Sku	0.01
Vvv	0.31	Ssk	0.11	S10z	0.01
Smr	0.29	Spd	0.09	S5p	0.01
Sxp	0.29	Sv	0.06	Sdv	0.01
Sa	0.19	Str	0.04	Vm	0.00
Smc	0.17	Sz	0.04	Vmp	0.00
Sq	0.17	Sp	0.02	Std	0.00
Vmc	0.16	Sda	0.02	Shv	0.00
Vv	0.16	Sal	0.01	Sha	0.00

In the first study, presented in paper 3, a band-pass method was tested. For the band-pass filters, combinations of low-pass and high-pass Gaussian filters were used. Three different bandwidths were used: 20, 50 and 100 µm. These band-pass filters were used with a range of centre wavelengths from 10 to 180 µm in increments of 10 µm. The surfaces were filtered using all combinations of filter parameters (bandwidth and centre wavelength). After that, surface roughness parameters were calculated and correlations between parameter values and friction were calculated using linear regression. The strongest correlation ($R^2 = 0.94$) was reached with the parameter Sa using two filters:

- Bandwidth 50 µm with centre wavelength 20 µm
- Bandwidth 100 µm with centre wavelength 10 µm

Results for the four roughness parameters with the strongest correlations are shown in Figure 27 (A)–(D). In each plot, the results from filters with the three different bandwidths (20, 50 and 100 mm) are presented as functions of the filter centre wavelengths. Also, relatively strong correlations ($R^2 > 0.75$) were found with the parameters Sdr, Sdq, Vv, Vmc, Vvc and Vvv, with similar patterns in the plots as the ones presented in Figure 27.

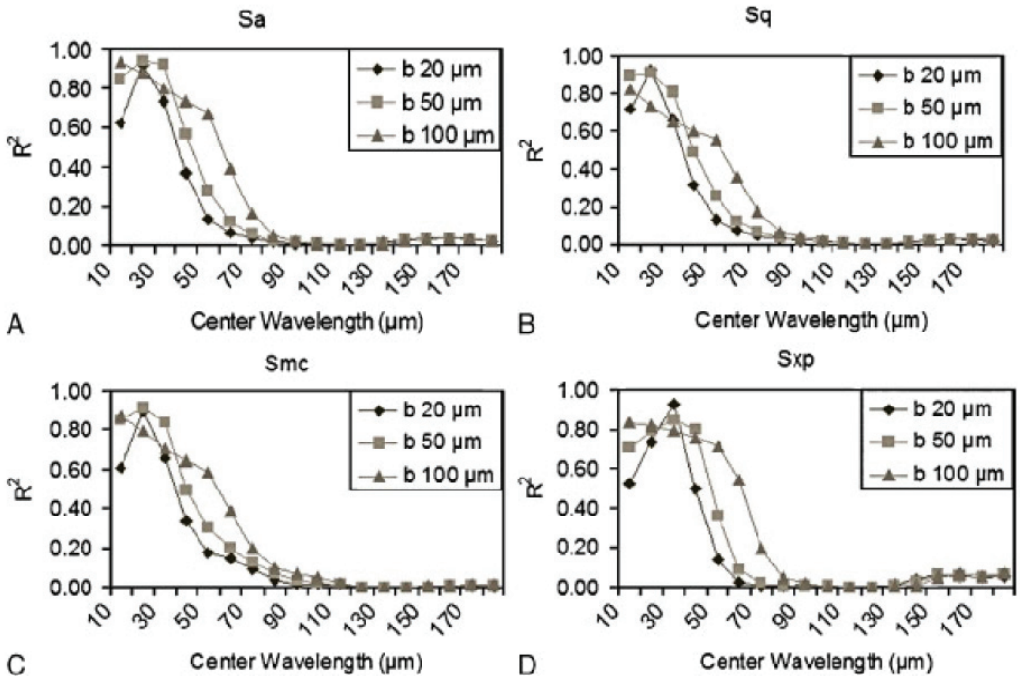


Figure 27: (A–D) Correlation coefficients, R^2, for the four roughness parameters with the strongest correlation to friction. In each plot, the results from filters with three different bandwidths (20, 50 and 100 mm) are presented as functions of the filter centre wavelengths.

In the second study, presented in paper 4, an approach with the two scale based roughness parameters relative area and complexity was tested. Relative area and complexity were calculated using scale-sensitive fractal analysis in the software Sfrax. The roughness parameters were correlated with the friction data using linear regression. The correlations with relative area and complexity were calculated at each scale. The resulting correlation coefficients, R^2, are presented in Figure 28 and Figure 29. Both plots indicate a scale where the correlations are at a maximum. For relative area R^2 approaches 0.9 around 10 μm^2 and for complexity it exceeds 0.9 at about 200 μm^2.

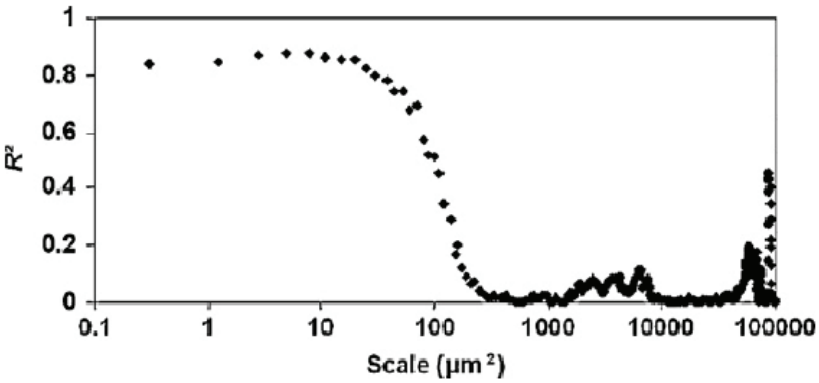


Figure 28: Correlation coefficient, R^2, for the correlations between relative area and friction at 587 scales.

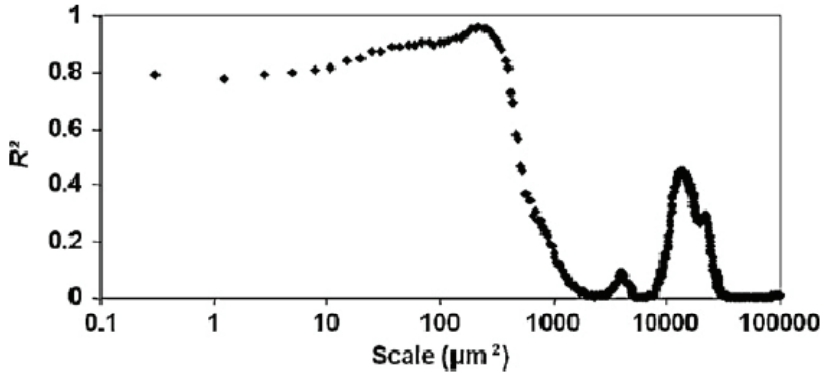


Figure 29: Correlation coefficient, R^2, for the correlations between complexity and friction at 587 scales.

4.2.2. Functional filtering

The main objective of the study presented in paper 5 was to develop a suitable method for relating surface roughness data to functional properties such as surface finish appearance which is traditionally used as a criterion on shop floors to evaluate the surface finish after finish milling of die surfaces.

A combination of the two techniques presented in chapter 4.2.1 was tested for defining and applying a functional filter. Scale-sensitive fractal analysis was used to find a bandwidth of interest. This bandwidth was used to define the limits for a band-pass filter which was applied to the roughness data to enhance the correlation between a selected roughness parameter and functional performance. Finish milled steel surfaces were inspected by an experienced operator and graded on a scale from 4 to 0, where 4 is a good surface finish and 0 a bad surface finish. This is later referred to as 'finish appearance grade' or 'finish'. Surface roughness measurements were made on replicas using an interferometer instrument. In total 48 measurements were made, 16 surfaces with 3 measurements on each surface. More details can be found in the appended paper.

For reference, a standard filter was applied and surface roughness parameters were calculated for all measurements. The standard filter was a robust Gaussian high-pass filter with cut-off 1.2 mm. These parameter values and the finish appearance grades were linearly regressed and correlation coefficients, R^2, were calculated. The results are presented in Figure 30. The strongest correlations are with Sq (R^2 = 0.61) and Spk (R^2 = 0.65).

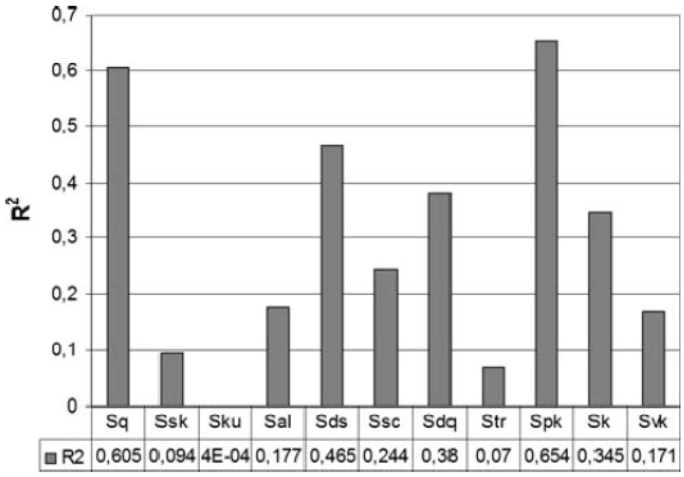


Figure 30: Correlation coefficients, R^2, for correlation between roughness parameters and finish appearance grade.

For the functional filter, the first step was to calculate relative areas for each measurement. This was done at 257 scales ranging from 7.6 to 502646 μm^2 using the Sfrax software. At each scale the relative area and the finish appearance grade was linearly regressed and the correlation coefficient, R^2, was calculated. These R^2 coefficients are plotted versus the scale in Figure 31. The strongest correlations occur at scales approximately from 200 to 12000 μm^2.

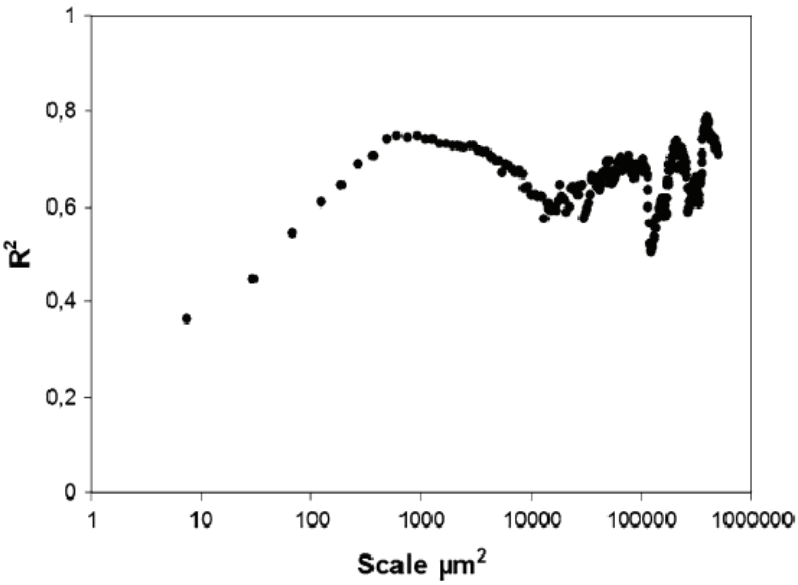


Figure 31: Correlation coefficient, R^2, for correlation between relative area and finish appearance grade at 257 scales.

To understand which scales that were important for the evaluated roughness parameters, these were regressed individually with the relative area for each scale in a similar manner as with the finish appearance grades. These results are plotted together with the R^2 coefficients for the finish appearance grades in Figure 32 and Figure 33. This was done so that it would be more easily observable which roughness parameters had a strong correlation at the same scales as the finish appearance grade.

In Figure 32 and Figure 33, it can be seen that only Sq has a strong correlation at the same scales as Finish. Sdq and Ssc have strong correlations at the smaller scales where the correlation for Finish is much weaker. Using the information from Figure 32, a band-pass filter was designed. The objective was to create a filter which made the correlation between Sq and Finish stronger than with the basic filter, compare with Figure 30. The range of scales from 2400 to 11000 μm^2 was chosen since within that range R^2 for Sq is around or above 0.9 and it is within the range of 200 to 12000 μm^2 previously described as scales interesting for the appearance.

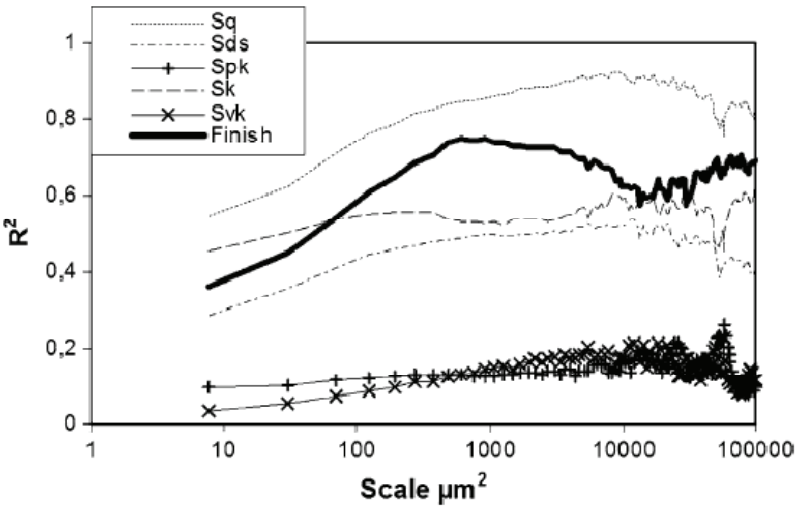


Figure 32: Correlation coefficient, R^2, for correlation between relative area and some roughness parameters as well as correlation between relative area and finish appearance grade.

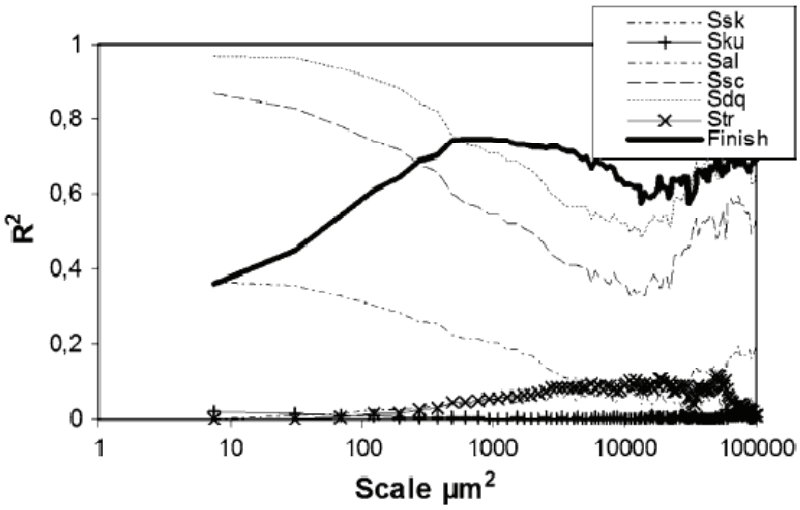


Figure 33: Correlation coefficient, R^2, for correlation between relative area and the remaining evaluated roughness parameters as well as correlation between relative area and finish appearance grade.

In the Sfrax software, right angled triangular elements are used to represent scale. Consequently, a scale of 2400 µm^2 corresponds to a length of 69 µm since $69 \approx \sqrt{(2 \cdot 2400)}$. A scale of 11000 µm^2 similarly corresponds to a length of 148 µm. With a high-pass robust Gaussian filter it is appropriate to use a cut-off length of about 3 times the length of the largest feature of interest. Similarly, for a low-pass filter, a cut-off length of a third of the smallest feature of interest is appropriate. Thus, the chosen cut-off lengths were calculated as 444 µm ($444 = 148 \cdot 3$) for high-pass and 23 µm ($23 = 69/3$) for low-pass filtration. This band-pass filter was applied to all surface measurements. New Sq parameters were calculated and these were once again linearly regressed with the finish appearance grades with a resulting correlation coefficient, R^2, which was raised from 0.61, see Figure 30, to 0.69. This was interpreted as a confirmation that the filtration technique worked.

4.2.3. Discussion

For the band-pass filters used in paper 3, a low-pass filter is first applied using the upper wavelength cut-off, λ_{uc}. Then, that result is filtered with a high-pass filter at the lower wavelength cut-off, λ_{lc}. The cut-offs refer to the wavelength where the filter has

approximately 50% transmission. The resulting overall 50% cut-off for the new filter is slightly different from the original specifications. See Figure 34 for an example the transmission characteristics of such a band-pass filter. This is caused by the resulting multiplication of the previous two filters in the frequency domain. Thus, it is difficult to specify the overall cut-off and transmission characteristics for this method. The technique for constructing the band-pass filter is explained in more detail in the master's thesis [64] of one of the co-authors of paper 3.

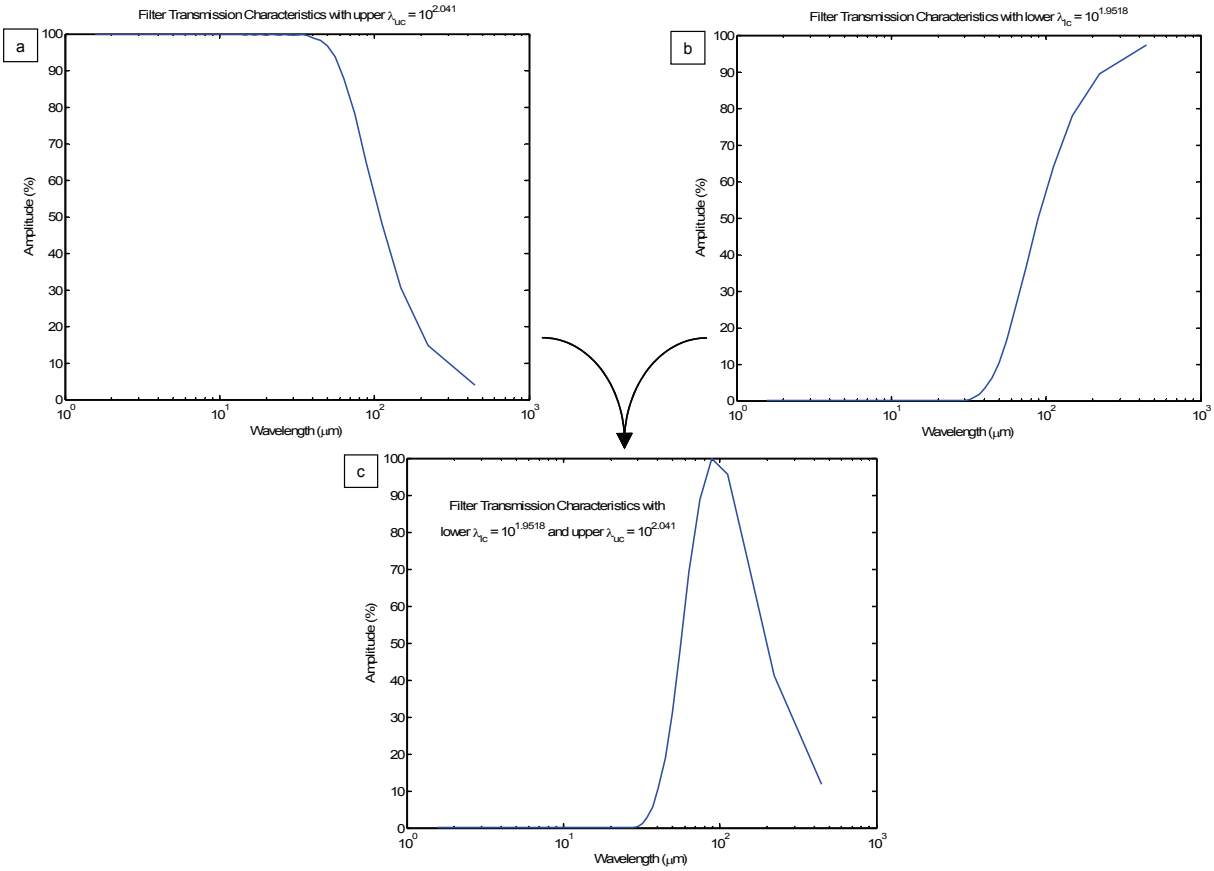


Figure 34: Example of transmission characteristics of the low-pass (a), the high-pass (b) and the of the combined band-pass filters [65].

In this study, a traditional Gaussian high-pass filter with a cut-off of 80 µm would probably produce similar results regarding correlations between calculated roughness parameters and friction. However, with such a method one would not know of the correlations which could possibly be found at other scales.

The relative area and the developed area ratio are essentially the same thing at the scale of the sampling interval. This similarity is shown in Fig. 6 in paper 4. The correlation coefficient between the two parameters is nearly one. The developed area ratio, like the relative area, can be related to the inclinations on the surface [66]. The relation between the developed area ratio and the RMS gradient is shown in Fig. 7 in paper 4. The correlation coefficient between the two parameters is nearly one. The strong relations between the characterisation parameters indicate that they do not contain additional information about the surface texture [67].

The texture characterisation parameters that show strong correlations with friction are all related to the inclinations and areas on the surface. Both area and inclination are sensitive to the scale, or wavelength, at which they are calculated. The relative area and complexity are calculated at all scales in the measurement, the developed area ratio and the RMS gradient are calculated at the sampling interval.

In the scale-sensitive fractal analysis with the parameters relative area and complexity, no consideration is made of texture anisotropy. Differences in texture direction and texture aspect ratio do not influence the results. However, it has been shown that these aspects are influential for the functional performance of pressing die surfaces [23]. To get sensible results when correlating relative area or complexity with functional performance in a case like this all surfaces have to have the same texture direction, or, separate analyses have to be made with only surfaces with a particular texture direction in each analysis. This is discussed further in chapter 5.3. All tested surfaces in papers 3 and 4 have texture in the same direction.

In manufacturing of pressing dies, the technique commonly used on the shop floor to evaluate the surface finish after milling is visual and tactile inspection by an experienced machine operator. The judgments are subjectively made and this is an obvious source of uncertainties. In paper 5, the roughness measurements were made on replicas which introduce other uncertainties. These uncertainties probably contribute to the rather low correlation between the roughness data and the evaluated roughness parameters. What is demonstrated in the paper is a method to find a 'functional bandwidth' and strengthen the functional correlation even with these existing uncertainties.

4.3. Visualisation of texture anisotropy

In the study presented in paper 5 the objective was to demonstrate a method for visualisation of a number of surface texture properties related to the anisotropy of surface texture in a single graph as a function of scale using ISO standard parameters and robust Gaussian filters. The purpose was to create a meaningful and understandable graph which can be used to explain anisotropy properties of a studied surface. To demonstrate the method for visualisation some examples were used. The roughness measurement used in the first example is presented in Figure 35 together with reference angles and some roughness parameter values. More details and additional examples are found in the appended paper.

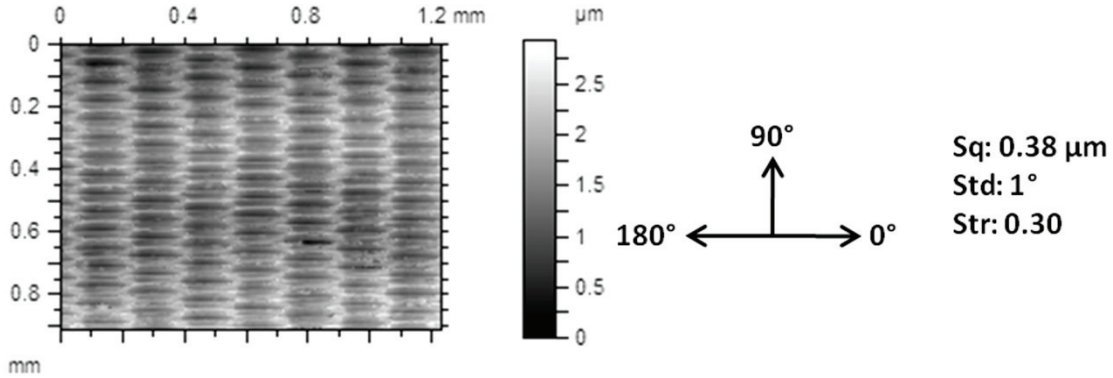


Figure 35: Unfiltered surface roughness measurement with reference angles and parameter values.

Band-pass filters were used to separate the surface roughness data into different ranges of scale. The band-pass filtering was achieved by a sequence of robust Gaussian low-pass and high-pass filters. For the examples presented in this summary the cut-off limits were selected with a ratio of 1 to 2 and there is a 50% overlap between the bands, for example 2-4, 3-6, 4-8 etc. The choice of cut-off limits is discussed further in chapter 4.3.1. The surface roughness parameters used were Sq (root mean square height of the surface), Str (texture aspect ratio of the surface) and Std (texture direction of the surface). Str can vary from 0 to 1 where Str = 1 is isotropic (similar in all directions) and Str = 0 is anisotropic (strong lay). Std is the dominant texture direction and can vary from 0° to 180°. The parameters were calculated separately for each scale.

To construct the anisotropy graph a cylindrical surface was created using the function cyl3d in MATLAB with the different levels of the cylinder representing different levels of scale. Two points were created at each level of scale in the anisotropy graph. Both points were based on the same parameter values of Std and Str calculated for that scale. The coordinates for the points were (1-Str, Std) and (1-Str, Std+180) respectively. 1-Str being the distance from the centre and Std and Std+180 are the angles. The purpose of having two points at each level instead of just one is that the symmetry will make the graph easier to interpret. For example, the texture directions 1° and 179° are very similar but could be misinterpreted for being dissimilar since they are directed in approximately opposite directions. Instead, having two symmetric points for each level with directions Std and Std+180 makes the graph clearer and easier to interpret. 1-Str was used instead of Str to create a graph were a strong anisotropy (low Str) would be shown more distinctly than a weak anisotropy The Sq value for each scale was used to create a colour bar. The filtered roughness data of example 1 together with the calculated roughness parameter values for each scale are presented in Figure 36 (a) to (o).

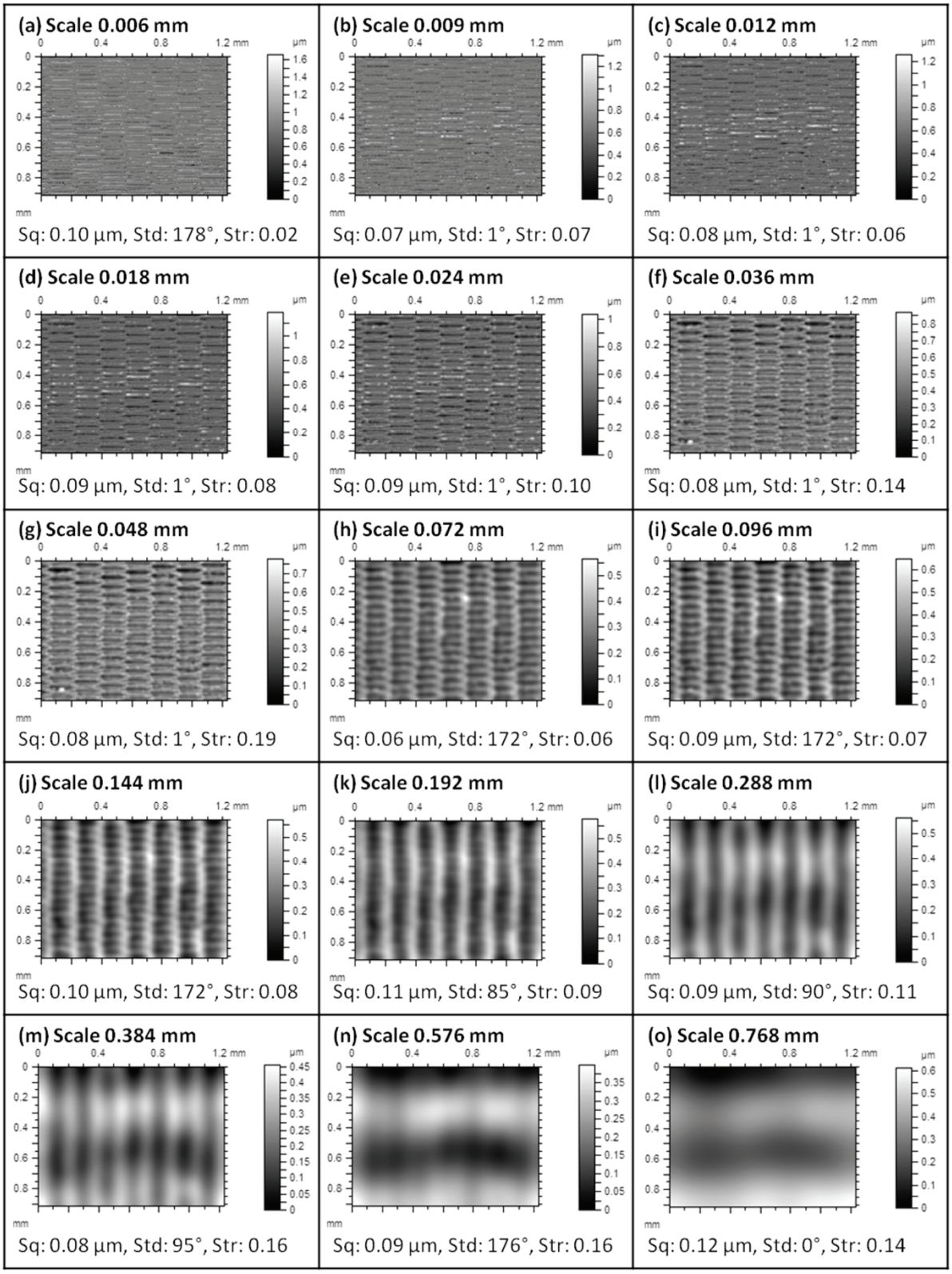


Figure 36: Surface measurement after the different filters were applied and the calculated parameter values. The colour bars represent the height and are different between the plots.

The parameter values in Figure 36 were used to construct an anisotropy graph which is presented in Figure 37.

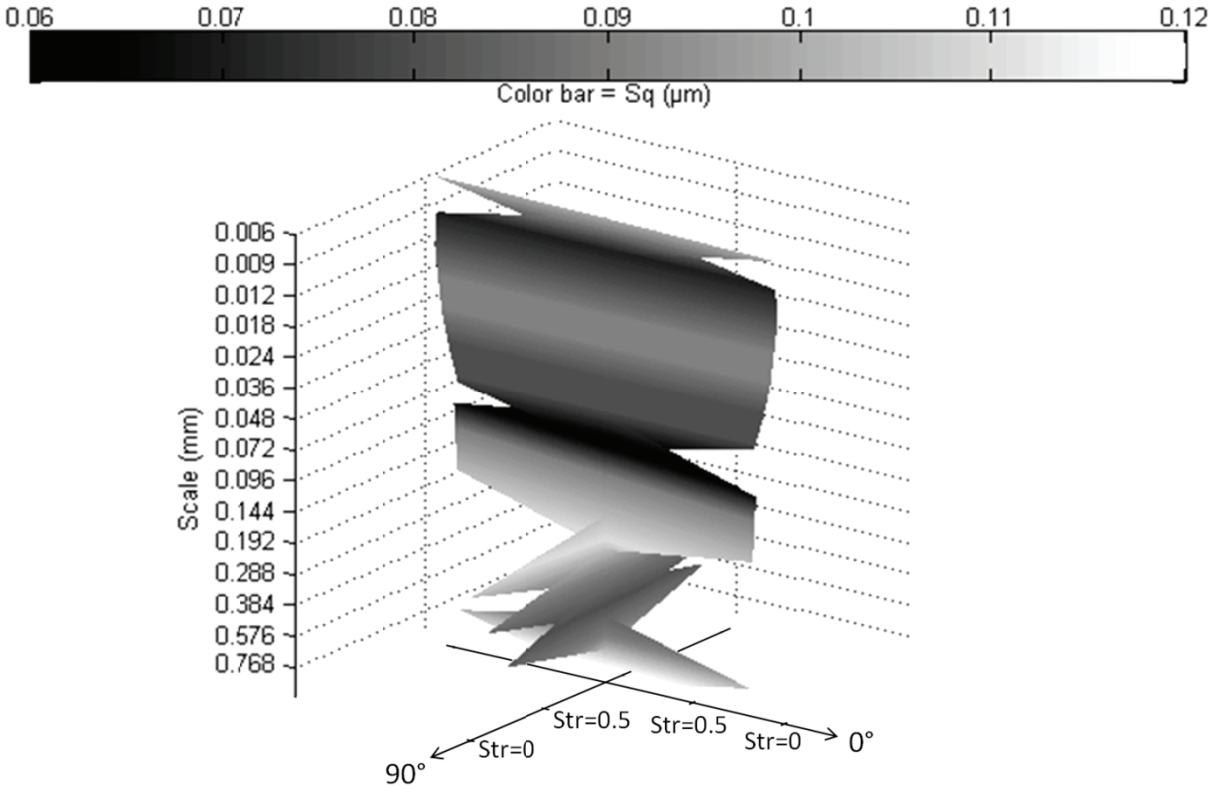


Figure 37: Anisotropy graph for roughness measurement in Figure 35.

Analysing Figure 37 it can be seen that the direction of the surface texture, the strength of the anisotropy and height of the texture differs between scales. An interesting observation to make is that the texture direction is close to 90° in three of the larger scales and close to 0° in the two largest and in the smaller scales.

The surface used in this example is a supposedly flat, steel surface which was milled with a ball-nose end-mill. Different aspects of this milling process can be observed in the images in Figure 36. For example, the regular pattern created by the feed per tooth can be seen in (f), the stripe like texture created by the side step is seen in (k). In (n) and (o) deviations from the flatness is seen. In (a) and (b) the texture created by the rotation of the cutting tool and interaction between the tool edge and workpiece material can be seen.

An example with a more isotropic surface texture is presented in Figure 38 for comparison. In contrast to Figure 37 there is no strong anisotropy in any of the analysed scales. However, there is a clear difference in the Sq parameter value between the scales with the highest values in scales around 0.02 mm to 0.05 mm.

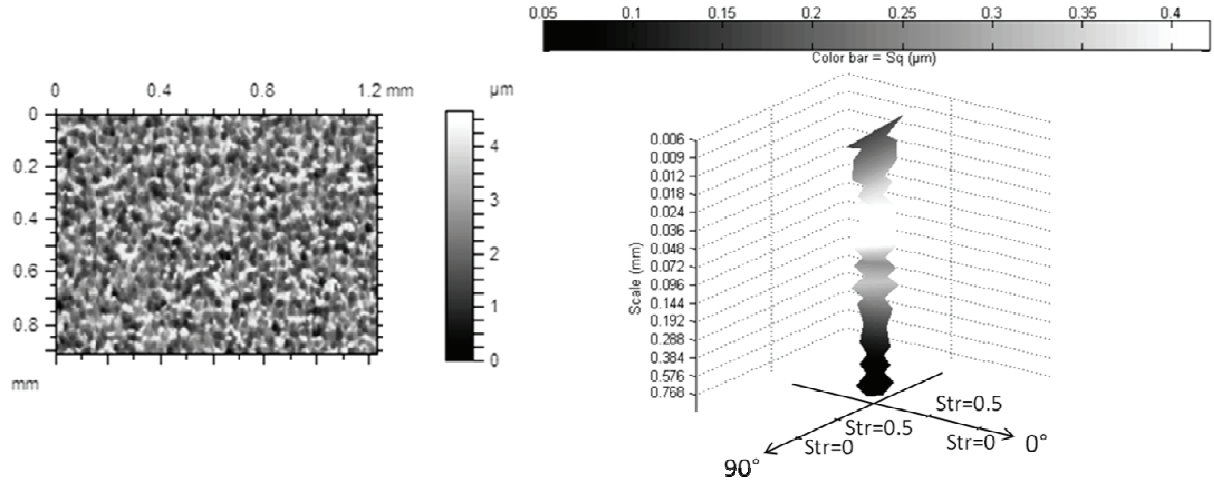


Figure 38: Flat surface with isotropic texture, roughness measurement (left) and anisotropy graph (right).

4.3.1. Discussion

In paper 6, the filtering approach used in the two examples above is referred to as filtering approach B. For filtering approach A the cut-off limits are chosen differently. This is described in more detail in the appended paper. The main difference is that the bandwidths are much wider in filtering approach A than in approach B. The reason for choosing approach B over approach A is that using approach A the bands are so wide that there is not so much difference between the scales.

In approach A, the filter cut-offs were chosen so that the transmission within the bands would be 100%. This means that the amplitude of the data (Sq) should be correct in the different scales. The filter cut-offs in approach B were chosen to produce narrower bands, the transmission of the band-pass filters never got to 100% within the bands. This means that the amplitude data for the scales is not correct. This is a big uncertainty using approach B regarding the amplitude. However, since all bands had the same ratio (1 to 2) it should still be possible to use the amplitude data for relative comparisons between the scales within one analysis. Moreover, the bands were chosen to have an overlap to make sure that no data was lost.

The method detailed in this paper can be divided into two parts:

1. The general method for visualization of texture anisotropy in different scales of observation by separating the roughness data into ranges of scale followed by calculating and plotting the roughness parameters Std, Str and Sq.
2. The filtration method used in the present study for separation of the roughness data into separate ranges of scale. In this case robust Gaussian filters with a certain selection of cut-offs.

It is possible to test the same methodology (point 1 above) with other types of filters. It would be especially interesting to use wavelet filters since the compromise with Gaussian filters regarding the gradual transmission roll-off at the cut-offs and the loss of amplitude caused by narrow bands could possibly be avoided.

5. Synthesis, discussion and future research

In this chapter the synthesis of the results from the previous chapter is discussed in relation to the research questions stated in chapter 1.2. The applicability of the results, the importance of texture anisotropy as well as suggestions for future research are also discussed.

5.1. Methods for characterisation

As discussed in chapter 1.2 a successful method for characterisation would consist of several steps. Surfaces must first be measured then data needs to be manipulated and evaluated. Next relevant parameters are to be calculated and the results should be presented in a meaningful way. Three specific research questions (RQs) were stated:

RQ1: *How can pressing die surface roughness be measured in a suitable way in the context of:*
  a. manufacturing process development?
  b. quality control in production?

RQ2: *What approach is suitable for data manipulation and finding parameters with high relevance?*

RQ3: *How should the surface roughness data be evaluated and results presented in a relevant way?*

Research question 1 is addressed in papers 1, 2 and 5.

For manufacturing process development the measurements will be used to relate surface topography to preceding manufacturing processes or to functional performance. In forming operations, the tribological effects and functions will be working in three dimensions and the surfaces of the die and the sheet may not be equal in all directions. Consequently, for characterisation and understanding of the correlation between surface topography and functional performance, measurements of the surfaces should also be done in three dimensions. The argument is also valid for evaluating the correlation between topography and manufacturing processes since different processes will create surfaces with different textures, different levels of anisotropy etc.

The appropriate level of magnification has to be found in each case. There are often different limitations when measuring surface topography depending on the instrumentation available and the geometry of the sample. With some types of optical instrumentation, for example confocal laser and focus variation, the lateral range and maximum lateral and vertical resolution are usually only available in some given combinations and depend on the selected lens. With interferometry the vertical resolution is independent of the lateral range and resolution. A practical issue encountered when measuring surface topography with many types of instrumentation is that at each level of magnification the instrument will produce a measurement with a fixed lateral range as well as a maximum lateral and vertical resolution. The lateral range has to be large enough to include a number of the largest features of interest to get a representative measurement. At the same time the lateral and vertical resolution must be good enough to detect the smallest features of interest. These contradictory requirements can be difficult to satisfy simultaneously. However, this issue can partly be solved by using stitching where data from neighbouring measurements are merged into a dataset covering a larger area than the individual measurements. However, stitching requires equipment and software with that ability and can introduce some uncertainties into the measurement. It also increases the measurement time significantly.

Since 3D measurements are required when measuring for process development, such measurements on large dies usually require the use of replica. The replication techniques tested in paper 1 work well enough if care is taken to ensure that the original surfaces are clean and that the analysis does not depend on measurements of individual peaks or valleys. For example, the evaluation in paper 1 showed that there were only a few per cent error in Sa (average roughness) between the original surface and the replica.

Instruments for 3D measurements are typically more expensive than 2D instruments. In addition, they are usually not very suitable to use in a workshop for quality control since they often are comparatively large and more difficult to handle. The measurement method has to be simple and easy to use but give good enough results. Consequently, portable and inexpensive 2D instruments are more suitable for quality control in a production environment.

The measurement method has to be simple and easy to use but give good enough results. In paper 2 it was shown that good enough results can be obtained with such instrumentation if some conditions are met. Most importantly, an appropriate measuring strategy must be used and limits for the evaluated parameters must first be established for each combination of cutting tools, cutting data, workpiece material etc.

Research questions 2 and 3 are addressed in papers 3, 4 and 5.

RQ2: What approach is suitable for data manipulation and finding parameters with high relevance?

RQ3: How should the surface roughness data be evaluated and results presented in a relevant way?

In traditional parameter analysis, all scales of topography in surface roughness measurements are evaluated together. With a multi-scale approach, ranges of scales of topography in measurements can be evaluated separately.

A comparison between correlations found in paper 3 using traditional parameter analysis (two parameters with $R^2 > 0.7$) with correlations found using band-pass filters (10 parameters with $R^2 > 0.75$, of which 6 parameters with $R^2 > 0.9$) shows that stronger correlations were found employing the band-pass filters. Similarly strong correlations were found with the parameters relative area and complexity at certain scales of observation in paper 4. This demonstrates that correlations that can be found between a functional parameter of interest and surface topography are dependent on the scale of observation.

The only parameters that correlated reasonably with friction in the study presented in paper 4 can be related to the inclinations on the surface. This suggests that when modelling friction interactions with rough surfaces, the inclinations on the surface should be considered to be more important than the asperity heights. This agrees well with the model developed in ref [23] which uses the slope of the surface together with two anisotropy parameters to predict the frictional response.

Another argument for using a multi-scale approach is that longer wavelengths on a surface tend to have higher amplitudes than shorter wavelengths [8]. So, if the relevant surface texture is constituted by shorter wavelengths it is difficult to characterise with a conventional parameter analysis using for example Sa since the higher amplitudes of the longer wavelengths will dominate the Sa parameter value.

Research question 3 is again addressed in paper 6.

RQ3: How should the surface roughness data be evaluated and results presented in a relevant way?

Surface texture anisotropy has been found to be important for the function of a die surface [23] and it has been observed that texture anisotropy can vary depending on the scale of observation as discussed above.

Therefore, a method to analyse and visualise texture anisotropy as a function of scale is a useful tool when evaluating die surfaces. Such method would be especially useful when analysing surfaces produced with different manufacturing methods, or variations of the same manufacturing method, to make sure that the surface has the required texture properties in the relevant scales.

In paper 6 such a method was developed and discussed together with some alternative methods. One of the alternative methods for multi-scale texture anisotropy analysis is the morphological tree approach described in chapter 3.4.2 and 3.4.3. The morphological tree analysis contains more information and is more detailed than the method developed in paper 6. However, the main advantage of the method developed in paper 6 compared to the alternative methods is that it relatively simple to perform and it uses standard filters and parameters which are already, to a large extent, implemented in available software packages. However, the technique use for filtration could probably be improved, as discussed in the paper and in the last paragraph of chapter 4.3.1, to give even better results.

More aspects of surface texture anisotropy are discussed in chapter 5.3.

5.2. Applicability of methods for characterisation

The methods for characterisation used in the appended papers have been applied to different extents to test their applicability in other related uses. The objective, from the point of view of this thesis, was to relate surface roughness of sample die surfaces to manufacturing processes or to different measures of functional performance. In the two published studies referred to below multi-scale methods were used to complement the conventional roughness parameter analyses and were shown to be helpful to explain more details of the obtained results.

In ref. [68] the authors applied scale-sensitive fractal analysis with the parameters relative area and complexity to characterise the change in topography due to the manufacturing process Machine Hammer Peening (MHP) as a complement to the conventional roughness parameters that were evaluated.

In the study, changes to the surface topography was analysed at different levels of scale using complexity, see Figure 39. At scales where the difference in complexity between the two surfaces does not change (lines are parallel) there has been no change to the topography due to the manufacturing process, at least not in terms of complexity. For example, there is a clear change between the surfaces at the scales around 250.000 μm^2. This relates well to the size of the texture created by the preceding milling process due to the step over. This texture clearly existed on the milled surface but was not visible on the subsequently hammered surface. There is another change staring at around 5000 μm^2 that goes all the way through the smaller scales. This relates to the smaller texture that could be seen on the milled surface but not on the subsequently hammered surface.

The evaluation of the conventional roughness parameters Sq, Sa and Sz also showed a significant difference before and after the hammering process. However, that analysis did not give any information on the lateral size of the texture or textures that were affected, only that there had been a general decrease in roughness. Using a multi-scale approach with scale-sensitive fractal analysis it was possible to find two ranges of scale where the change of roughness had occurred.

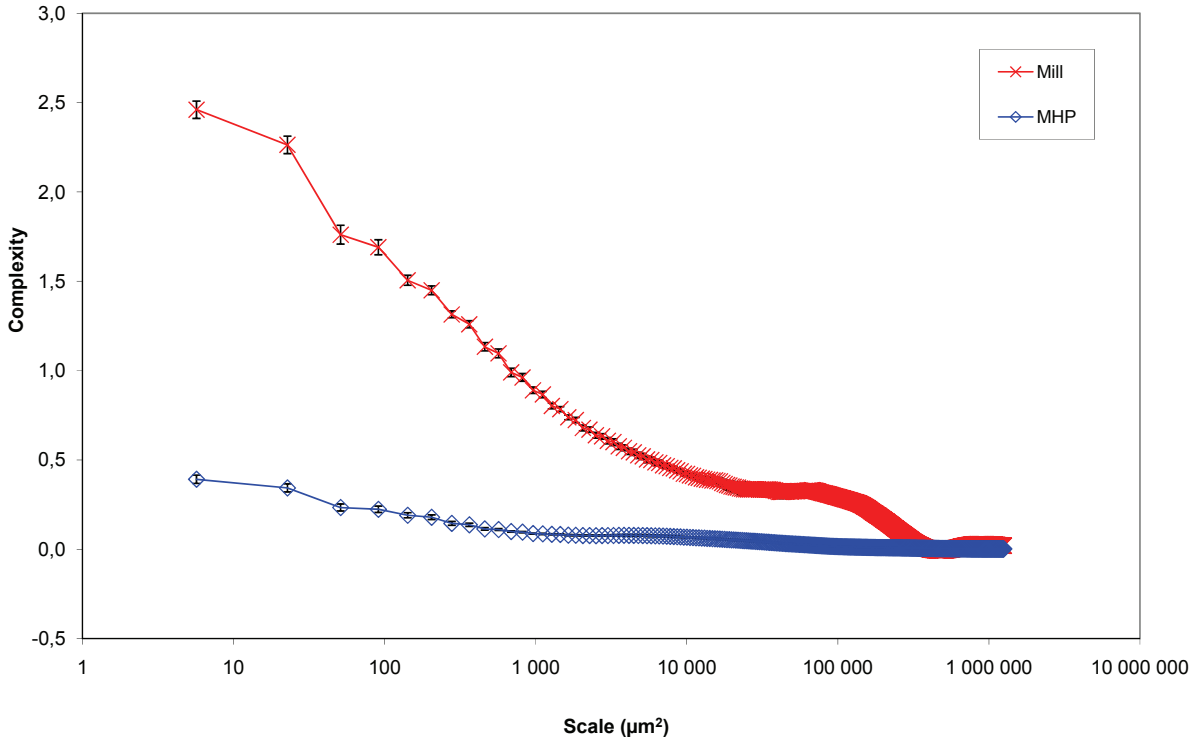


Figure 39: Complexity calculated at 471 scales after milling (Mill) and subsequent hammering (MHP). Mean values of five measurements with 95% confidence intervals. From ref. [68].

The main objective of the study presented in ref. [23] was to develop a model to describe the friction between a steel sheet and a die surface in a BUT (Bending Under Tension) test rig. The surface roughness of the die surfaces was characterised using a number of conventional roughness parameters as well as the multi-scale parameter relative area. A model of the friction was developed using parameters describing the slope of the surface, texture strength and texture direction.

In addition, with relative area it was possible to get some clues regarding the different frictional response depending on the sliding direction of the steel sheet in relation to the texture direction, see Figure 40. When sliding parallel to the surface texture direction the correlation between friction and relative area was strong in the smaller scales and decreased as scale became larger, Figure 40 left. When sliding perpendicular to the texture direction there was a peak in the correlation coefficients at scales around 200 to 300 μm^2, Figure 40 right. This size corresponds to the width of the ridges and dales produced by the polishing and milling processes. The results suggested that lubricant pressure was built up by features of this size when sliding perpendicular to the texture direction.

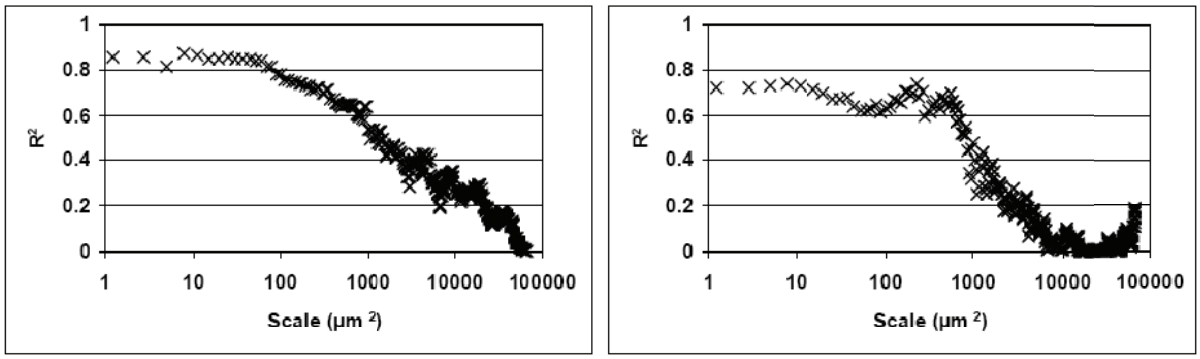


Figure 40: Correlation coefficients (R^2) for correlations between relative area and friction at 471 scales for two groups: texture direction along sliding direction (left), texture direction perpendicular to sliding direction (right). From ref. [23].

5.3. Texture anisotropy

In ref. [23] it was shown that the texture anisotropy (texture strength and texture direction) was influencing the functional performance of the die in a BUT (Bending Under Tension) test rig. The frictional response between the steel sheet and die surface was used as a measure of functional performance in this case. When manufacturing the die surfaces for that study it also became evident that texture strength and texture direction can vary depending on the scale of observation. This idea was developed further in appended paper 6.

When manufacturing a die surface texture, for example a draw radii, using a traditional method such as manual polishing, the texture direction will be perpendicular to the sliding direction of the sheet metal at all, or most, scales of observation, see Figure 41. This is because, for practical reasons, the polishing will most likely be done along the curved shape, which is perpendicular to the sliding direction of the sheet metal. When manufacturing such a die surface using milling the surface texture can be different in terms of both strength and direction depending on the scale of observation. This is because the milling parameters, such as tool diameter, feed direction, feed per tooth, step over etc, can be selected in many different ways. Thus, to be able to analyse die surfaces with milled textures from a functional perspective, the ability to analyse texture anisotropy at different levels of scale is important.

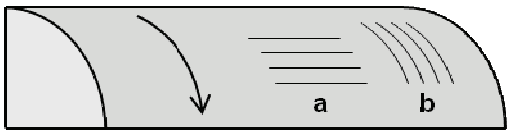


Figure 41: Illustration of a draw radii in a forming die. Sliding direction of sheet metal (arrow), lines showing a texture direction perpendicular to the sliding direction (a), lines showing a texture direction parallel to the sliding direction (b).

Scale-sensitive fractal analysis, with the parameters relative area and complexity, is unfortunately not sensitive to texture anisotropy. For example, a surface's relative area is unchanged when it is rotated 90 degrees in lateral space or inverted in vertical space. To be able to use the parameters relative area or complexity from scale-sensitive fractal analysis in a reasonable way to evaluate correlations between surface topography and some function or process parameter one has to be sure that either the texture direction is similar for all roughness measurements or that the texture direction does not influence the function or is influenced by the process parameter. For the scale-sensitive fractal analysis in ref [23] the surfaces were divided into two groups depending on texture direction and analysed separately, see Figure 40.

With scale-sensitive fractal analysis there are other possible analyses than the area-scale analysis such as length-scale analysis. Using length-scale analysis it is possible to evaluate texture anisotropy in a 3D measurement. With this method relative length is calculated and compared in different directions, thereby showing texture anisotropy. The method is further described in described in chapter 3.4.2. However, this method only evaluates the texture anisotropy in one specific scale of observation, not in all available scales. If the method was extended to do the anisotropy analysis in all available scales simultaneously, such as the area-scale analysis, it would probably be a very good complement to conventional parameter analysis and area-scale analysis.

5.4. Future work

The continued research related to this work will be focused in three areas.

- The first is multi-scale analysis using wavelet filtering. This will be tested for parameter evaluations, such as the one performed in paper 3, to find functional bandwidths and parameters with high relevance. It will also be tested for the band-pass filters used for visualisation of texture anisotropy described in paper 6.
- Scale-sensitive length-scale anisotropy analysis is also a promising area for future research. If it is developed to be scale-sensitive similarly to area-scale analysis it will probably be a good complement to conventional parameter analysis as well as area-scale analysis.
- To work with applications of the methods for characterisation of pressing die surfaces in more cases is also a natural future step. This will be done to further develop and validate the methods as well as to improve the understanding of relation between manufacture and function of die surfaces.

6. Conclusions

The objective of this thesis was to develop methods for characterisation of functional pressing die surfaces to enable future manufacturing process development. This was an important step towards the long term aim to improve and streamline the process of manufacturing dies and moulds. The methods for characterisation presented in this work can be used to relate functional performance of die surfaces to their respective surface topographies as well as to relate the surface topographies to the processes used for manufacture. The development of effective methods for characterisation of pressing die surfaces will enable future manufacturing process improvements which will hopefully result in shorter lead times and higher quality in die manufacturing.

The most important conclusions are summarised below:

- Surface roughness measurement of dies with the purpose of manufacturing process development requires 3D data. Replication often needs to be used in these cases since dies usually are too large to bring into a lab measurement equipment. The replication techniques tested in this thesis function well enough if care is taken to ensure that the original surfaces are clean and that the analysis does not depend on measurements of individual peaks or valleys.
- Good enough results can be obtained using a relatively inexpensive handheld 2D profiler for surface roughness measurements for quality control in production if some conditions are met. Most importantly, an appropriate measuring strategy must be used and limits for the evaluated parameters must first be established for each combination of cutting tools, cutting data, workpiece material etc.
- Using a multi-scale approach when analysing roughness data it may be possible to find so called functional bandwidths. With the analysis focused on the functional bandwidth the characterisation is more effective and it is easier to identify roughness parameters which correlates to the functional property or the process parameter of interest. A method for doing this was developed and presented in this work.
- Surface texture anisotropy has been found to be important for the function of a die surface. It has also been observed that texture anisotropy can vary depending on the scale of observation. The method developed in this work to analyse and visualise texture anisotropy as a function of scale can be a helpful tool when evaluating die surfaces. The method can be especially useful when analysing surfaces produced with different manufacturing methods, or variations of the same method, to make sure that the manufactured surface has the required texture properties in the relevant scales.

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