The impact of honing process parameters on the surface quality of cylinder liners

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Abstract

During recent years, legislation regarding emissions and fuel consumption levels for the automotive industry has become increasingly comprehensive. In order for automotive manufacturers to reach the demands, engine friction needs to be reduced. The cylinder liner is considered to be one of the most critical engine components regarding friction and high demands are put their surface texture.

No process has been found to create efficient cylinder liners as good as honing. Honing is an abrasive process, using three simultaneous movements of abrasive stones to remove material and create grooves. Since honing is an abrasive process, analytical prediction of the process outcome is difficult. In order to describe the process, empirical modeling has to be applied.

The objective of this thesis is to, by using design of experiments, understand the honing process in the cylinder liner manufacturing at Scania CV AB and identify key parameters in the process control connected to surface roughness. Furthermore, the aim is to find an optimal setting of the machine to produce the demanded surface texture.

Through screening experiments, five parameters were found to be the most significant in the process. These parameters were then further investigated in an optimization test. The results of this test showed that the plateau honing step was of main importance for the resulting surface texture. The factors with the largest impact were the honing force and number of strokes used in this operation. The results also suggested that the reciprocating speed influences the surface parameters and can be used to decrease the core roughness of the surface without affecting the valley depth negatively. Due to high correlation between surface parameters, compromises need to be made in order to find an optimal setting.

Sammanfattning

Under de senaste åren har lagstiftningen gällande utsläpp och bränslekonsumtion för fordonsindustrin blivit mer omfattande. För att fordonstillverkarna ska kunna möta dessa krav behöver friktionen i motorerna reduceras. Cylinderfoder har identifierats som en av de viktigaste motorkomponenterna när det gäller friktion och hårda krav ställs därför på deras ytstruktur.

Idag är hening den enda bearbetningsmetoden som kan skapa den önskade ytprofilen hos cylinderfoder. Hening är en slipande bearbetningsmetod som använder tre simultana rörelser av slipstenar för att bearbeta ytan och skapa repor. Eftersom hening är en slipprocess så är det svårt att analytiskt förutspå utfallet i processen. För att beskriva processen måste istället empirisk modellering användas.

Syftet med detta examensarbete är att, med hjälp av metoder för försöksplanering, skapa en förståelse för heningsprocessen i Scanias cylinderfodertillverkning och identifiera nyckelparametrar i maskinstyrningen kopplade till ytstrukturen. Vidare så är målet att hitta optimala inställningar av maskinen för att producera foder med den rätta ytstrukturen.

Med hjälp av screeningexperiment identifierades fem parametrar som de mest signifikanta i processen. Dessa parametrar undersöktes sedan ytterligare genom ett optimeringstest. Resultaten från detta test visade att platåoperationen är viktigast för den resulterande ytstrukturen. Kraften och antalet slag i detta steg var de parametrar som visade sig vara mest signifikanta. Resultaten visade också på att slaghastigheten i platåsteget påverkar ytan och att den kan användas för att minska ytjämnhetens kärndjup utan att minska ytans daldjup. Eftersom ytparametrarna är sammankopplade i hög utsträckning måste en optimering innefatta kompromisser emellan dem.

Acknowledgements

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1. Introduction

Scania is one of the world’s leading heavy duty truck manufacturers. In 2014, Scania had a 15.1 percent share of the European market with 33,800 units sold [1]. The company also produces buses and coaches as well as industrial- and marine engines [2]. Scania is a global company with production sites in Europe, Asia and Latin America.

Figure 1.1 Scania truck

Trucks, buses and coaches produce five percent of the total emissions of greenhouse gas within the EU. During recent years, the legislation regarding emissions has become more comprehensive. The European commission aim to reduce the greenhouse gas emissions from transport by 60 percent from 1990’s level by 2050. Nitride oxides and particulate matter are some of the emission types that are covered by the European legislation. The allowed amount of emissions has been significantly reduced during recent years as can be seen in Figure 1.2.

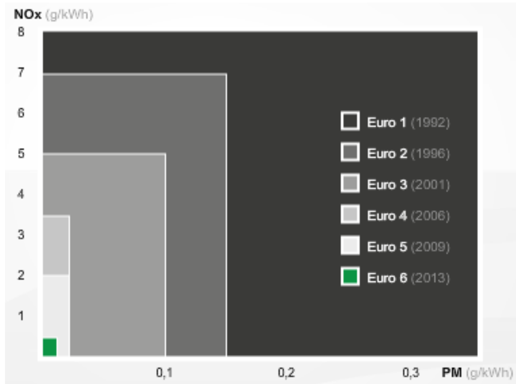


Figure 1.2 Emission legislation development for nitride oxides (NOx) and particulate matter (PM) [3].

In order for modern trucks to keep up with the emission legislation, the manufacturers have to produce engines with a low level of fuel consumption and low emissions [4]. A large part of the work is focused on systems for exhaust treatment but there is also a lot to be gained from optimizing other engine components. One of these components is the cylinder liner.

1.1 Cylinder liners

In a Scania truck engine, one cylinder liner is mounted inside every cylinder. Figure 1.3 shows a cross sectional view of a Scania engine with the piston-cylinder liner ineraction visualized.

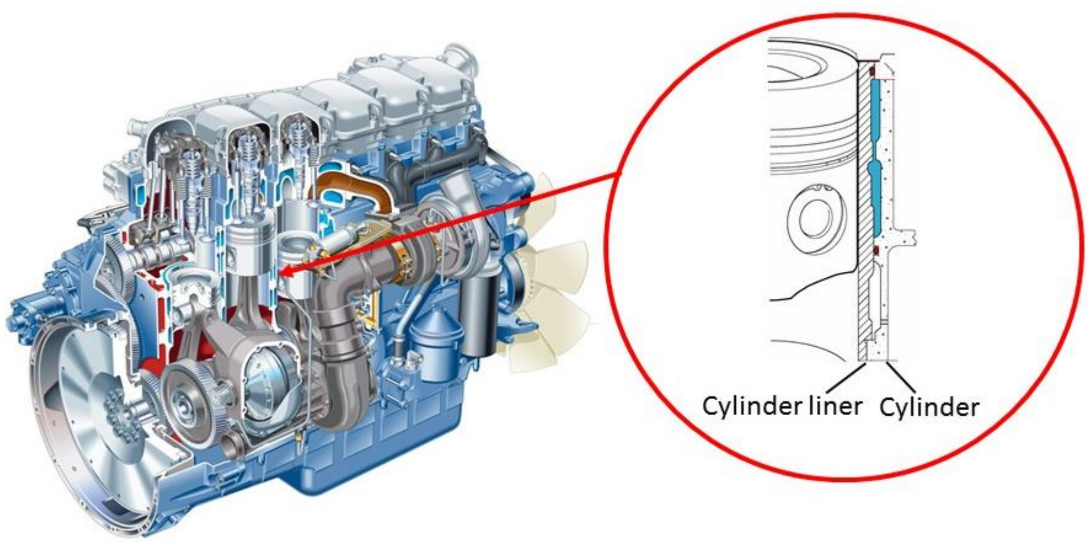


Figure 1.3 Scania engine

As can be seen in the figure, the piston runs within the cylinder liner. The detailed view also shows that the space between the liner and the cylinder is filled with cooling water.

Cylinder liners are among the most critical engine components when it comes to oil consumption and frictional losses. Researchers have estimated that as much as 40% of the frictional losses in an engine arise from the friction between the cylinder liner and the piston ring [5]. Therefore, high demands are set on the surface finish of the liner. In order for the liner to hold a satisfying amount of oil and to reduce friction between the liner and the piston ring, the surface has to consist of a mixture of deep enough valleys and smooth plateaus. The scratches in the surface make out a crosshatch pattern and the angle between the scratches is called the crosshatch angle. How the crosshatch pattern is distributed within a cylinder liner can be seen in Figure 1.4.

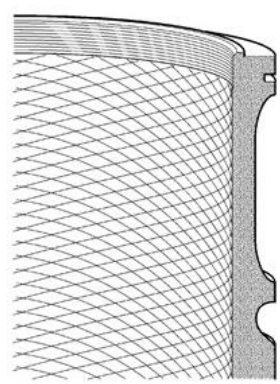


Figure 1.4 Section view of a cylinder liner with crosshatch pattern

The angle of the crosshatch pattern also has a great influence on the lubrication of the liner. The manufacturing method used to achieve these functional surfaces is called honing [6].

1.2 Honing

There are several types of honing used in the manufacturing industry. These include gear honing and surface honing among others. In this thesis, honing refers to longitudinal honing. Longitudinal honing is an abrasive method for processing inner, cylindrical surfaces and is commonly used in the manufacturing of cylinder liners. The process is known for producing products with high geometrical accuracy and surface quality [7]. Honing is, and will continue to be the only process that can create the demanded surface texture as well as the crosshatch pattern needed in cylinder liners [6]. During the honing process a tool called honing head, which is equipped with abrasive stones, is moved through the cylinder bore. The head is subject to a rotational and reciprocal speed throughout the operation. While the head is traveling through the cylinder, the honing stones are simultaneously pressed against the bore wall and are thereby removing material. This will create the characteristic crosshatch pattern on the surface, which will serve as channels for lubrication.

In order to create the desired crosshatch pattern with the right honing angle, there needs to be a correlation between the rotational- and reciprocal speed. This relationship is described in Equation (1).

$$\alpha_h = tan^{-1}\left(\frac{v_a}{v_r}\right) \tag{1}$$

where α_h is half the crosshatch angle, v_a is the reciprocating speed and v_r is the tangential speed of the honing stones. A graphical representation of the crosshatch angle can be seen in Figure 1.5.

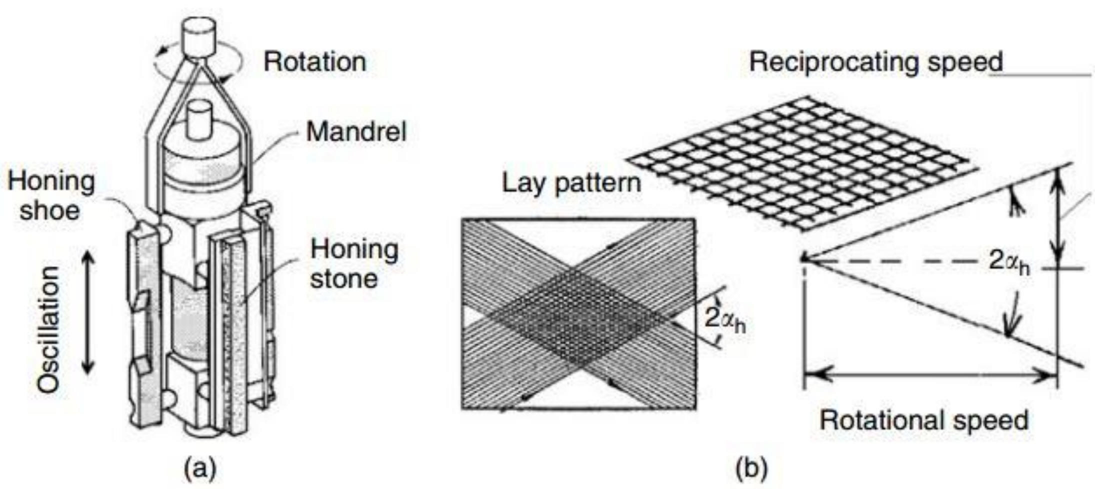


Figure 1.5 a) Honing head with rotational- and linear movement. b) Crosshatch pattern and crosshatch angle [7].

The radial feed is achieved by actuators pressing a rod equipped with cones against the stone attachments. Through this movement, the stones are moved towards the bore surface. The force needed to press the rod downwards can be generated by hydraulic- or electrical actuators. Figure 1.6 shows the principle of the two different expansion mechanisms.

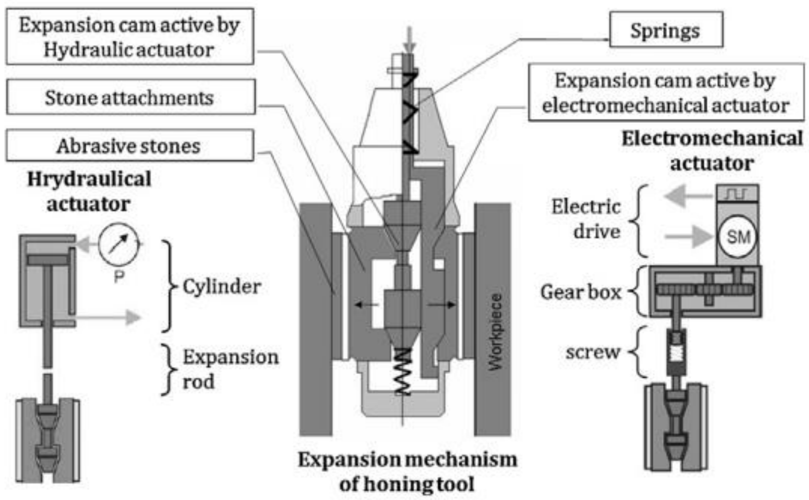
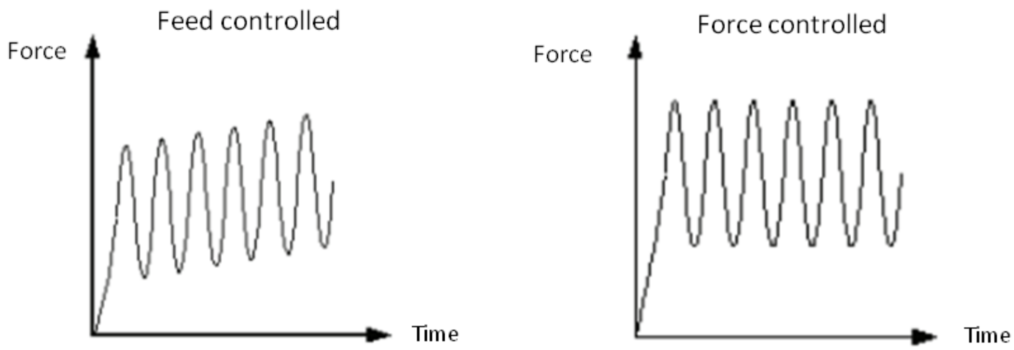


Figure 1.6 The different types of feed control in honing [8].

When using an electromechanical actuator, the feed is constant which results in a constant material removal rate. It is an open loop controlled system, given user-defined feeding steps. With the hydraulic servo actuator on the other hand, the stone is fed with a constant pressure resulting in a variation in the material removal rate. Unlike the electromechanical system, a hydraulic actuator is a closed loop control system where the feed will be controlled to stay within a user-defined interval. This makes it possible for the machine to automatically compensate for operation variations, such as tool wear.

In the beginning of the honing process, the surface roughness is relatively high from earlier operations. This will result in a low amount of force needed to press the stone against the surface with a constant feed. As the surface roughness decreases, the amount of material to be machined will increase. This will in turn, when using constant feed, lead to an increase in force needed to press the stones outward. The result will be an increase in force throughout the process. By controlling the material removal with constant force, the machining system is more stable and less variation in surface roughness can be detected compared to processes with constant material removal rate. The process force varying over time can be seen in Figure 1.7.



a) b)

Figure 1.7 Process force over time for constant feed (a) and constant force (b) [9].

As can be seen in the figure, there is a variation in process force in both principles of control. The controls with constant feed however have an overall increase in force over time. The joint variation is connected to the longitudinal deformations that occur during the axial oscillation of the honing head. This oscillation causes a relative movement between the feeding cone and tool body, resulting in the variation in force between workpiece and tool [9].

1.2.1 Honing stones

The honing stone contains three material components, abrasives, bonding material and additives. The abrasives can be divided into two groups, conventional and super-abrasives. Conventional abrasives are ceramics such as aluminum oxide and silicon carbide while super-abrasives are made out of diamond or cubic boron nitride [10]. Diamond grains have been proven to better resist wear and create a better surface than other abrasives [6]. The size of the abrasive grain varies depending on the required surface texture and metal removal rate [7]. Larger grain sizes will increase the material removal rate but lead to a poor surface quality [11].

The purpose of the bonding material is to fix the abrasive grain during the honing process. The bonding materials can be of vitreous, organic or metallic types. The bond should wear at a suitable rate in respect to the abrasive and be able to resist the large centrifugal forces that can occur during the honing process [10]. It should also enable worn grains to be removed so that new, sharp, cutting edges appear [6]. By doing so, the stone is regenerated and its ability to cut is restored. This means that the stone is able to sharpen itself during production [12].

The honing stone is one of the major factors connected to the high variability in honing processes in general. The grains are inconsistently distributed in the honing stone, resulting in a variation in number of cutting edges in contact with the workpiece surface. There is also a size difference between different grains in the stone, which will create a variance in depth of cut. Other variations that can occur, in both honing and grinding in general, are material side flow, built up edge phenomena and vibrations as well as the risk of grains detaching from the stones and then embedding in the material [13]. During studies made by Malkin and Lee, a great inconsistency in stone behavior was identified. Differences were found between different stone sets as well as from stone to stone [14].

Honing stone size and geometry can vary depending on the application. Long stones in the honing tool have a better ability to create a good cylindricity of the bore. The material of the honing stone will decide the need for forming the tool before production. If a ceramic abrasive is used, no forming is needed because the stone will rapidly adapt to the bore surface. If the stone is of a super-abrasive type, a forming is required where the stone surface is grinded into the radius wanted on the bore [11].

1.2.2 Honing oil

A critical part of the honing operation is the honing oil. Additional to the lubrication, the honing oil contributes by cooling the workpiece and honing tool as well as by flushing the swarfs away from the cutting process [7]. By keeping the process at the right temperature, both cylinder liner and stone can be preserved to ensure quality and lower production cost [6]. The most common fluid used is mineral oil. This is due to its high viscosity and high flash point. Another benefit of the oil is that it does not irritate the skin of the machine operators [7].

1.3 Surface characteristics

In order to produce cylinder liners for engines with high demands regarding emissions and fuel consumption, the surface need to be characterized. There are multiple surface parameters that can be used to define the surface. Some of the most frequently used are the mean parameters. The most common one is the average roughness, Ra. This is, as the name states, an average of the surface roughness over the sample length [15]. The parameter is described according to Equation (2) [16].

$$Ra = \frac{1}{l}\int_0^l \left|Z(x)\right| dx \tag{2}$$

Where $Z(x)$ is the distance between the profile curve and the mean line and l the sample length. Another parameter that is widely used in the industry is the R_q or RMS parameter. This is the root mean square of the surface roughness over the sample length and is calculated according to Equation (3) [15] [16].

$$Rq = \frac{1}{l}\int_0^l \left|Z^2(x)\right| dx \tag{3}$$

The root mean square is an important statistical parameter because it represents the standard deviation of heights of the surface profile. The mean line is defined so that the sum of squares of the deviation from the line is equal to zero. These are the traditional surface parameters used but like all average measurements they have drawbacks. None of the mentioned parameters can distinguish between peaks and valleys, profile characteristics critical to the function of the cylinder liner. Figure 1.8 describes multiple surfaces, with completely different characteristics but with the same average roughness.

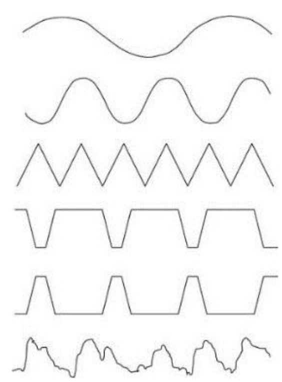


Figure 1.8 Different surfaces with the same average roughness. Modified from source [17].

In order to better define and describe surface characteristics, the parameters described can be replaced by parameters describing the distribution of peaks and valleys on the surface. In this way, process control can be more accurate and it is possible to produce parts with the demanded surface texture. Parameters found to best correlate with engine performance are the R_k -family parameters. The parameters are graphically explained in the Abbott-Firestone curve or area bearing curve [6]. By drawing an equivalent straight line, the peak-, valley- and core areas can be identified. The line is calculated for the central region of the curve which includes 40 percent of the measured profile. The line is drawn where these 40 percent has a minimum gradient. From the curve, five parameters characterizing the different parts of the surface can be obtained. The parameters are described in the standard ISO 13565-2 as follows.

- Core roughness depth – R_k: Depth of roughness core profile.
- Material portion - M_{r1}: Material portion, a level in percent(%), determined from the intersection line that separates the protruding peaks from the roughness core profile.
- Material portion - M_{r2}: Material portion, a level in percent(%), determined for the intersection line that separates the deep valleys from the roughness core profile.
- Reduced peak height - R_{pk}: Average height of the protruding peaks above the roughness core profile
- Reduced valley depths - R_{vk}: Average depth of the profile valleys projecting through the roughness core profile.

The mentioned equivalent line intersects with material ratio at 0 and 100 percent. By plotting horizontal lines from these intersection points to the vertical axis, R_k, M_{r1} and M_{r2} can be obtained. The core roughness is the vertical distance between the lines and the material ratios are the intersection between the plotted lines and the curve. The peak height and valley depth can then be calculated as the height of two right-angle triangles that have the same area as the peaks and valley respectively. The triangle corresponding to the valley depth has M_{r2} as its base while the peak height has M_{r1}. The illustration of the parameters can be seen in Figure 1.9.

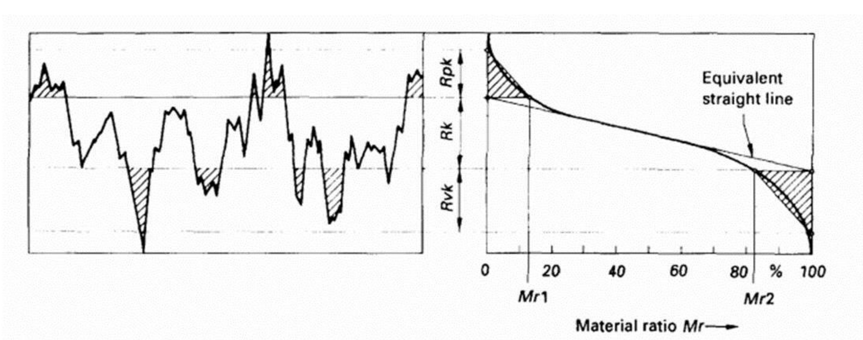


Figure 1.9 Abbott-Firestone curve explaining roughness parameters [18].

In order to use these parameters, the Abbott-Firestone curve needs to be shaped like the letter S. According to the standard, this is the case for a honed surface [18]. Close relationships between these parameters and engine performance has been reported in multiple studies [6].

The R_k -family are profile measuring parameters, showing the surface roughness in two dimensions. There are however some drawbacks to using two-dimensional parameters when defining a surface. Surface characterization can be controlled with profile parameters but in order to be able to predict and understand the function of the surface three dimensional surface parameters are needed. When using a profile parameter, it can be hard to understand the true topography of the surface. If an areal parameter is used instead, the surface can be better understood. An areal measurement has the ability to detect whether the surface has discrete pits or valleys, a difference which is significant to the function of the surface. An areal measurement also has more statistical significance because of the increase of data-points in the measurement.

There are areal parameters equivalent to the R_k -family. These parameters are S_k, S_{pk}, S_{vk}, S_{r1} and S_{r2} and they correspond to the profile parameters with the same suffix. There are also corresponding areal factors for the mean parameters [19].

Lastly, there are extreme parameters that can indicate different variations in the surface that the previously mentioned parameters cannot. The maximum roughness of the surface can sometimes be of importance. Maximum roughness, R_z, is defined as the height difference between the deepest valley and the highest peak over a sample length [16].

1.4 Objectives and research questions

In order to achieve a good and stable quality output for any machining operation a deep understanding of the process is important. Since honing is an abrasive process, it is hard to analytically predict the resulting quality. To increase the understanding, empirical modeling is required. In Scania's manufacturing of cylinder liners, honing is the final machining operation. The control of this honing process is based on experiences as to what has been working historically. Previous tests have however not been based on any experimental design but have consisted of changing one factor at a time until desired results are reached. This has resulted in some technicians and operators having a sense as to which parameters to change when a certain measurement is out of tolerance. The process is however complex and a deeper understanding is needed.

The purpose of this thesis is to reach a deeper understanding of the process control in Scania's honing of cylinder liners and how it affects the quality of the produced parts. The research questions to answer in the project are:

- Which honing process parameters have the largest impact on the resulting quality?
- How do these parameters affect the quality and how do they relate to each other?
- What is the most efficient way to control the process?

The aim is to clarify both how the process should be controlled in order to achieve certain outcomes on the measured quality and to explore how to find the optimal control settings.

1.5 Delimitations

There are many variables influencing a machining system and thereby the outcome of a process. In the case of honing, the resulting quality of the cylinder liner depends on the machine process control, the honing stones used and their grain sizes, their wear, machine structure, vibrations etc. To investigate all possible variables influencing the resulting quality would however be very difficult and time consuming. This thesis will only be focused on the machine controls. Figure 1.10 shows the scope of this thesis within the green marking.

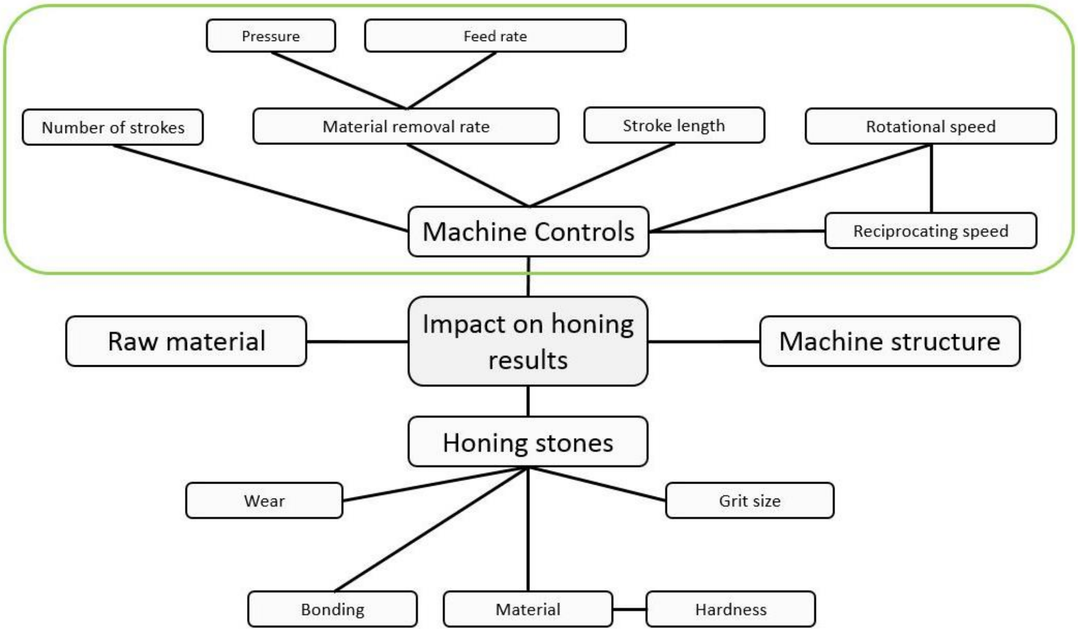


Figure 1.10 Variables affecting the honing results with the scope of this thesis within the green marking

Furthermore, there are several aspects to consider when it comes to the quality of the cylinder liners. There are both geometrical tolerances and surface tolerances that have to be met. The main focus in this thesis will be on the surface quality. The geometrical tolerances will however be considered to some extent. This is since it is important that the geometrical tolerances are met even though the focus of the optimization lies on the surface quality. The actual experiments and the theoretical study will however not take the geometry into account.

2. Problem description

As described in Chapter 1, a cylinder liner has to have a surface texture with deep grooves complemented with a large bearing area. The peaks of the surface should be cut off during machining to reduce the need of running in. A desired surface texture is described in Figure 2.1 with an enlarged picture of the surface profile.

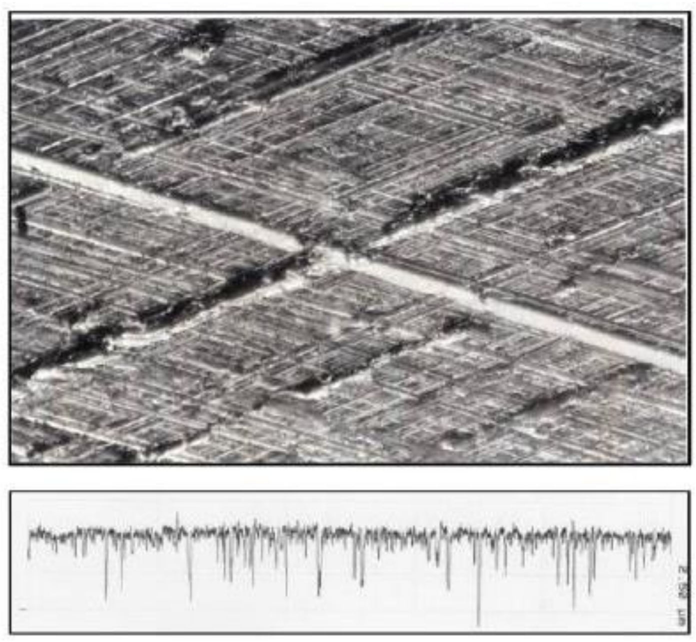


Figure 2.1 Desired surface texture of a cylinder liner

Scania has described the ideal surface texture using R_k-family roughness parameters. The deep valleys result in a high R_{vk}-value. The M_{r2}-parameter should also be relatively high, due to the desire to have a large amount of material in the core of the surface. The large bearing area wanted is presented by the slope of the central part of the Abbot-Firestone curve. The desired surface should have as low slope as possible, i.e. a low R_k-value. Lastly, a low R_{pk}-value is wanted, since this represents the peak height of the surface. The surface parameter M_{r1} is not used when defining the surface texture. This is since it is not considered to have any significant connection to the function of the product.

In practice, the described surface can be difficult to produce. There are relationships between the different parameters that are hard to define. This can result in that compensation for deviating values in one surface parameter will change the outcome of other parameters as well. As stated in the objectives, a greater understanding of the process is desired in order to know more about these relationships and which machine parameters should be controlled.

2.1 The cylinder liner machining

The raw pieces used in the cylinder liner manufacturing are created through centrifugal casting. Before being introduced to the cylinder liner manufacturing, the liner is rough machined by the supplier. This includes drilling of the bore and rough turning to obtain the desired geometry. Once introduced to the production line it is processed in three steps before being washed and packaged. The different processes and their order are shown in Figure 2.2.

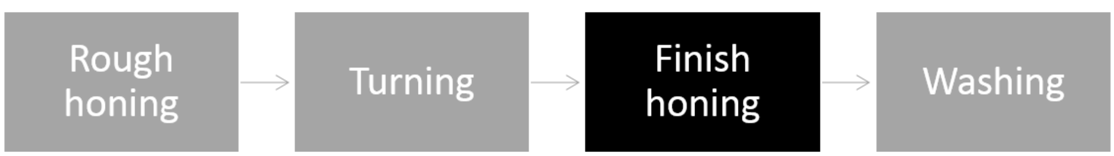


Figure 2.2 Schematic of the processing of cylinder liners

In the rough honing process, the inner cylindrical surface of the cylinder liner is processed. Honing stones with a large grain size, 151 µm in diameter, are used and the aim is only to increase the inner diameter and improve the geometrical accuracy. The surface texture created in this step will be removed from later process stages. Next, the critical outer surfaces of the cylinder liner are turned in order to ensure proper sealing when it is mounted in the engine block. The surfaces turned are identified in Figure.2.3.

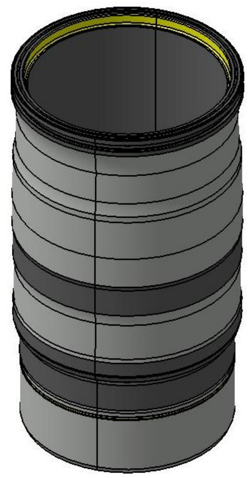


Figure.2.3 Illustration of outer- (marked with dark) and inner (yellow) turned surfaces of a cylinder liner.

The third step is the finish honing step, which is the one investigated in this thesis. This step will be described in detail in section 2.2. When the liners have been readily processed, they are washed in order to remove residual oil. All liners are then visually inspected and packaged.

2.2 The finish honing process

The finish honing operations are performed in a vertical honing machine manufactured by Nagel. There are three different operations included in the honing process, all with different objectives. The different steps in the finish honing process are coarse-, base- and plateau honing. These operations are performed in three different spindles. In the coarse honing operation, honing stones with a large grain size are used which enables a high material removal rate. The feed of the stones is controlled with an electromechanical actuator, which presses the stones towards the liner surface with a constant speed. The machining of the bore will continue until a predetermined diameter is reached. The diameter is measured with a gauge using air pressure. This process is important for the resulting geometry of the cylinder liner but the surface created has to be removed by the later operations to avoid too wide valleys.

After the coarse honing operation, the cylinder liner is transported to the next spindle. During the process the product is transported and machined while in the same fixture. There are a total of seven fixtures used in the finished honing. Each fixture contains two rubber sleeves, one upper and one lower. The cylinder liner is clamped in the fixture by an oil pressure that builds up between the fixture and the rubber sleeves. The sleeves are thereby pressed against the liner and hold it in place. The oil pressure is kept throughout the whole honing operation.

The second machining operation, conducted in spindle two, is divided into two steps. The first step is feed controlled, set to remove a certain amount of material. The second step in the base honing is a force controlled operation, using the same honing stones as step one. The duration of the operation is controlled by the number of strokes. These two steps will create the grooves with a crosshatch angle, characteristic for honing. The honing stones consist of grains with a medium diameter.

Before the final operation the cylinder liner is cleaned using a brush. The objective is to remove residue from the earlier operation in order to reduce the risk of surface deformation. The residue can consist of both swarfs from the cutting process and grains broken off from the honing stones.

The last machining step of the honing process is plateau honing. The objective of the operation is to remove the peaks of the surface, reducing the demand for a running-in period once the engine is in use. The plateau honing operation is quite different compared to earlier stages. A small grain size and a relatively low pressure is used. The low pressure is used because of the fact that no grooves are created in the operation. Since only peaks are removed, no crosshatch pattern needs to be created. This means that the rotational- and reciprocating speeds are uncorrelated. As for the second step in the base honing, the duration of the plateau honing is controlled by the number of strokes. An overview of the machining steps in the finish honing process is presented in Table 1.

Table 1. Overview of the finish honing process.

	Spindle 1 Coarse honing	*Spindle 2 Base honing*	*Spindle 2 Base honing*	*Spindle 3 Plateau honing*
		Step 1	*Step 2*	
Grain size	Large	Medium	Medium	Small
Actuator type	Electromech.	Electromech.	Hydraulic	Hydraulic
Process duration set by	Diameter	Diameter	No. of strokes	No. of strokes

During the operations the honing stones will be worn and deteriorate. The stones will both become smaller in size and the grain will become dull, reducing the cutting ability of the stone. The machine is able to compensate for the geometrical wear of the stone while the sharpening of the grain is generated by the stone itself as described in section 1.2.1.

The final step in the finish honing is an online measuring station. At the station, the diameter of the liner is measured and communicated to the operator. The operator can then compensate the allowance between spindle one and two in order to get the correct diameter on finished part.

3. Methodology

Since honing is an abrasive process, it is extremely difficult to analytically predict the outcome of the process. Therefore, empirical modeling is required to understand the process and predict its output [6]. Based on this, experimentation was an important part in understanding and optimizing the honing process of interest. All experiments were designed using the software MODDE [20]. MODDE was also used to analyze the data collected through the experiments.

In order for these experiments to be relevant, the first part of the work was to reach a basic understanding of the process to make sure that significant variables were tested. A literature study was conducted to gain theoretical knowledge of honing. The literature study was focused on both honing as a process and on previous studies made on how honing process parameters affect the surface quality.

Since the actual outcome of the honing process is so hard to predict analytically, it is not certain whether the outcome of a certain honing process is the same as the outcome of a previously studied process. Therefore, the current control of the process was also mapped. This mapping was performed by talking to technicians and operators working with the cylinder liner manufacturing. The machine manufacturer, Nagel, was also contacted in order to resolve some uncertainties.

With the combined knowledge from these sources, the parameters of interest that should be further investigated with experimentation were identified. A visual representation of the sources of information used to identify relevant parameters is found in Figure 3.1.

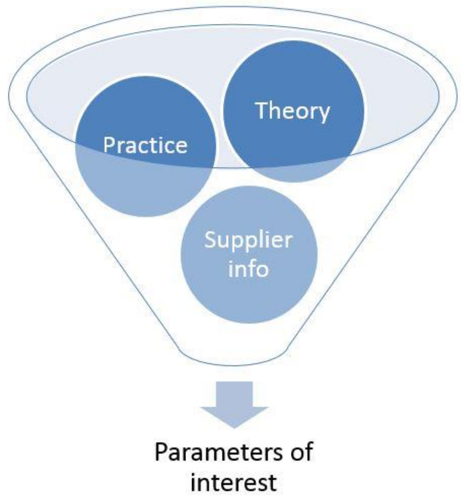


Figure 3.1 Sources of information used to identify parameters of interest.

The parameters that were considered interesting for further investigation were explored with experiments. These experiments were carried out in several steps. The first tests had the purpose to identify which parameters affect the surface quality the most. Once the most influential parameters had been identified, these were subject to further experimentation with the purpose to find optimal working conditions for the machine to achieve satisfying and stable surface quality. All experiments were planned using Design of Experiments methods. Some theory on Design of Experiments is found in the next section. Information on how the actual tests were developed and performed is found in Chapter 5.

3.1 Design of Experiments

An experiment can be defined as "a test or series of tests in which purposeful changes are made to the input variables of a process or system so that we may observe and identify the reasons for changes that may be observed in the output response" [21]. These input variables, which are changed in order to study the resulting effects, are called factors [22].

Statistical Design of Experiments involves careful experimental planning in order to, through experimentation, collect the data needed for drawing valid and objective conclusions [21]. In other words, it is a working methodology used to make the most out of experimentation, i.e. to get the best possible results with respect to the objective of the experiments and available resources [23].

In order to continuously improve a process, it is crucial to understand its behavior. Therefore, industrial experimentation is often focused on exploring and understanding how the process variables affect the output performance characteristics. Figure 3.2 shows a representation of a process and components considered in an experiment.

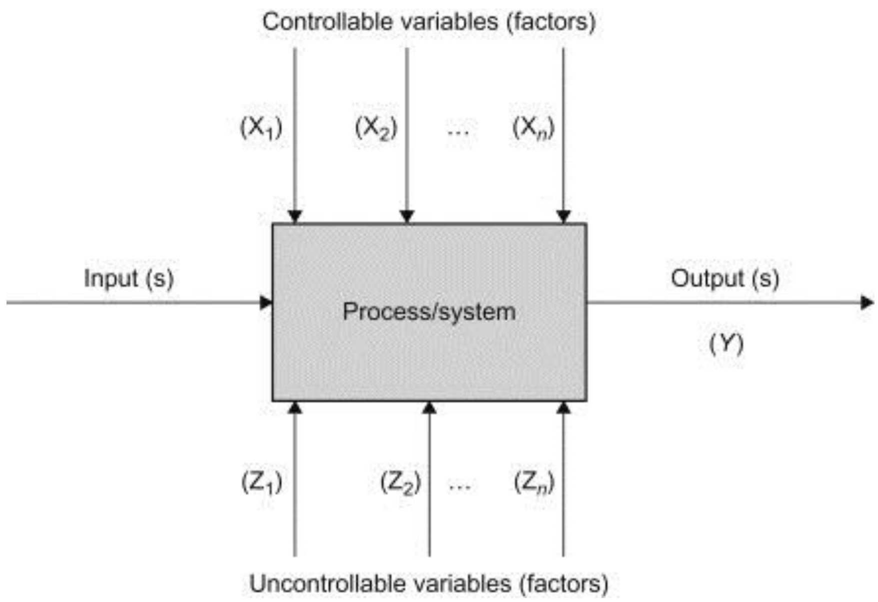


Figure 3.2 Schematic of a process with inputs, outputs and variables represented [23].

The controllable variables are parameters which can be controlled by the experimenter. These can include factors such as machine control parameters or type of tool that is being used. The uncontrollable variables are factors which may affect the process outcome but are not controllable by the experimenter. These may include factors such as ambient temperature and humidity. The output is the measured characteristics which are used to evaluate the performance of the process [23]. The experiments might have different objectives including [21]:

- Identifying which factors have the largest impact on the output
- Finding the optimal value for the factors X in order to keep the output Y near its nominal value
- Finding the values for the factors X where the variability in Y is small
- Finding the values for the factors X where the impact of the uncontrollable factors Z is as small as possible

3.1.1 Benefits of DOE

Even though DOE today is a widely known concept which provides efficient methods for performing these kinds of experiments, it is not always used for industrial experimentation. Two commonly used approaches for industrial experiments are the Best-Guess approach and the One-Variable-At-a-Time approach [21].

The best-guess approach involves that the experimenter first reasons which should be the optimal settings for the process and then performs a test to see if the output is within the tolerances. If it is not, another guess is made and new tests are performed. This method can often work quite well if the one performing the experiments has a lot of knowledge and experience of the process. There are however, two major disadvantages to the approach. The first is that even an experimenter with the best knowledge of the process could go on trying different settings for a long time without finding any optimal settings. The other one is that an experimenter might settle for settings that are only good enough once they are found. This is since it is impossible to know what the best possible settings will yield in advance.

The One-Variable-At-a-Time (OVAT) approach means that the experimenter changes the levels of one factor at a time while keeping the other factors constant. A series of tests with different levels of the factors are performed before the outputs are measured and plotted in graphs. There are some disadvantages to the OVAT approach as well. This type of experiments does not give reliable result, they require large quantities of time and resources in order to gain small amounts of information or false optimum conditions on the process [23]. One reason for OVAT experiments not giving reliable results is that they do not consider any factor interactions. Interaction is when the effect from changing one factor to a certain value is not the same regardless of the settings of the other factors. When this type of joint factor effects occur, the factors that are interacting with each other cannot be evaluated individually [24].

In order not to miss interactions and thereby misinterpreting the results, carefully planned factorial experiments should be conducted. This type of experiments makes a much more efficient use of the data [21].

3.2 Factorial experimentation

Factors can be either quantitative or qualitative. Quantitative factors can be set in numerical values. In a machining process, quantitative factors can be rotational speed, depth of cut and such. For quantitative factors it has to be decided which range of the settings should be used and how these are to be controlled and measured during experimentation [23]. Qualitative factors are those that cannot be measured in numerical values. An example of a qualitative factor is supplier of raw material. All factors which impact the process will be tested at different levels. For a qualitative factor, such as the raw material supplier, the different suppliers will be the different levels of the factor. If the test includes two different suppliers, then this factor has two levels. For a quantitative factor the experimenter might have a span within which the factor settings are to be tested. The levels here represent values within this span. Usually experiments are performed with two or three levels of every factor. In a three level factorial experiment, every factor is tested at its lower, upper and middle value of the investigated value span.

In factorial experimentation, the different levels of the factors are tested in several different combinations. Each test with a specific combination of levels is called a run [25].

3.2.1 Full factorial designs

Factorial designs can be divided into full factorial and fractional factorial designs. In a full factorial experiment, all levels of the factors investigated are tested in all possible combinations. If k factors with two levels are to be investigated in a full factorial experiment, this experiment will consist of 2^k runs. 2^k is often also used as a symbol to represent two level full-factorial designs [22]. For a three level factorial design the number of runs needed is instead 3^k. The number of runs needed for a three level full factorial design increases quite fast with an increase in the number of factors. For example, a full factorial design for investigating 5 factors with two levels requires $2^5=32$ runs while a full factorial design with three levels requires $3^5=243$ runs. Since two level factorial designs require relatively few runs per factor it is the most economical way to investigate a process with many factors [22].

A test which includes two levels of all factors cannot identify any nonlinear effects on the process. Thus, using a two level factorial design implicates the assumption that the effects of these factors are approximately linear over the testing range.

One way to detect tendencies regarding curvature in the model is to add center points to the two level experimental design. Center points are experimental runs with all factors set to a medium level. A graphical representation of a 2^3 factorial design with three center points is presented in Figure 3.3.

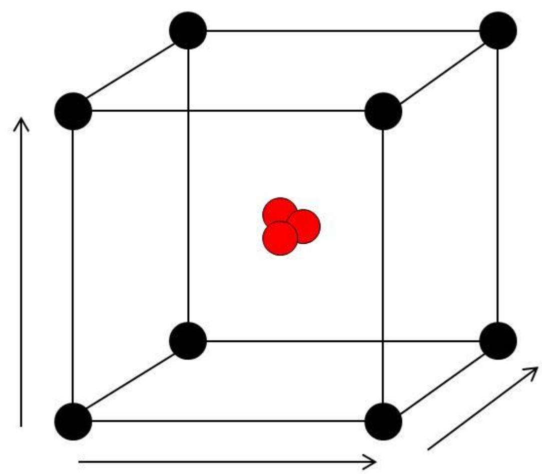


Figure 3.3 Graphical representation of a 2^3 factorial design.

Every axis in the figure corresponds to a factor and the corner points represent high and low values of these factors. The center points are represented by the red points in the middle of the cube. Adding several center points, preferably as the first, middle and last run in the experimental design can also allow the experimenter to comprehend how stable the investigated process is [23].

3.2.2 Fractional factorial designs

If there are many factors which might influence the investigated process, even a 2^k experiment might result in a large number of runs. In these cases fractional factorial designs are often used. In a fractional factorial experiment design, only a fraction of the runs required for a full factorial experiment is performed. For example, if five parameters are to be investigated, a two level factorial design would require 2^5=32 runs. If the experimenter wishes to explore these parameters with only eight runs, i.e. a one-fourth fraction of the 32 runs, this is called a quarter fraction of the full factorial design. Fractional factorial designs are regularly referred to as 2^{k-p} designs where the p stands for the design being a $\left(\frac{1}{2}\right)^p$ fraction of a 2^k design. Thus, the quarter fraction of the 2^5 design is referred to as a 2^{5-2} design since $\frac{1}{4} = \left(\frac{1}{2}\right)^2$ [25].

Resolution

The resolution of an experimental design displays the confounding patterns in the design. Confounding refers to when the influence of a factor cannot be estimated independently. This means that an effect might be observed from the analysis of the test responses but that it is not possible to tell which of, for example two factors have affected this response. These two factors are then confounded with each other. The design resolution reveals the order of confounding of the main effects and interactions for a designed experiment. Resolution is an important tool for deciding what fractional factorial design to use for a problem. For these types of experiments, designs of resolution III, IV and V are of great importance.

- In a resolution III design, no main effect is confounded with other main effects. There is however, confounding between main effects and two-factor interactions. Two-factor interactions may also be confounded with other two-factor interactions.
- In designs of resolution IV, no main effects are confounded with each other or with any two-factor interactions. Two factor effects though, are confounded with each other.
- In resolution V designs, no main effects are confounded with each other or with any two- or three-factor interaction effects. Two-factor interactions are however, confounded with three-factor interaction effects [23].

The resolution of a design is denoted by a Roman numerical subscript. For example a quarter fraction factorial design with five parameters tested at two levels is of resolution III and is thereby denoted by 2_{III}^{5-2}.

3.2.3 Randomization

There are always several uncontrollable factors affecting the outcome of a process. These factors can be for example be humidity, human factors, power surges and machine wear over time. The impact of such factors cannot be fully controlled or eliminated but there are ways to minimize the risk of them disturbing the experiment results. One of these methods is randomization. Using a randomized run order for the experimental runs allows the experimenter to spread out the effect of the uncontrollable factors and thereby the noise in the process [23].

For example, in a non-randomized experimental design all runs with the high level of a certain factor might be performed in a row. If the humidity in the factory increases after half of the experiments and affects the outcome of the process, the data analysis might suggest that this variation is due to the change to the lower level of this factor. This can be prevented by using randomization. If instead, the runs are mixed with high and low levels of every factor spread out, the effect of the change in humidity will also be spread out on several settings of the factors. Thereby the risk of misinterpreting the results is lowered.

3.2.4 Screening tests

Since conducting a full factorial test with many factors requires many runs and thereby takes a lot of resources, the first step in industrial experimentation is often to identify which factors affect the process outcome the most. This is regularly done through a screening test which is commonly performed as a 2-level factorial experiment [23]. The factors that, through the screening tests, are found to be of significance to the process output can then be subject to further investigation through optimization tests.

3.2.5 Optimization tests

By conducting an optimization test, the best settings of the machine can be applied in aspect of selected responses. In order to generate the optimization point, a wide set of parameter combinations have to be understood. When conducting optimization tests, three level full factorial experimentation can be applied. This kind of test will however, as mentioned in section 3.2.1, generate a large number of test runs. Due to this fact, this test is not always the most effective way of identifying model curvature, one of the goals of optimization. A two level factorial test can, as mentioned in section 3.2.2, identify curvature tendencies with the use of center points. By combining this sort of test with further, carefully selected, experimental points a more effective design can be created [21].

One design type, generated from a two level full factorial test are central composite designs. These designs are preferred when the objective of the experimentation is to optimize a process. They can generate a relatively high resolution, depending on number of factors used, and at the same time be reasonable from a practical point of view. There are two different composite designs that can be applied. A graphical representation of these designs is presented in Figure 3.4.

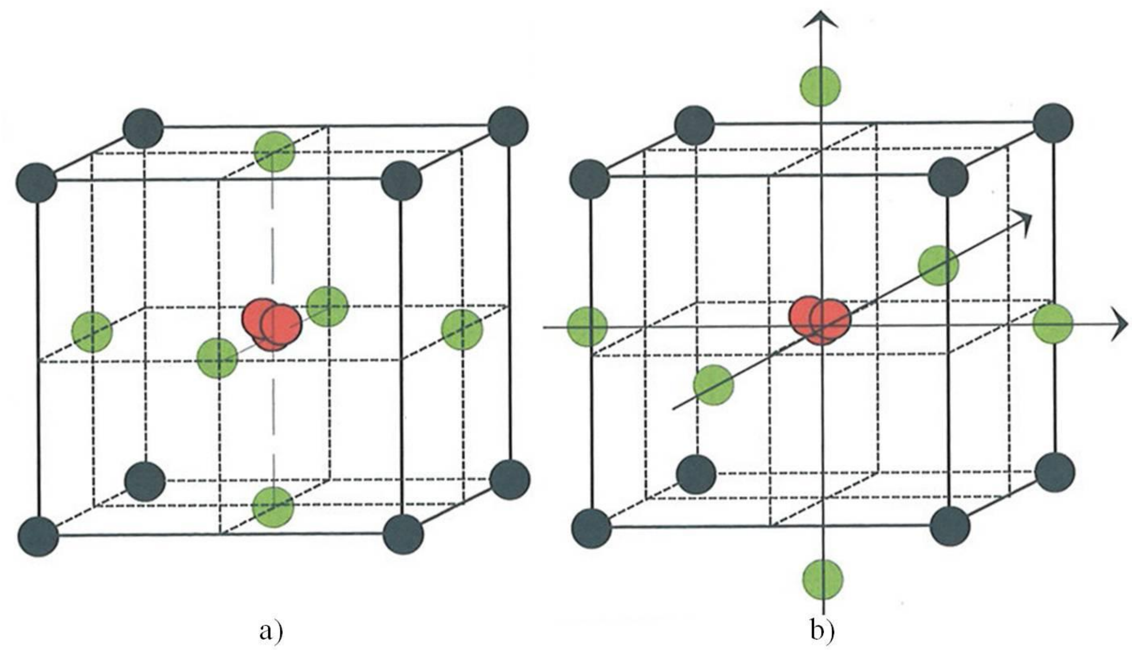


Figure 3.4 Graphical presentation of three factorial designs CCF (a) and CCC (b) [26].

Design b in the figure, a central circumscribed (CCC) design, corresponds to a full two-level factorial design when using two to four factors. The design considers five levels per factor by placing test points outside of the experiment matrix. The other design is a central composite face-centered (CCF) design. This design is similar to the CCC but only considers three levels of each factor. Due to the higher amount of levels per factor, CCC has a better ability to detect curvature in the data compared to the CCF design. This makes the CCC model slightly superior in theory. The CCF design is however more practical which often is a desired quality in a design [26].

3.3 Data analysis

There are several tools that can be applied when validating a model. In the software used, two parameters are considered to be of greater importance than others. One parameter is the goodness of fit, denoted R_2. This parameter indicates how well the chosen regression model fits the collected data. The goodness of fit has a numerical value between zero and one, with zero being no model at all and one a perfect model. An issue with the parameter is that its value can be increased by merely acquiring more data points. Due to this fact, the parameter needs to be complemented with other tools. The most important parameter in regression analysis is the goodness of prediction, Q_2. This parameter gives a value of the models capacity to predict future outcomes, which is the ultimate goal of any study.

Other important tools connected to regression analysis are model validity and reproducibility. As can be derived from the name, model validity indicates how well the model, fits to the collected data. This is based upon a lack of fit test.. Reproducibility is a value of to what extent the model can be repeated. This is based on the replicates of the test. Less variation between replicates increases the value of reproducibility. Range, target values and recommendations for the different parameters are presented in Table 2.

Table 2 Summary of fit parameters.

Parameter	*Range*	*Target value*	*Recommendation*
Goodness of fit, R_2	0 - 1	Maximize	No more than 0,2-0,3 units between R_2 and Q_2.
Goodness of prediction, Q_2	$-\infty$ - 1	> 0,5 – Good model > 0,9 – Excellent model	No more than 0,2-0,3 units between R_2 and Q_2.
Model validity		> 0,25 – Good model	
Reproducibility		> 0,5 – Good model	

When creating a model in MODDE, a summary of fit plot is created, visualizing how the model fulfills these criteria. An example of such a plot is presented in Figure 3.5.

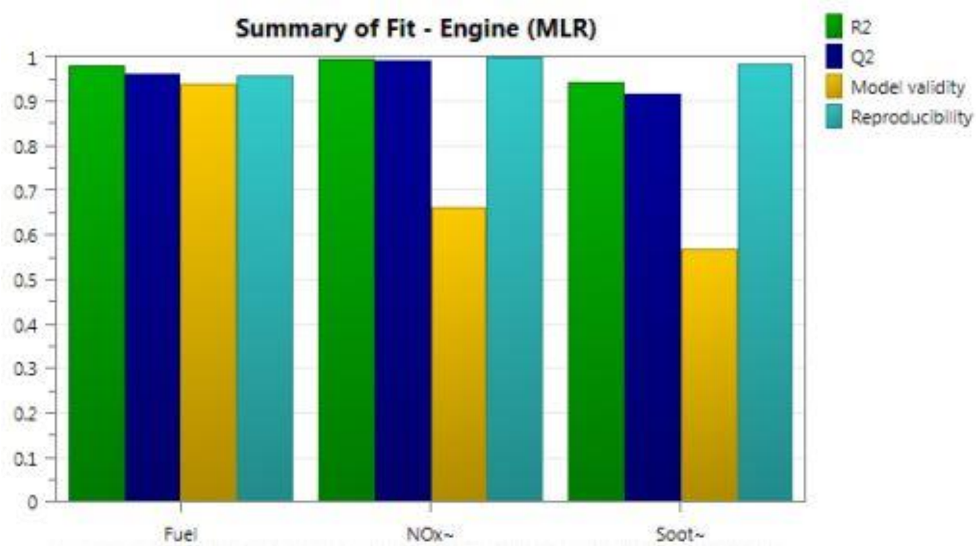


Figure 3.5 Example of a summary of fit plot [27].

The tools mentioned above are the ones that every model made for prediction should pass. There are however complementing tests that can be performed to further analyze the model. One test that should be conducted is analysis of distribution. If a non-normal distribution is found, transformation may have to be conducted due to the fact that the software MODDE applies models based on normal distribution [26].

When displaying the results in MODDE, effect plots can be used. These plots visualize the effect of the different factors on the response parameter. An error bar is included, showing the 95% confidence interval. An example of an effect plot is shown in Figure 3.6.

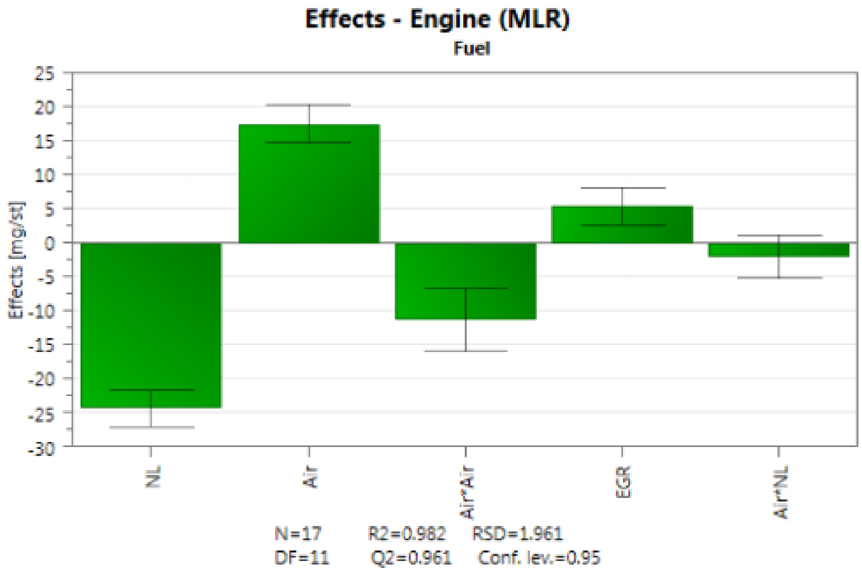


Figure 3.6 Example of an Effect plot [27].

The factors are sorted by the magnitude of their impact on the response parameter with a descending order from left to right. When an error bar extends past zero, the factor impact can be deemed as negligible for the response and removed from the model. If however the model Q_2 value is decreased by such an action, it should be reversed [27].

4. Parameters affecting the process

As mentioned in section 3.1, the first part of DOE is to map and understand the process which is to be investigated. In order to recognize which parameters might influence the honing results a pre study was conducted. The data collected was from a combination of previously performed studies and operator experience.

4.1 Theory

In a honing process there are numerous parameters that can be varied in order to control the machining procedure. Multiple studies have been carried out on the subject on honing process control with the aim to understand the effect on resulting quality. By analyzing literature on previous studies, some parameters were found to be of larger interest than others. These parameters are presented in the following sections.

4.1.1 Honing pressure

Several of the previous studies have identified the honing pressure to be a parameter of importance when it comes to surface roughness. There are however some differences in the findings regarding in which of the honing operations the pressure affects the surface the most. In a study by Kanthababu et al., experiments were conducted in order to analyze the effect of process parameters on surface roughness. In this study, the surface texture was characterized with R_a and R_k -family values. It was found that the pressure is of great importance in all steps, i.e. coarse-, base- and plateau honing. The authors also state that the surface constructed in the first spindle is of minor importance for the resulting surface roughness since this profile is removed in later operations [28].

The findings of Kanthababu et al. regarding the importance of honing pressure are supported by a number of other reports on the subject. Vrac et al. performed a study on the honing of grey cast cylinder liners, comparing the effect of the process parameters pressure, feed and cutting speed. In this study, the authors compared the surfaces produced in aspect of average roughness. It was found that honing pressure is the main parameter affecting the condition of the final surface. The study also presents the formula found in Equation (4), describing the specific cutting pressure, P_{hd}.

$$P_{hd} = \frac{A_p \cdot p_p}{A_h \cdot \tan\beta} \tag{4}$$

where A_p is the surface area of the honing machine piston, p_p is the hydraulic oil pressure in the piston, A_h is the honing head metal working surface and β is the honing tool angle [29]. A greater cutting pressure results in a rougher surface. This is since the grains of the honing stones are pressed further into the workpiece. The increase in pressure will also increase the depth of the grooves [30].

In a report by Buj-Corral et al., it is presented that honing pressure is the most influential machine control parameter affecting the surface. Of all parameters investigated in the study, grain size of the honing stones proved to have the largest impact on surface quality. This is because the larger stones create larger and deeper grooves, increasing overall roughness [13].

A study by Rosén and Thomas also confirms the theory of pressure being of great significance. This paper suggests that the pressure in both finish- and plateau honing affect the results. A low pressure during base honing complemented with a high pressure during plateau honing is stated to create a favorable surface [31].

The only research found, that contradicts the statement of pressure influencing the surface roughness throughout all processes is performed by Pawlus et al.. In this study the authors found that the pressure in the base honing has a great effect on the surface condition. The surface parameters R_k and R_{vk} were found to be proportional to the surface pressure, i.e. an increase in pressure will increase R_k

and R_{vk}. The report does however deem the plateau honing pressure as insignificant and states that its effect on the resulting surface is negligible [32].

4.1.2 Honing time

Another parameter found relevant is the honing time. Pawlus et al. identified the plateau honing time to have a major influence on the resulting surface texture. The findings were that with an increase in honing time, a smoother surface will be created [32]. This theory is confirmed by Klocke who also states that a longer honing time will create surfaces with lower roughness. The decrease in surface roughness is non-linear with a rapid reduction rate in the beginning which is then leveled out over time, according to Figure 4.1. This is since the stone will first come in contact with the peaks of the surface, creating a very high pressure on those peaks. When the peaks are removed, the pressure will stabilize as a result of the honing stones coming in contact with the core of the surface. The decrease in pressure will decrease the rate of which the stones can remove material [11].

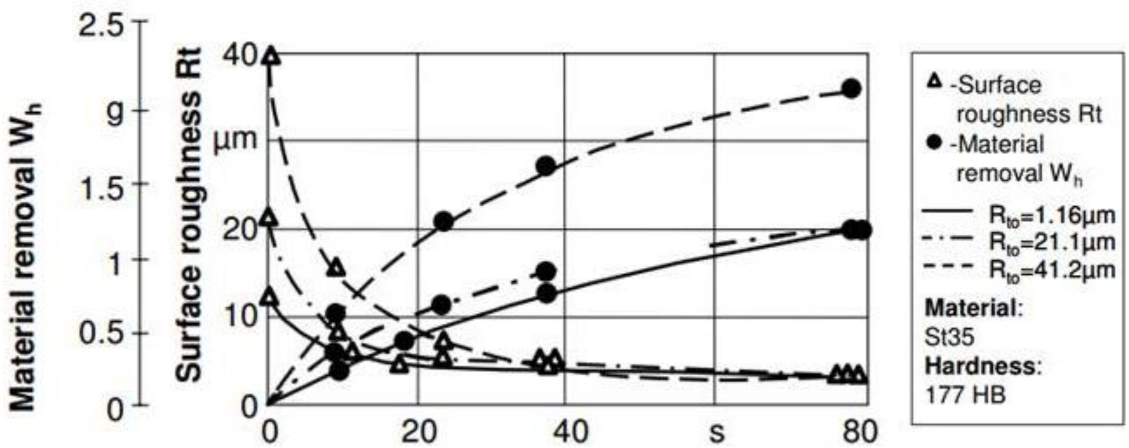


Figure 4.1 The effect of honing time on surface roughness [11].

The honing time was also examined in the previously mentioned study by Kanthababu et al.. It was found that the base honing time has an effect on the surface texture. In this stage it mainly affects the M_{r2}-parameter and according to the study, the highest M_{r2} is found with medium honing time [28].

By increasing the honing time, the number of rotations of the honing tool increases. A larger number of rotations has also been proven to reduce the roughness of the surface. The surface structure after a certain number of tool rotations can be seen in Figure 4.2.

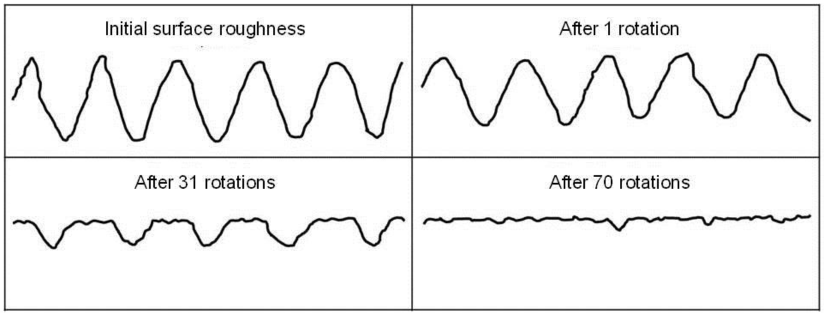


Figure 4.2 Surface roughness after different number of tool rotations. Modified from source [11].

4.1.3 Number of strokes

Instead of setting the honing time, the duration of a honing process can in some cases be controlled by the number of strokes. Regardless of the controlling factor, the number of tool rotations is varied with the process duration in combination with the rotational speed. Because of this, the resulting surface of the cylinder liner is dependent on the number of strokes in the same way as with the honing time. In one study it is stated that no fewer than four strokes should be used in the plateau honing process. It has been found that it is after this point that a change in surface texture can be identified. There is also an upper limit to the number of strokes that should be used. When using too many strokes, the surface will have a low amount of deep valleys and a too large plateau area. This will decrease the ability of the surface to retain oil and will thereby result in poor lubrication properties of the cylinder liner. The previous mentioned study showed that no more than seven strokes should be used in order to prevent this from occurring [33].

4.1.4 Cutting speed

According to the analyzed literature, honing pressure and honing time are the two parameters with the largest effect on surface texture. There are however several other parameters that have been found to be of significance even if their effects have not been confirmed in as many studies. One of these parameters is the cutting speed. The cutting speed is the resulting vector from the rotational- and the reciprocal speed. These speeds are connected to each other according to the formula for the crosshatch angle, described in Equation (1). In the earlier mentioned study by Buj-Corral et al. tangential speed was identified to have some effect on the surface roughness. It was found that with high and medium grain sizes roughness decreased when increasing the tangential speed. This is due to the fact that the cutting operation is easier performed at higher speeds. When using a smaller grain size on the other hand, an increase in tangential speed results in higher roughness. A higher rotational speed increases the vibrations in the tool, generating a higher roughness of the workpiece surface. It is important to note that the experimenters varied the rotational speed while keeping the reciprocating speed constant, thereby neglecting the crosshatch angle [13].

The reciprocating speed of the honing tool has also been subject to some studies. Kanthababu et al. found the reciprocating speed to be an important parameter in the plateau honing process, mainly affecting the M_{r2} surface parameter. Another study showed that the cutting speed, as a function of the reciprocating speed, is the most influential parameter when using a large grain size. In this case the grain size was 181 µm, a grain size used when conducting rough honing. With smaller grain sizes however, pressure was considered to be the main influencing parameter. [34]. It has also been presented that an increase in cutting speed results in a decrease in surface roughness. The roughness decreases in a non-linear way. Larger changes in roughness were detected at changes in lower speeds than in high speeds.

Except for its effect on surface quality, the cutting speed has major influence on material removal rate of the process. An increase in cutting speed will increase the removal rate, decreasing the cycle time for the operation. It will however also result in an increase in wear on the tool [11]. The wear itself will also affect the condition of the surface. An increase in wear i.e. a blunting of the cutting stone, will decrease the ability of the stone to cut the material. The result is a deterioration of the surface, mainly affecting peak- and core surface parameters [35].

4.1.5 Acceleration

The acceleration of the honing head has a great effect on the geometry of the cylinder liner. It also has an effect on the surface roughness, mainly at the lower turning point. At this point, the reciprocating speed will vary while the rotational speed is constant. This results in a deviation from the crosshatch pattern. In a study conducted by El-Mansori et al., it was found that surface roughness decreases with an increase in acceleration [36].

4.2 Current process control

The current control of the process parameters is based on a combination of recommendations from the machine supplier and operator experience. As stated in section 2.2, the machining in the finish honing is carried out in three different spindles of which the process in the second spindle is divided into two steps.

4.2.1 Parameters controlled

The parameters controlled in the machine are the feed rate, force, number of strokes, stroke length and amount of material to be removed in the process. In the first spindle, both feed rate and force are controlled. The force is a limiting factor in order to reduce the risk of machine overload. If the force reaches a certain user defined level, the feed will be set to the corresponding value. With the feed used in current production, the force limit is always reached. This indicates that a too high value of the feed rate is used.

The force is used for compensation in the second step in spindle 2 as well as in spindle 3. This is consistent with analyzed literature which states that force is the parameter with most influence on surface quality. When controlling the force in the machine at hand, no numerical value can be set. Instead the operators set a percentage value that represents a fraction of the maximum machine force. The machine has a specification regarding the maximum pressure that can be generated in the system. The friction of the system is however unknown, making it impossible to calculate machine force in the spindle using Equation (4).

The number of strokes used during the honing process is controlled in the second step in spindle 2 and in spindle 3.

4.2.2 Machine compensation

In the present production there are two major approaches when dealing with surface deviations. One is compensating for deviating R_{vk}- and M_{r2}-values and one for deviating R_{pk}- and R_k-values. When compensating for R_{vk}-values, the operators have found that the M_{r2} will be affected in an inverse manner. This means that a compensation for a low R_{vk} will decrease the M_{r2}-value. The R_k- and R_{pk}-parameters on the other hand, are according to the operators connected in such a way that if one is increased, the other one increases as well.

Since R_{pk} and R_k only have an upper limit, the compensation for these parameters are due to high values. These are mainly corrected by increasing either the force or the number of strokes in spindle 3. One of the machine parameters is chosen at a time and there is no standard procedure for when a certain one of them is used. The work sequence for compensation of deviating R_{pk}- and R_k-values can be seen in Figure 4.3.

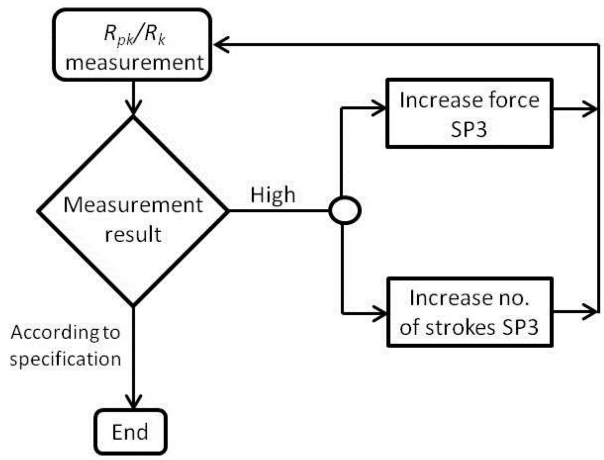


Figure 4.3 Machine control when compensating for deviating R_{pk} / R_k .

The R_{vk} and M_{r2}-parameters have, as earlier stated, an upper and a lower limit. Therefore, compensation has to be made both for high and low values. When compensating for a high R_{vk}, the operator controls that the machine leaves the correct amount of material from spindle 1 to spindle 2 for machining. If this is not the case, the operator compensates by increasing the allowance left from spindle 1 to spindle 2. If however the allowance is sufficient, the usual action is to either increase the force in spindle 2 or the number of strokes in spindle 3. One parameter is changed at the time until the problem is corrected. This is consistent with the OVAT approach, mentioned in section 3.1.1, which has been proven to be flawed. High R_{vk}-values are rarely occurring in production and therefore these compensations are seldom performed. Low R_{vk}-values on the other hand appear more frequently. There are some disagreements regarding the compensation of low R_{vk}-values. Some operators focus on the rough honing operation to make sure that a suitable surface is left from spindle 1 to spindle 2. The theory is that if the surface texture is too smooth, the second spindle will not be able to create grooves deep enough. The other opinion is to focus on the later stages in the process. The work sequence for compensating for low R_{vk}-values are described in Figure 4.4.

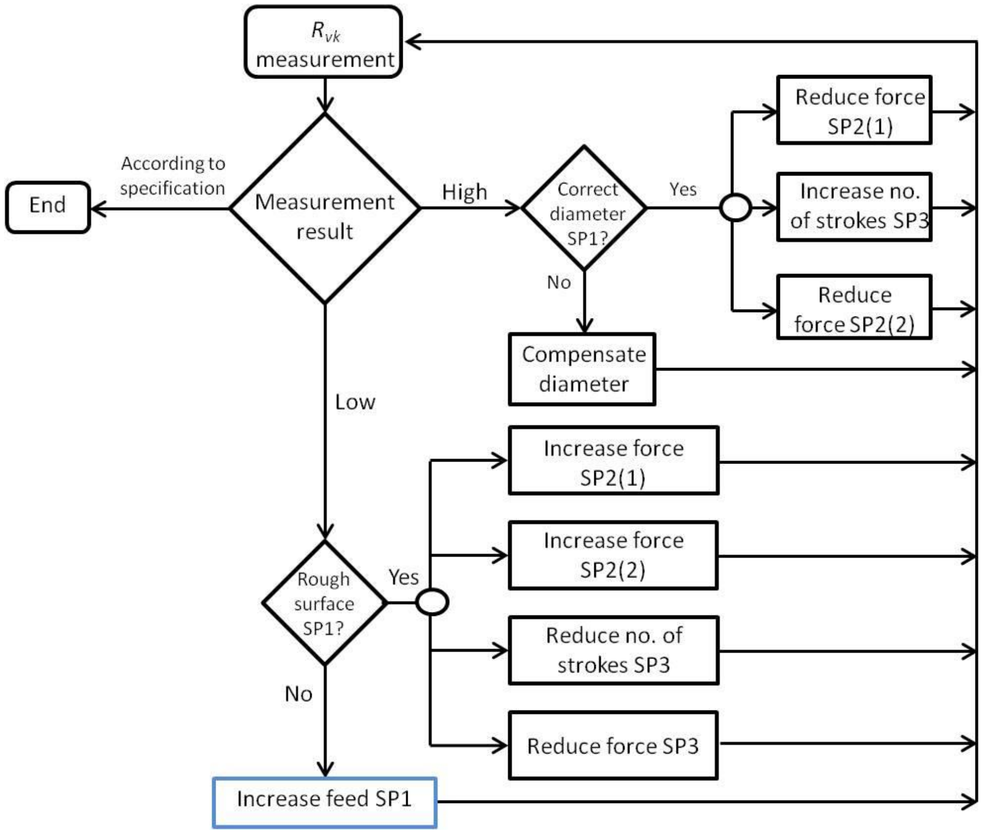


Figure 4.4 Machine control when compensating for deviating R_{vk}.

The blue color indicates that there is no consensus among operators. As mentioned, R_{vk} and M_{r2} have an inverted relationship. This means that the actions used to increase R_{vk} are also used to decrease M_{r2} and vice versa.

4.3 Parameters to be investigated

Several parameters are of interest for investigation. In order to not exclude any parameters prematurely, as many as possible should be included in the tests and then reduced. A factor not taken into consideration is the acceleration of the honing head. According to the analyzed literature, the factor mostly affects the lower part of the cylinder. During the tests, this part of the liner will not be subject to measuring which makes an investigation of the parameter excessive.

As stated in 2.2, the duration of the process is controlled differently in the different stages of the process. Because of this, the honing time will not be subject of investigation as a single parameter but instead be a result of a combination of factors. In step one in the base honing and in the coarse honing, parameters influencing the material removal rate will affect the resulting honing time. In the second stage of the base honing as well as the plateau honing, the number of strokes will be the defining factor.

An overview of the parameters to be investigated is presented in Figure 4.5.

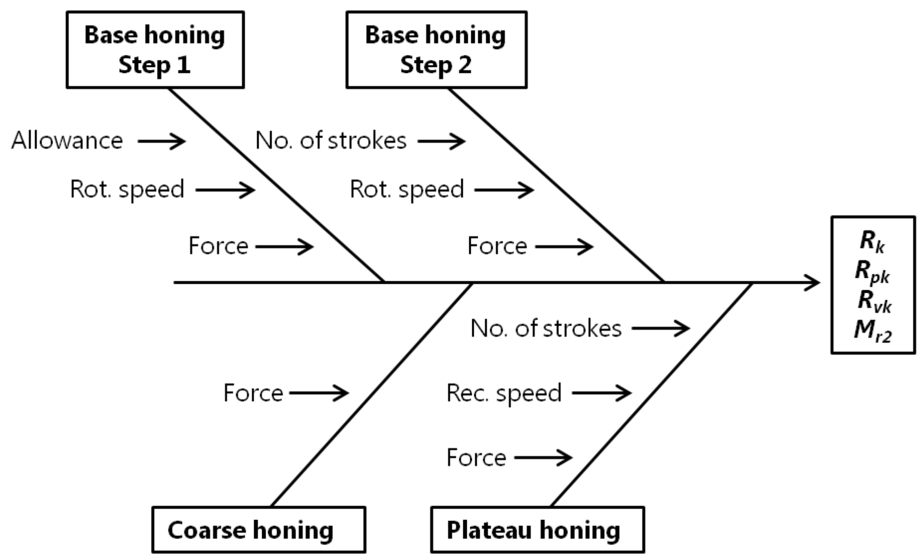


Figure 4.5 Parameters to be investigated with experimentation.

5. Experimental procedures

In order to identify which process parameters influence the surface texture as well as in what way they do, experiments were performed. All experimental designs were created in the software MODDE [20] which was also used for analyzing the data. The tests were conducted using grey cast iron cylinder liners. The matrix of the material was pearlitic with no more than five percent ferrite. The honing oil used was Castrol Honilo 981. The honing stones were diamond abrasives supplied by Nagel. Different grain sizes were used for different spindles. The sizes are presented in section 2.1.

Measurements were performed using a perthometer, MahrSurf XR1. The tool was equipped with a diamond stylus with a radius of 2 µm according to ISO 3274 standard. The resolution of the tool was 7 nm in height and 0,5 µm in length according to the same standard. The measurement speed was 0,5 mm/s. During the measurements ISO 4288 was applied, which among other things results in a measuring length of 5,6 mm and an evaluation length of 4 mm. The measuring tool is calibrated according to ISO 12179.

Every liner was measured on six predetermined heights distributed on a vertical line. The number of lines measured in each liner was determined for the different experiments and can be found in the experimental details. Figure 5.1 illustrates the distribution of measuring points along one line in the cylinder liner.

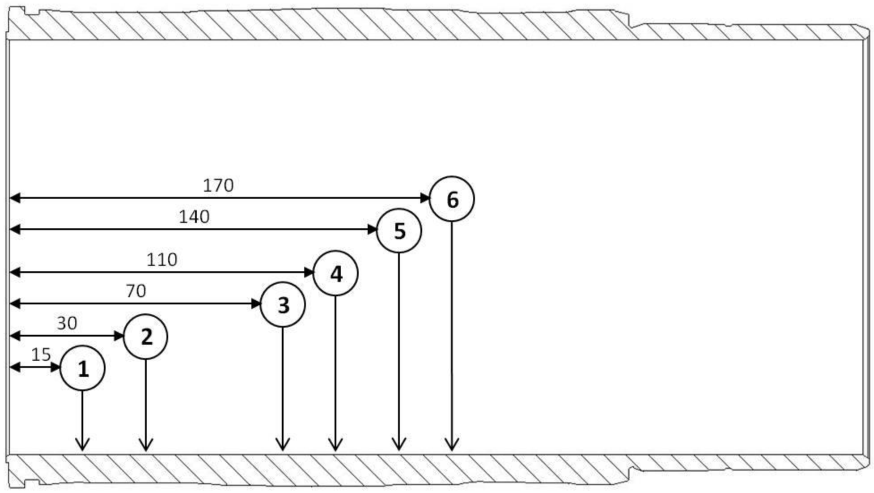


Figure 5.1 Overview of the different measurement points on the liner [mm].

5.1 Screening tests

In order to find which parameters have the largest influence on the surface quality, screening tests were performed in two stages.

5.1.1 Experimental details

For every test run in the screening tests, three cylinder liners were processed of which the third served as the reference piece that was measured. Three liners were used for each run to give the machine some time to adapt to the new settings. The decision to use two pieces for the transition was based on discussions with technicians with knowledge of the process. According to their experience, it usually takes a while before changes to the process parameters show any result on the surface quality of the machined cylinder liners. No explanation for this phenomenon has been found in literature but it was decided to use transition pieces based only on experience of the process.

For every reference liner, the surface parameters R_k, R_{pk}, R_{vk} and M_{r2} were measured along three lines, i.e. at 18 different points, with the earlier mentioned perthometer. For every test piece, a mean value for the 18 measurement points was calculated for each surface parameter. Values that diverged more than three standard deviations from the mean were excluded from the results and the mean values for the remaining measurements were then used for the data analysis.

During the execution of the test runs, the machine was set with the process parameter values corresponding to the current run and the liners were then processed. Each run was ended when the last of the processed pieces was transported from the machine to the conveyor belt.

In order to reduce the variation in the process, the tests were performed with stones of average wear. By using stones in the middle of their life span, the wear is negligible during the test course. To reduce the effect of other variations in the process, the test runs were completely randomized except for three center points that were performed as the first, middle and last run for each screening test.

5.1.2 Screening 1

With consideration to both theoretical and empirical knowledge of the process, ten parameters were found to be of interest for further investigation. In order to gain knowledge regarding which of these parameters affect the surface the most, a screening test with a 2_{III}^{10-6} design was performed. All investigated parameters as well as the higher and lower levels for which they were tested can be found in Table 3.

Table 3 Parameters investigated in the first screening test.

Spindle	*Parameter*	*Abbreviation*	*Low level*	*High level*	*Unit*
1	Force	F1	60	95	%
2 Step 1	Allowance	A21	30	50	µm
2 Step 1	Force	F21	45	70	%
2 Step 1	Rotational speed	RoS21	130	190	rpm
2 Step 2	Force	F22	70	100	%
2 Step 2	Rotational speed	RoS22	130	190	rpm
2 Step 2	Number of Strokes	NoS22	5	15	strokes
3	Force	F3	30	70	%
3	Reciprocating Speed	ReS3	26	38	m/min
3	Number of Strokes	NoS3	4	14	strokes

For all test runs, the relationship between the rotational speed and reciprocating speed was kept constant according to Equation (1), i.e. whenever the rotational speed for a spindle was changed, the reciprocating speed was changed accordingly. In spindle 3 the reciprocating speed was the controlled parameter. Here the rotating speed was kept accordingly to keep a fixed honing angle mainly for practical reasons. Reciprocating speed was controlled primarily since, according to analyzed literature, it has been found to be of larger importance than the rotational speed in the plateau honing operation. The full test plan with all levels of the parameters can be found in A1.

Results

The data retrieved for each response was fitted to a model using multiple linear regression (MLR). A summary of fit plot for the models obtained for the different responses is found in Figure 5.2.

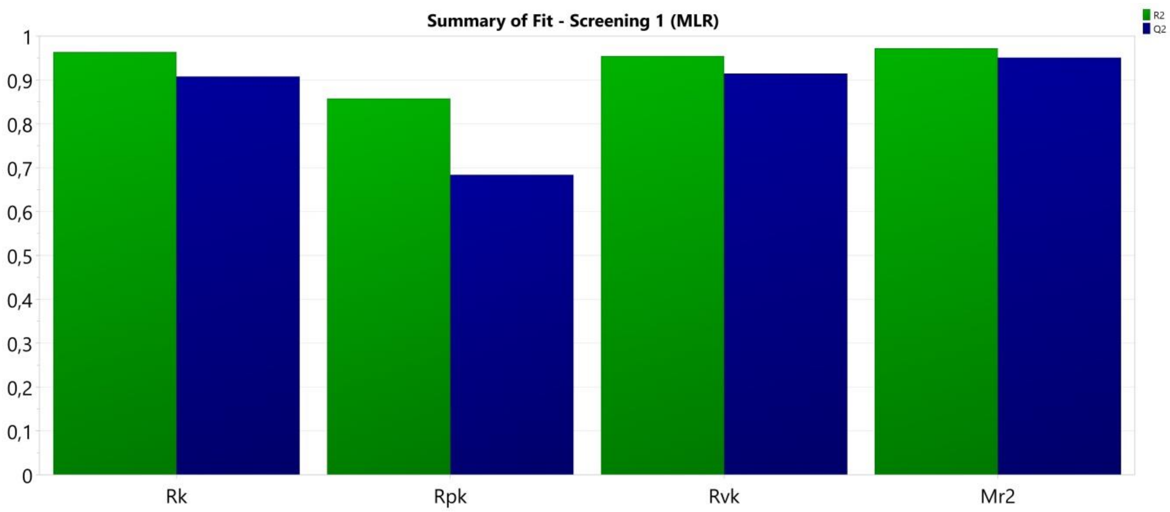


Figure 5.2 Summary of fit plot for the first screening test.

The demands stated in Table 2 are fulfilled in regards of R_2 and Q_2 which indicates that the models are good.

The number of strokes in spindle 3 showed to have the largest total impact on the surface texture. Furthermore, the force in spindle 3 proved to have a large impact on all output parameters. Figure 5.3 shows an effect plot for all the surface roughness parameters with the factors that showed to be most significant represented.

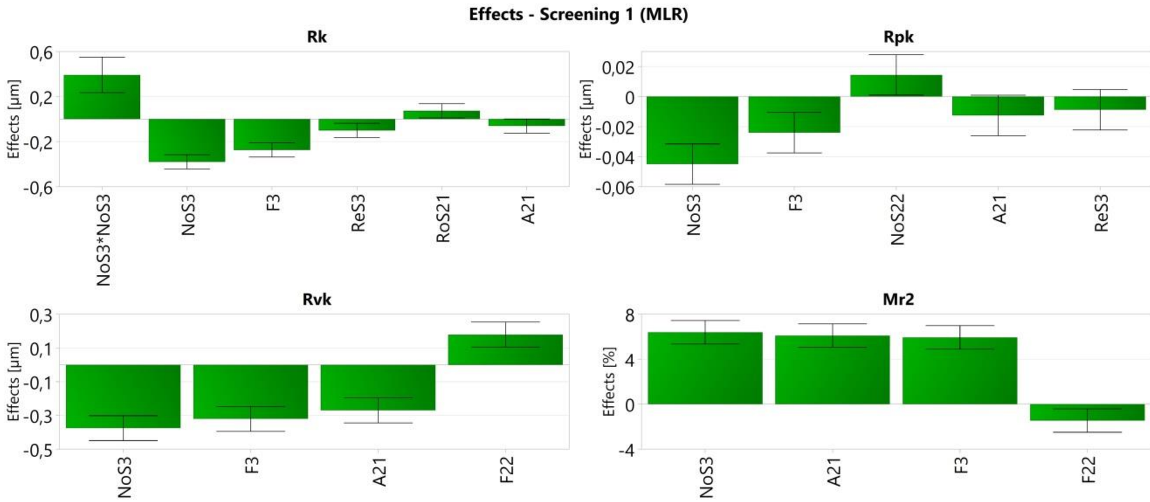


Figure 5.3 Effect plot of results from the first screening test.

The indicated significance of the allowance between the first and second spindle was quite unexpected. These results suggested that a larger allowance would have a negative impact on the R_{vk}-parameter. This arose some suspicion that the whole surface profile from spindle 1 was not removed in the machining in spindle 2 with the lower allowance. This made the allowance a subject of discussion prior to the second screening test. Moreover, the number of strokes in spindle 2, step 2 showed to have an impact on the R_{pk}-parameter. This was also quite unexpected which made the parameter interesting for further experimentation.

There were two factors that did not show to be of significance for any of the resulting surface parameters. These were the force in spindle 1 and the force in spindle 2 step 1. Because of this, it was decided that these factors would not be subject to any further investigation.

5.1.3 Screening 2

The purpose of the second screening test was to further limit the number of factors to investigate in an optimization test. For the second screening test, a 2^{8-4}_{IV} fractional factorial design was used. By using a higher resolution than in the first screening test, some factor interactions could also be identified. All parameters investigated in this test as well as their high- and low levels can be found in Table 4.

Table 4 Parameters investigated in the second screening test.

Spindle	*Parameter*	*Abbreviation*	*Low level*	*High level*	*Unit*
2 Step 1	Allowance	A21	35	55	µm
2 Step 1	Rotational speed	RoS21	110	190	rpm
2 Step 2	Force	F22	50	100	%
2 Step 2	Rotational speed	RoS22	110	190	rpm
2 Step 2	Number of Strokes	NoS22	5	14	strokes
3	Force	F3	50	90	%
3	Reciprocating Speed	ReS3	15	35	m/min
3	Number of Strokes	NoS3	5	14	strokes

In this test, the relationship between reciprocal speed and rotational speed was kept fixed for both steps in spindle 2. Spindle 3 does not create any deep grooves in the surface which makes the relationship between the different speeds in this spindle redundant. Therefore, the rotational speed in spindle 3 was kept fixed while reciprocating speed was varied for this test. The lower limit of both the rotational- and reciprocating speed was significantly lowered in the second screening test. These parameters did not show any major influence on the surface texture in the first screening test. A possible explanation for the results could be poorly chosen levels of the parameters. By lowering the lower limit, further testing of these factors could be made before making a ruling whether to discard them or not.

To investigate the suspicions regarding the amount of allowance between spindle 1 and 2, the R_z surface parameter was measured after spindle 1. The R_z parameter needs to be smaller than half the allowance in order to make sure that grooves created in spindle 1 does not show on finished surface. This is since the allowance is quantified as the increase in diameter of the bore. Measurements were conducted on six points in the liner and an average was calculated. The average R_z value was found to be 16.85 µm. This would suggest that an allowance of 30 µm is an insufficient value for the allowance between the spindles. To make sure that no texture created in spindle 1 remains, the allowance levels were shifted up. The values set for the factor can be seen along with the other factor levels in Table 4.

Another factor with altered levels was the force in the last spindle. The aim of the change was to observe whether the factor had the same effect on the surface with higher levels. Therefore the amount of force used was increased, shifting the levels with 20 units compared to screening 1. The full test plan can be found in A2.

Results

Data gathering and analysis was performed as described for screening 1. The summary of fit plot for the second screening test is presented in Figure 5.4.

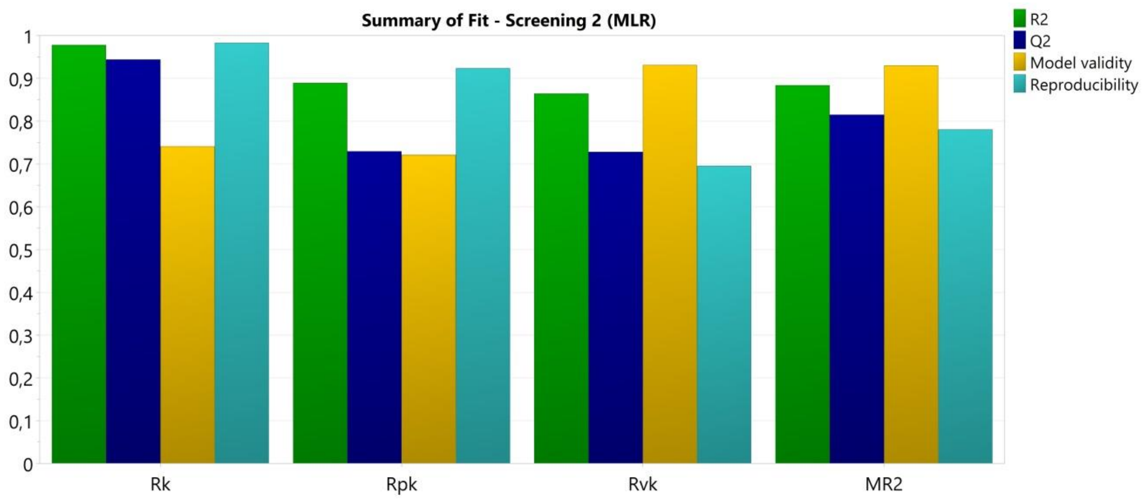


Figure 5.4 Summary of fit plot for the second screening test.

The summary of fit plot implies that the models for all responses are good. All requirements stated in Table 2 are fulfilled.

The factors that were found to be of little or no significance for the response parameters were removed before the models were fitted. The effects of the remaining and most significant parameters are presented in Figure 5.5.

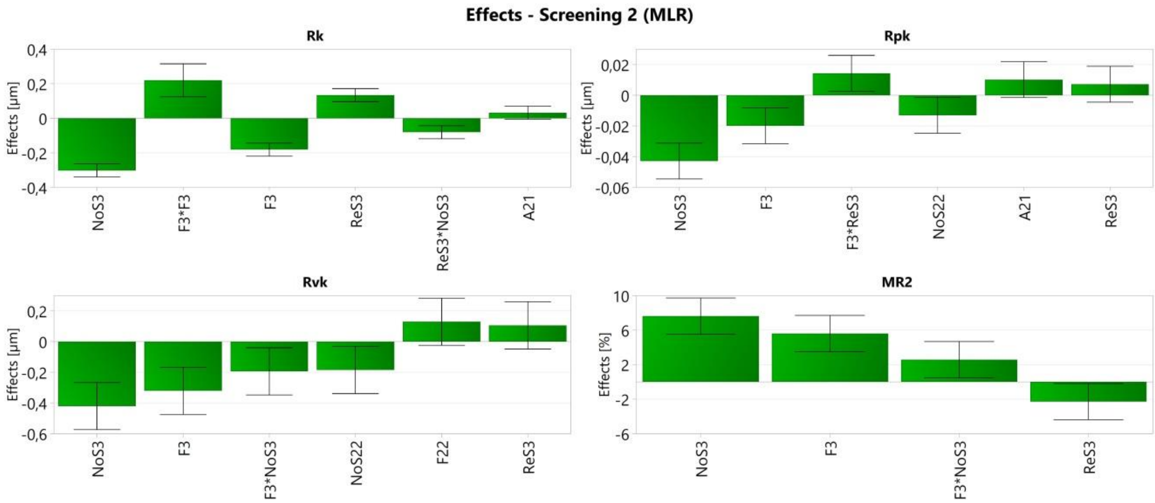


Figure 5.5 Effect plot for the second screening test.

According to the second screening, honing force and number of strokes in the plateau honing has the largest total effect. These factors show to have a large effect on all surface parameters, consistent with results from the first screening.

As suspected after screening one, the allowance in spindle two was found to have a negligible effect on the surface roughness once the levels were increased. The parameter could therefore be excluded from further tests.

A factor with a large increase in significance, compared to screening 1, was the reciprocating speed in the plateau honing operation. By controlling the reciprocating speed while having a fixed rotating speed, the number of passes of the abrasives against the workpiece can be controlled. As stated in section 4.1.2, a larger number of tool rotations will result in a smoother surface. In these tests, the number of tool rotations per stroke increases with a decrease in reciprocal speed. An increase in reciprocal speed will increase R_k and decrease M_{r2}. This contradicts the results from screening 1 which showed that an increase in reciprocating speed will decrease the core roughness. The difference in the effect of the reciprocating speed was believed to be related to de decoupling from the rotational speed in the spindle. An interesting observation is the small significance of the factor presented for the R_{vk}-parameter. These results would suggest that by controlling the reciprocal speed, R_k can be decreased without affecting R_{vk}. The increase in significance joint with the change in effect calls for further exploration of the reciprocating speed. The lowering of the rotational speed in spindle two on the other hand had no effect on the significance of the factor. This indicates that no further investigation is needed.

Another observation was the increase in significance for the number of strokes in the second step in the second spindle. An interesting fact is that the number of strokes seems to affect the R_{vk}-parameter in a negative way, reducing the valley depth as the number of strokes increases. This would suggest that a higher number of strokes will, instead of increasing the amount of grooves, create a smooth surface. In order to increase the understanding of the parameter, a larger amount of data is needed.

5.2 Optimization

Based on the results from the second screening test, five factors were found to be of interest for an optimization test. All factors tested in the optimization test as well as their high and low values that were investigated can be found in Table 5.

Table 5 Factors investigated in the optimization test and their value spans.

Spindle	*Parameter*	*Abbreviation*	*Low level*	*High level*	*Unit*
2 Step 2	Force	F22	70	100	%
2 Step 2	Number of Strokes	NoS22	5	13	strokes
3	Force	F3	40	80	%
3	Reciprocating Speed	ReS3	12	24	m/min
3	Number of Strokes	NoS3	5	13	strokes

A CCF design was applied generating 29 test runs. This was complemented with the runs of a 2_{III}^{5-2} fractional factorial design and an additional center point to increase the accuracy of the experimental design. The total number of tests was thereby 38. The full experimental design is presented in A3.

5.2.1 Experimental details

To increase the statistical significance of the results from the optimization test, the number of liners measured was increased. Because of the increase in test pieces, the transition pieces became subject to discussion mainly for economic reasons. The first two liners produced in tests 17, 18 and 19 from both screening tests were measured in order to evaluate if the machine needs a number of liners to adapt to the new settings. It was found that changes in machine settings could be observed on responses instantly. Based on this information, no running-in liners were used in the optimization test.

Three liners were machined for each test run and each liner were then measured at 12 points with 180 degrees between the measuring lines. The specifications for the measurement equipment can be found in the beginning of the chapter. Outliers in the measurement data were excluded using the same criteria as in the screening tests.

The workpieces used during the test series were machined in one sequence in the production line. As a result, all pieces were rough honed and turned during similar conditions.

6. Results and Analysis

As for the screening tests, the data collected in the optimization test was analyzed using MODDE. Models for each response parameters were fitted using MLR. A summary of fit plot for these models can be found in Figure 6.1.

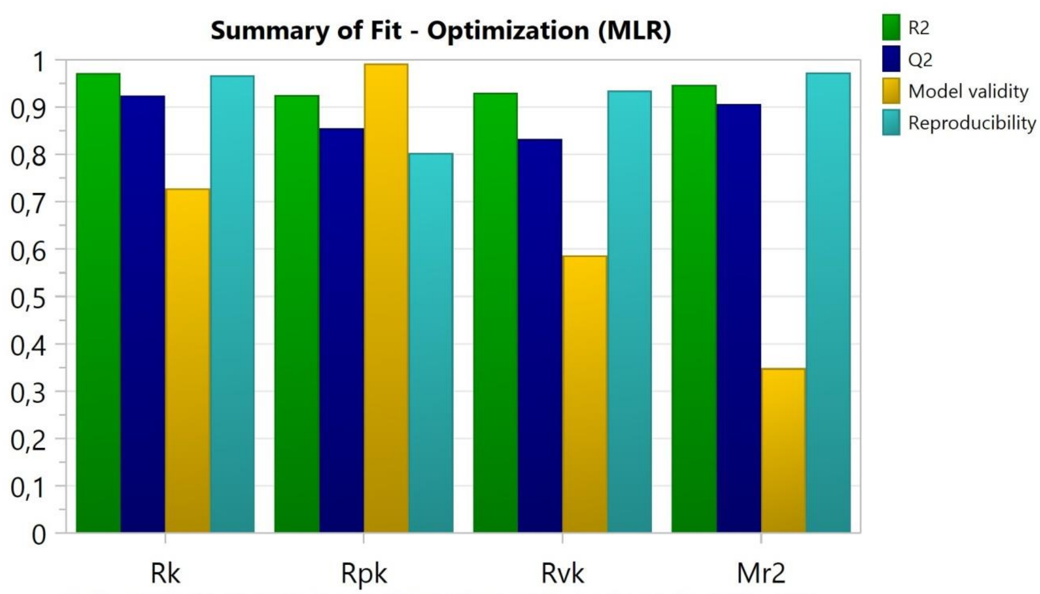


Figure 6.1 Summary of fit plot for the optimization test.

All requirements are fulfilled and the models are considered to be good based on the demands stated in Table 2. The values were approximated to be normally distributed and no reasons for transforming models were found.

6.1 Effects per surface parameter

Since the surface parameters relate to each other in different ways, an optimization of the process must be a balance between the factors affecting the different parameters. In order to do this, the parameters were first analyzed one by one.

6.1.1 Parameter R_{vk}

No factors were found that significantly increase the value for R_{vk}. Since relatively high values for the R_{vk}-parameter are preferred an optimization means knowing how to achieve good values for the other surface parameters without decreasing the R_{vk}-value too much. An effect plot with all factors influencing R_{vk} is found in Figure 6.2.

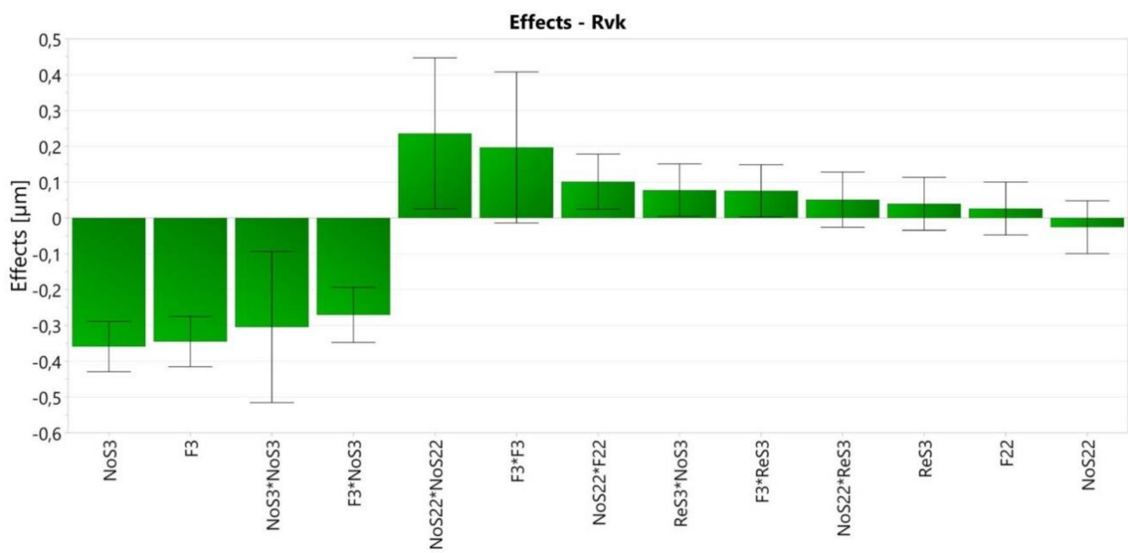


Figure 6.2 Effect plot from the optimization test for Rvk.

As indicated by the screening tests, the force and number of strokes in the plateau honing operation have the most significant effect on the reduced valley depth. The optimization results did however give some clarity regarding in what way these factors affect the R_{vk}-parameter. The squared terms for the force and number of strokes indicates that these factors have non-linear effects on the valley depth. Furthermore, the combined term F3*NoS3 indicates that the factors are dependent on each other. Combined factor effects are important to analyze. This is since the effect of a changes to a factors might show in different ways depending on the settings of the other factor in the combination. A contour plot showing the joint effect of force and number of strokes in the plateau honing on R_{vk} is found in Figure 6.3. The figure shows the effect when all other parameters are set to medium values. The R_{vk}-values are symbolized by a colored scale with yellow representing low values and blue representing high values.

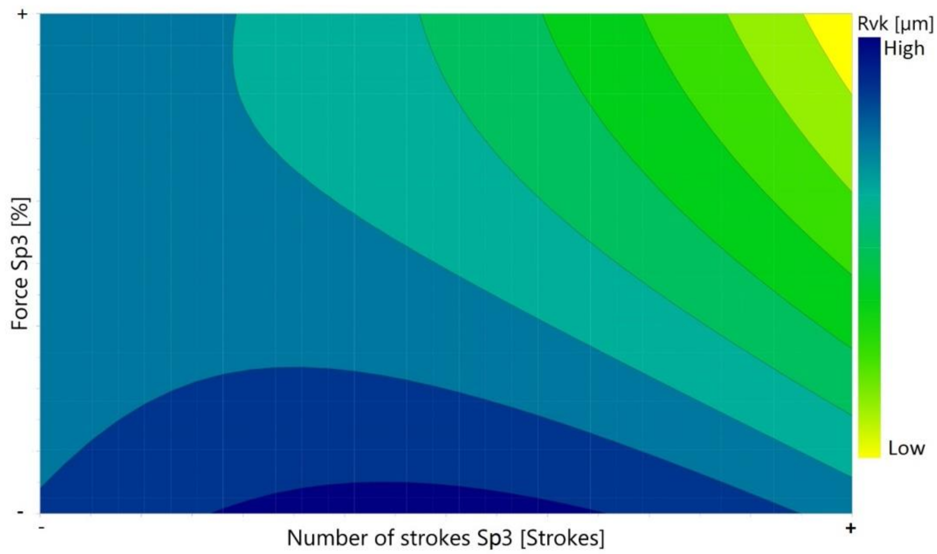


Figure 6.3 Joint impact of number of strokes and force in spindle three on R_{vk}.

According to the results, the largest values for valley depth can be generated when using a low force and a medium number of strokes in the plateau honing operation. High values for both factors result in a low R_{vk}-value. When using a low force, the effect of changes in the number of strokes is much smaller than when using a large force. The same applies for changes in force when using a low number of strokes.

In the screening tests, the number of strokes in spindle 2 showed to have a negative effect on the R_{vk}-parameter. In the model obtained from the optimization test however, the factor contributes with a squared term. This indicates that the number of strokes in the base honing operation in fact has a non-linear effect on the reduced valley depth. Figure 6.4 shows a graph representing the effect with different numbers of strokes in spindle 2.

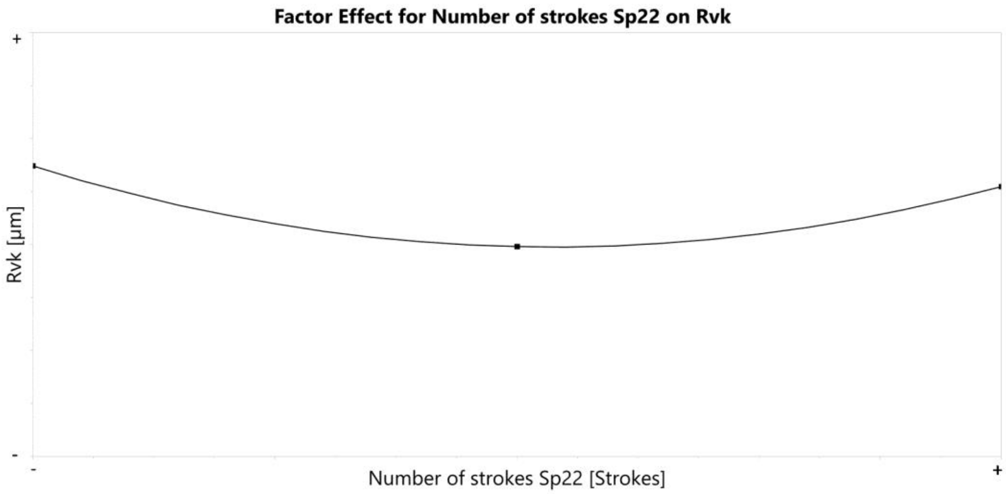


Figure 6.4 Factor effect for number of strokes in the base honing on R_{vk}.

The graph indicates that favorable values for the R_{vk}-parameter are obtained by using either a low or a high number of strokes in spindle 2. This factor also showed to have a combined effect with the force in the same operation. The combined effect of these factors can be viewed in Figure 6.5. As in the previous contour plot, lower R_{vk}-values are represented by yellow and high values by blue color. Important to note is however that the scale in this plot includes a smaller range of R_{vk}-values since the effect of these factors in spindle 2 are less significant than from the corresponding ones in spindle 3.

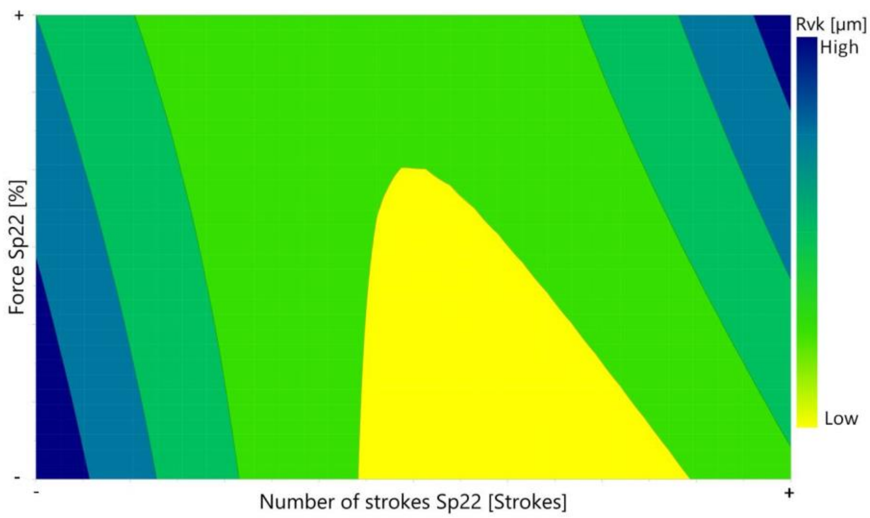


Figure 6.5 Combined effect of number of strokes and force in spindle two on R_{vk}.

The largest valley depth can be found when combining either low force and few strokes or large force and a large number of strokes. When using a medium number of strokes, the effect of changing the force showed to be insignificant and these settings always generate lower values for R_{vk}, which is also consistent with the non-linear effect of the number of strokes.

6.1.2 Parameter R_k

The main effects on the core roughness depth showed to come from the plateau honing operation. This is consistent with the results from the screening tests. The force in spindle 3 did however, in the optimization test, show to have a larger impact than indicated by the screening tests. The force as well as the number of strokes in the plateau honing also contribute with quadratic factors to the model. This indicates that their effects on the R_k-parameter are non-linear. All factors and their effect can be seen in Figure 6.6.

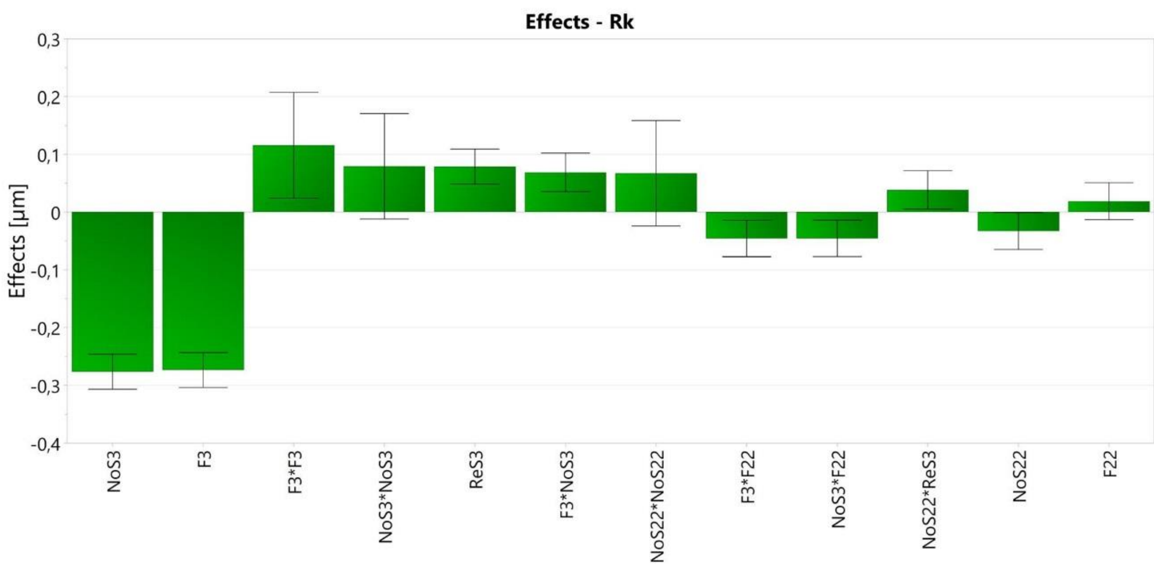


Figure 6.6 Effect plot from the optimization test for R_k.

As for the valley depth, force and number of strokes in the third spindle also have a joint impact on the core roughness depth. This combination term is further discussed in section 6.2. The reciprocating speed in the plateau honing operation still showed to have a positive impact on the R_k-parameter. This indicates that lowering the reciprocating speed in the third spindle will reduce the core roughness depth of the surface. This is an interesting observation since this is the only factor that can be used for reducing the R_k-parameter which does not have a significant negative impact on the R_{vk}-parameter for which high values are desired.

6.1.3 Parameter R_{pk}

As for the other surface parameters, the factors in the plateau honing operation are of the most significance for the resulting R_{pk}-value of the surface. The results are to a large extent consistent with those in the screening tests. All factors and their effect can be viewed in Figure 6.7.

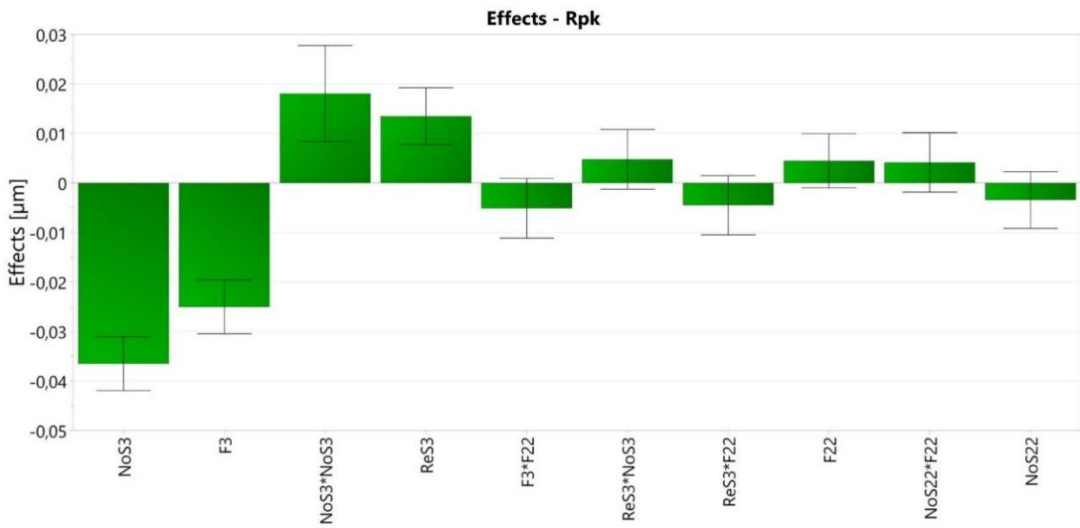


Figure 6.7 Effect plot from the optimization test for R_{pk}.

The squared term for the number of strokes in spindle 3 is a new contribution indicating a non-linear impact on the R_{pk}-parameter. In all, the reduced peak height is to a large extent affected by the same factors as the R_k-parameter. The main difference is that the impact of the different factors is of smaller significance for R_{pk} than for R_k. This suggests that the reduced peak height is a more stable parameter than the core roughness depth.

The reciprocating speed in spindle 3 showed to be of significance influencing the reduced peak height in the same way as the core roughness depth. This is, as mentioned in the previous section, interesting from a optimization point of view since the reciprocating speed has no major impact on the R_{vk}-parameter.

6.1.4 Parameter M_{r2}

The results regarding the M_{r2}-parameter are to a great extent consistent with those from the screening tests. As in the second screening test, all factors from the base honing step has been excluded from the model which thereby only consists of factors in the plateau honing step. All significant factors and their effect can be seen in Figure 6.8.

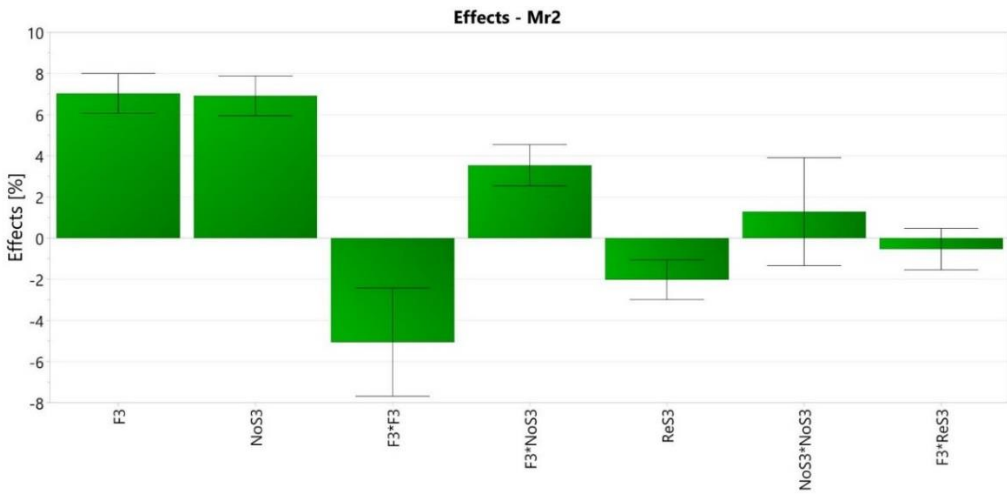


Figure 6.8 Effect plot from the optimization test for M_{r2}.

As for the other surface parameters, the force and the number of strokes in the plateau honing operation has the largest impact on the resulting M_{r2}-value. The model also contains a squared term for the plateau honing force which indicates a non-linear impact on the parameter. A plot for the effect of the force in spindle 3 on M_{r2} with all other factors set to their medium values is found in Figure 6.9.

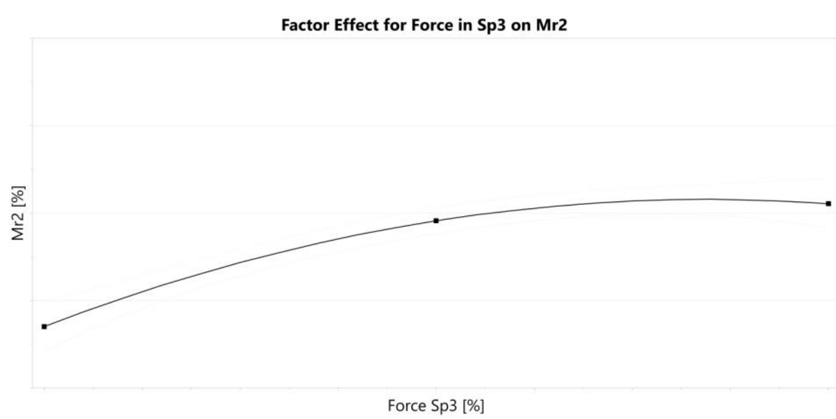


Figure 6.9 Effect plot for plateau honing force on the M_{r2}-parameter.

As can be seen in the plot, changes in the lower regions of the plateau honing force showed to have a larger impact on the resulting M_{r2}-value than changes in the higher region.

6.2 Finding optimal settings

In order to create the optimal surface, the machine settings need to be appropriate in aspect of all surface parameters. Since some factors have different effect on different surface characteristics, compromises have to be made. The correlation between the different surface parameters must also be taken into consideration. The constants for all surface parameter correlations found by MODDE when fitting the models are found in Table 6. The scale of the coefficients goes from -1 to 1 where values close to 0 indicates that no linear correlation exists between the parameters.

Table 6 Correlation matrix for surface parameters.

	R_k	R_{pk}	R_{vk}	M_{r2}
R_k	1	0,891	0,725	-0,848
R_{pk}	0,891	1	0,768	-0,853
R_{vk}	0,725	0,768	1	-0,951
M_{r2}	-0,848	-0,853	-0,951	1

The strongest correlation was found to be between R_{vk} and M_{r2}. A coefficient value so close to -1 indicates an almost linear relationship between the parameters. The fact that the coefficient is negative means that an increase in one of the parameters will result in a lower value of the other parameter. This result is consistent with operator experience. This negative correlation is important to take into consideration when optimizing the process since high values for both parameters are desired.

There are also negative correlations between R_k and M_{r2} as well as between R_{pk} and M_{r2}. These negative correlations are however favorable from an optimization point of view since the aim is to minimize R_k and R_{pk} while maximizing M_{r2}. Furthermore, the R_k- and R_{pk}-parameter s both have positive correlations with R_{vk}. This means that an increase of the R_{vk}-parameter often also leads to an increase in the values for R_k and R_{pk}. This is an important observation when it comes to optimization and further promotes the need for compromises between the parameters.

The force and number of strokes in the plateau honing have shown to be of great significance for all surface parameters. These parameters have also contributed with combination factors to the models. The combined effect of these factors on the different surface parameters can be seen in Figure 6.10. For R_k and R_{pk} low values are favorable, indicated by yellow color, while for R_{vk} and M_{r2} high values are preferred, which is indicated by blue color.

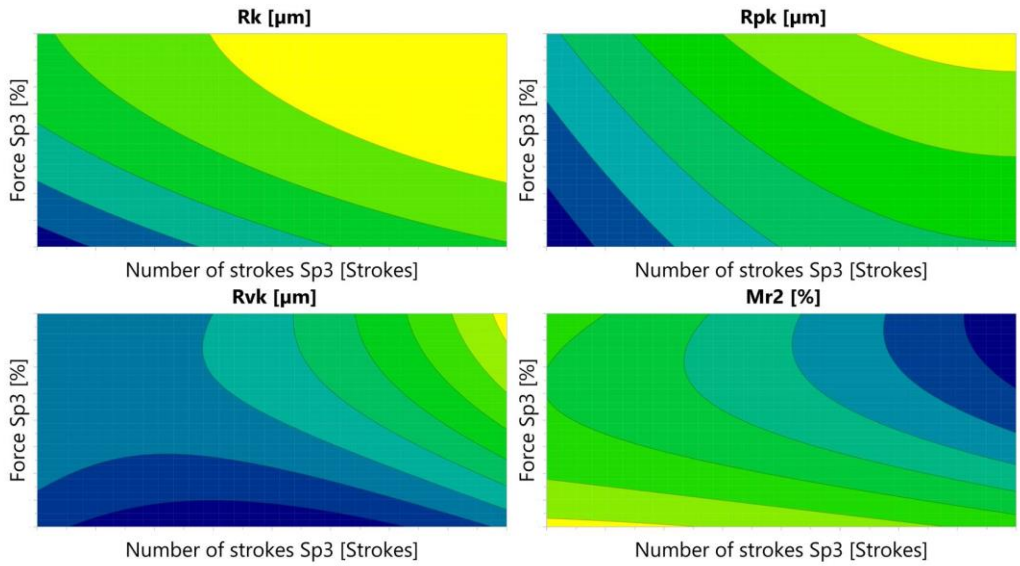


Figure 6.10 Response contour plot for surface parameters as a function of force and number of strokes in spindle 3.

The plots suggest that the areas in the upper right corners with high settings for both factors will generate good values for R_k, R_{pk} and M_{r2}. The R_{vk}-value however, will be low when using such settings. Favorable R_{vk}-values will be generated when using low settings for both factors. This indicates that a compromise is needed to get a surface satisfying the demands for all surface parameters. This finding is also consistent with the found correlations between the parameters. As mentioned in section 6.1.1, no parameters that have a linear positive impact on the R_{vk}-parameter have been found. The optimization of this parameter instead needs to be a balance of minimizing the negative impact on the value when optimizing the other parameters. The only parameter that has been found to improve the values of all other parameter without having a negative impact on the R_{vk}-value is the reciprocating speed in the plateau honing. Even though this factor is not the one with the largest effect on the R_k-, R_{pk}- and M_{r2}-parameters, it should be taken into consideration when optimizing the process. This is since the cylinder liner surface demands are so thorough that all improvements can make a difference. If the use of a lower reciprocating speed can enable a lowering of the use of number of strokes or force in the plateau honing, a more beneficial cylinder liner surface can be created.

6.3 Analysis

The force was one of the main influencing factors out of those tested for each step. This is consistent with a major part of the research conducted on the subject. When analyzing the spindles all together, there was however a great variation in impact on resulting surface. The plateau honing operation has the main effect on all response parameters. The base honing affects the surface texture to some extent while the coarse honing can be considered negligible. This strongly contradicts the research conducted by Pawlus et.al. in which it was found that the plateau honing pressure was to be considered insignificant. No valid explanation has been found regarding the difference in stated impact from the plateau honing force. A larger amount of information from the study conducted by Pawlus et. al. would be necessary to draw further conclusions.

According to analyzed literature, a higher base honing pressure should press the grains further into the workpiece, creating deeper grooves. This suggests that an increase in force in the base honing should be an effective way to increase the valley depth of the surface. In the tests performed, no factors have been found to significantly increase the R_{vk}-parameter. These results indicate that the grains of the stones used will not penetrate the surface deeper with an increase in force. This calls for further analysis of the use of different stones to see if the effects of changes in parameter settings differ between stone types.

In the performed experiments, the number of strokes in combination with other parameters was used to control the duration of the honing. The number of strokes in the plateau honing showed to be of large significance for the surface roughness. This is consistent with previous studies where the honing time has been found to be of great importance. It is however difficult to make a solid conclusion whether the effect of honing time is the same as in analyzed literature due to the use of different surface response parameters.

A parameter that according to literature should be of significance is the cutting speed. When the factor was varied during experimentation, with a constant honing angle, no major effect could be identified. When the reciprocating speed instead was varied independently of the rotational speed, the impact on the surface roughness increased. This is to some extent consistent with the research conducted by Kanthababu et al. which stated that reciprocating speed in the plateau honing should have an effect mainly on M_{r2}. In the experimentation performed during this project, the reciprocating speed did however show to have some effect on all surface parameters.

Results were also found that can be used to make the current machine compensation procedure more efficient. The results presented shows, in line with analyzed literature, that the coarse honing process has a negligible effect on the resulting surface roughness. The effect of varying the allowance in the base honing operation was also significantly reduced once it was determined that no grooves created in the coarse honing step were to be found on finished surface. This suggests that the allowance should not be varied once a good setting for this factor is found.

With the apprehended results, the procedure regarding compensation for low R_{vk}-values can be modified. In current production, the base honing pressure is increased to get deeper grooves. Since it was found that this will not have any significant effect on the valley depth, the factor should instead be set to an appropriate level and then kept fixed. An efficient way of increasing R_{vk} is to vary the force and number of strokes in the plateau honing operation. Even though this compensation was applied before, it did not take the combined effect of the factors into consideration. When varying the force and number of strokes individually, there is a substantial risk that no significant change is observed in valley depth while the values for the other surface parameters are worsened.

The current compensation for R_k- and R_{pk}-values are focused on the correct parameters. As for the compensation for low R_{vk}-values, the joint effect of the force and number of strokes in the plateau honing should also be taken into account. By understanding the combination, smaller changes can give a more successful result. A factor that should also be added to this compensation is the reciprocating speed. It is the only parameter found that can decrease R_{pk}- and R_k-values without affecting the R_{vk}-values negatively.

6.3.1 Result uncertainty

Like all processes, honing has built in variations which involve some uncertainty of the results. The variation that could not be controlled during the experiments is described in this section. There are different variation sources such as machines, human factors and environmental effects.

Some of the variation in the process originates from the machine itself. During the optimization tests, the honing stones were subjected to wear. This suggests that the cutting ability of stone will vary over the length of the experimental run. This variation is however hard to predict since the breakage of the grain and generation of new cutting edges in the stone are stochastic variations.

Another machine variation that was hard to take into account during the tests, were the different fixtures used. In order for the tests to be practically feasible, all fixtures had to be included. The liners position in the fixture was also a parameter that could not be traced. This means that the measurements performed were conducted on different places in the liner relative to the position in the machine.

Some variation also originates from the environment in contact with the machine. Parameters connected to the location of the machine such as humidity, temperature and other processes generating vibrations can affect the output of the machine. The temperature in this case should have lower effect than many other machining processes due to the use of honing oil.

During the measurements of the liners machined in the optimization test, 12 points were measured in every liner. One major uncertainty during the measurement is the liner surface itself. Since surface roughness can vary greatly on the same liner it is difficult to determine whether the data is representative for the whole surface or not. The amount of time needed to measure the liners once they were machined were however an issue. Due to the time limitation of the project, a compromise was made in order to collect a sufficient amount of data without spending too much resources.

The previously mentioned uncertainties all relate to the physical process of honing. Another kind of uncertainty that has to be accounted for is the sample size during the experiment. The larger the sample size is, the better it is out of a statistical point of view. During the optimization tests the sample size was limited to three pieces per test run. This was considered to be reasonable number in regards of statistical significance and practical feasibility.

The only measures taken to reduce the effect of time dependent variation was to randomize the test. By applying this technique, the effect of these variations should be reduced. Even though this measure is taken, all of these uncertainties should be taken into consideration when reviewing the results.

7. Conclusions

By using Design of Experiments (DOE), the honing process parameters with the largest influence on the surface roughness of a cylinder liner have been identified. Models were created in order to understand and predict the impact of these factors, both individually and in combination with other factors. The main conclusions drawn are presented below.

- The plateau honing step is of main importance for the surface roughness.
- The force and the number of strokes in the plateau honing step are the main influencing factors.
- Due to correlation between response parameters, compromises have to be made when searching for the optimal settings.

By identifying the plateau honing step as the one having the largest impact on surface roughness, machine controls can be reduced. The coarse- and base honing can be set to appropriate levels and be kept fixed during production. Instead, the operators can focus on compensating for deviating surface parameter values by altering the plateau honing step. This enables a more stable process with a reduced number of factors that can be changed, ultimately reducing the risk of compensation error in the process.

Besides from their individual effect on the surface, the number of strokes and the force in the plateau honing showed to have a large combined effect for all surface parameters. This means that machine compensation using one of these variables

can be insignificant depending on the settings of the other factor. Another important discovery is the effect from the reciprocating speed. When disconnecting the relationship between the reciprocating speed and the rotational speed in the plateau honing, it can be used to affect the surface quality. The reciprocating speed was found to be the only factor able to reduce R_k and R_{pk} without also reducing R_{vk}. There are no results in analyzed literature showing this effect.

In this thesis, multiple non-linear and combination factor effects were identified. No such combination effects have been found in the studied literature. The discoveries of this paper would be hard to detect using the current methodology based on the OVAT-approach. When the method of DOE was applied complemented with thorough research, the investigation could be performed in an efficient way. No evident flaws were detected in the method and it is to be considered as very useful for the kind of investigations performed in this project. To complement the method with software is however recommended due to the high amount of data generated.

Since all experiments in this project were performed in the same honing machine there is no guarantee that the results apprehended will be applicable in other machines. Some of the findings do however have support in existing literature which indicates that the results can to some extent be considered general. Furthermore, the experiments have been performed with honing stones in varying conditions and the results have still been consistent between the different test series. The fact that, to a large extent, the same factors has shown to affect the surface in the same manner indicates that the results are applicable regardless of the state of the honing stones. The main difference between the honing machine in question and general honing machines is that the base honing operation is divided into two steps. Therefore the applicability of the results regarding this spindle in other machines might be questionable. Overall, the results should still be of interest for other honing processes as well. The way the different factors affect the surface should be similar even though the extent of their effect may vary from machine to machine.

7.1 Future work

The objective of this thesis was to increase the understanding of honing process parameters on surface roughness. As stated in the introduction chapter, several factors with a probable effect on the process was disregarded from due to the limited amount of time and resources available in the project. To focus on the process parameters and get a greater understanding of their effect was a first step in understanding the whole process of honing. Further research should be conducted to get a better overview of factors with impact on the process.

A major factor excluded from this thesis is the honing stone used in the machine. There has been research made on the different bonding- and grain materials while the deterioration of the stones is an area where further investigation is needed. In order to apply the settings and machine compensation techniques presented in this thesis, the wear over time and its effect on surface roughness should be mapped. If the natural variation of the process is unknown, there is a risk that compensation will be performed at the wrong time, generating a unsatisfactory surface.

An interesting next step to understand honing would also be to use the results in this thesis and apply these using different honing stones. This would give and understanding regarding both the relevance of the stated results as well as the effect of different honing stones.

Lastly, the impact of workpiece material and geometry on surface roughness should be researched. By getting a better understanding of the deformation of the liner during honing the setting of machine controls can be appropriately adjusted and better results generated.

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A1. Test runs Screening 1

	Spindle 1	*Spindle 2 step 1*				*Spindle 2 step 2*				*Spindle 3*			
Run	*F1*	*F21*	*Rot21*	*ReS21*	*A21*	*F22*	*RoS22*	*ReS22*	*NoS22*	*F3*	*RoS3*	*ReS3*	*NoS3*
1	78	58	160	32	40	85	160	32	10	50	160	32	9
2	60	45	130	26	30	70	130	26	5	30	190	38	14
3	95	45	130	26	50	100	190	38	5	30	190	38	4
4	95	45	190	38	30	70	190	38	5	70	190	38	4
5	60	45	130	26	50	70	190	38	15	70	130	26	14
6	60	70	130	26	50	100	130	26	15	30	190	38	4
7	95	70	190	38	30	100	130	26	5	30	130	26	14
8	60	45	190	38	30	100	190	38	15	30	130	26	14
9	60	70	190	38	30	70	130	26	15	70	190	38	4
10	78	58	160	32	40	85	160	32	10	50	160	32	9
11	95	70	190	38	50	100	190	38	15	70	190	38	14
12	95	70	130	26	30	70	190	38	15	30	190	38	14
13	60	70	190	38	50	70	190	38	5	30	130	26	4
14	60	70	130	26	30	100	190	38	5	70	130	26	4
15	95	70	130	26	50	70	130	26	5	70	130	26	14
16	95	45	190	38	50	70	130	26	15	30	130	26	4
17	95	45	130	26	30	100	130	26	15	70	130	26	4
18	60	45	190	38	50	100	130	26	5	70	190	38	14
19	78	58	160	32	40	85	160	32	10	50	160	32	9

A2. Test runs Screening 2

	Spindle 2 step 1			*Spindle 2 step 2*				*Spindle 3*			
Run	*Rot21*	*ReS21*	*A21*	*F22*	*RoS22*	*ReS22*	*NoS22*	*F3*	*RoS3*	*ReS3*	*NoS3*
1	150	30	45	75	150	30	10	70	140	25	10
2	190	38	35	50	110	22	14	50	140	35	14
3	110	22	55	50	110	22	14	90	140	15	14
4	110	22	35	100	190	38	14	50	140	15	14
5	190	38	35	100	110	22	14	90	140	15	5
6	190	38	55	50	110	22	5	90	140	35	5
7	110	22	55	100	190	38	5	90	140	15	5
8	110	22	55	50	190	38	5	50	140	35	14
9	190	38	35	50	190	38	5	90	140	15	14
10	150	30	45	75	150	30	10	70	140	25	10
11	190	38	55	50	190	38	14	50	140	15	5
12	190	38	55	100	190	38	14	90	140	35	14
13	110	22	35	50	190	38	14	90	140	35	5
14	190	38	55	100	110	22	5	50	140	15	14
15	110	22	55	100	110	22	14	50	140	35	5
16	110	22	35	100	110	22	5	90	140	35	14
17	190	38	35	100	190	38	5	50	140	35	5
18	110	22	35	50	110	22	5	50	140	15	5
19	150	30	45	75	150	30	10	70	140	25	10

A3. Test runs Optimization

Run	*F22*	*NoS22*	*F3*	*ReS3*	*NoS3*	*Run*	*F22*	*NoS22*	*F3*	*ReS3*	*NoS3*
1	85	9	60	18	9	**20**	100	5	40	12	5
2	85	9	60	12	9	**21**	70	5	40	12	13
3	100	5	80	24	5	**22**	70	5	80	12	5
4	100	5	40	24	13	**23**	85	9	80	18	9
5	70	5	40	24	5	**24**	85	9	60	24	9
6	85	9	60	18	5	**25**	70	13	80	12	13
7	100	9	60	18	9	**26**	70	13	40	24	13
8	85	5	60	18	9	**27**	85	13	60	18	9
9	70	9	60	18	9	**28**	85	9	40	18	9
10	100	13	40	24	5	**29**	85	9	60	18	9
11	70	13	40	12	5	**30**	100	5	80	12	5
12	70	13	80	24	5	**31**	100	5	40	12	13
13	85	9	60	18	13	**32**	70	5	40	24	13
14	100	13	80	24	13	**33**	70	5	80	24	5
15	85	9	60	18	9	**34**	70	13	40	12	5
16	70	5	80	24	13	**35**	100	13	80	24	13
17	100	13	80	12	5	**36**	100	13	40	24	5
18	100	13	40	12	13	**37**	70	13	80	12	13
19	100	5	80	12	13						