Surface Characteristics and Their Impact on Press Joint Strength

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Abstract

Press fitting is a commonly used method in the assembly of shafts and gearwheels in gearboxes and are using the friction created between them to hold them together. To increase productivity Scania CV AB in Södertälje, Sweden, are going to replace the current hard machining method for layshafts. While testing the new methods in rig it occurred that the gearwheel slipped in tangential direction towards the layshaft at a lower torque then with the current method even through all requirements on the layshafts surface was meet. The purpose and aim with this study is to investigate differences between the methods and to find new requirements for the layshaft. The torque of slip, (Ms) established in a torque test rig and analysis of surface roughness, hardness and microstructure conducted of both the layshafts and gearwheels. The characteristics of the layshaft surface was also analysed and compared between the different hard machining methods. The study concludes that no correlation between the surface parameters and the Ms occurred and no major differences in the material between the methods. The study also concluded that the Ms between the layshaft and gearwheel is lower if the layshaft surface is harder and smoother than the gearwheel surface.
Contents

Abstract .............................................................................................................................................. i

1. Introduction .................................................................................................................................... 1
  1.1 Background .................................................................................................................................. 1
  1.2 Environmental Effects .................................................................................................................. 2
  1.3 Purpose ....................................................................................................................................... 2
  1.4 Aim ............................................................................................................................................... 3

2. Theory ............................................................................................................................................. 3
  2.1 Gearbox ...................................................................................................................................... 3
  2.2 Process Methods .......................................................................................................................... 4
    2.2.1 Grinding ................................................................................................................................. 4
    2.2.2 Tape Finishing ....................................................................................................................... 4
    2.2.3 Hard Turning .......................................................................................................................... 5
    2.2.4 Rotational Turning .................................................................................................................. 5
  2.3 Material ....................................................................................................................................... 5
    2.3.1 Metals Structure ..................................................................................................................... 5
    2.3.2 Surface Roughness ................................................................................................................ 6

3. Method ............................................................................................................................................ 8
  3.1 Layshaft ..................................................................................................................................... 8
  3.2 Sample Preparation .................................................................................................................... 9
  3.3 Experimental .............................................................................................................................. 10
    3.3.1 Hardness Measurement .......................................................................................................... 10
    3.3.2 Microstructure Analysis ......................................................................................................... 11
    3.3.3 Surface Measurement ............................................................................................................ 11
    3.3.4 Surface Visualization ............................................................................................................ 12

4. Result ............................................................................................................................................. 12
  4.1 Torque Testing ............................................................................................................................ 12
  4.2 Microstructure and Hardness Analysis ....................................................................................... 12
  4.3 Surface Analysis ......................................................................................................................... 15
    4.3.1 Surface Parameters ............................................................................................................... 15
    4.3.2 Surface Characterization ...................................................................................................... 16
    4.3.3 Layshaft-Gearwheel Interface .............................................................................................. 18

5. Discussion ..................................................................................................................................... 20
  5.1 Hardness and Microstructure ...................................................................................................... 20
  5.2 Surface Parameters and Characterization ................................................................................... 21
  5.3 Layshaft-Gearwheel Gap ............................................................................................................ 23
1. Introduction

1.1 Background

In the manufacturing industry, press fitting is a common used method to attach two items only by the friction occurring from the tightening effect between them. This method is used to assemble gearwheels on to layshafts which is used in truck gearboxes. For this application there is important that the fitting is tight enough to generate enough friction to prevent the gearwheel from sliding on the layshaft, but not so tight that the stresses in the gearwheel will decreasing its fatigue strength.

The layshafts are manufactured from low carbon steel forgings that are soft-machined using turning, drilling and milling processes, hardened by carburizing and then hard machined before being assembled by press fitting and mounted into the gearbox.

![Diagram of process steps of layshaft and gearwheels production.](image)

In order to increase the production of layshafts to meet higher demands the hard machining process of the layshafts are to be replaced at Scania. Earlier test of the torque of slip ($M_s$) e.g. the torque required to rotate the gearwheel on the layshafts, have shown that $M_s$ is lower for the layshafts hard machined with other methods than with the current one [1] [2].

The hard machining process is an important step in manufacturing to get rid of the changes in shape that can occur in the hardening process [3]. The hard machining is also important because the surface structure and roughness will be formed in this step. The surface roughness of the layshaft press-positions e.g. the position where the gearwheels are placed on the layshaft, along with the counter surface from the gearwheel is important to achieve the friction needed to prevented movement between the two components. Studies has shown that for joint strengths where an adhesive is used surfaces with a Ra of 1.5 µm will have the highest resistance against movement compared with both rougher and smoother surfaces [4].

The material properties and especially the hardness for the steels used in the layshaft and gearwheels are also important on the issue of friction. If one surface is smooth and hard while the other is rougher and softer, the friction will depend on the adhesive part of the friction. The peaks of the rougher surface will then deform plastically as they are pressed towards each other. The friction force will then depend on the shear strength of the softer material and the contact area between the two surfaces. On the other hand, if one of the surfaces is softer and smoother than its counter surface, the peaks in the harder and rougher surface will plastically deform the softer surface and creating notches as they are moved and a so called ploughing effect are occurring along with the abrasive contribution to the friction seen in Eq. (1) [5].
\[ F_f = F_{\text{adhesive}} + F_{\text{abrasive}} = \tau \cdot A_r + H \cdot A_p \quad (1) \]

Where \( \tau \) is the shear force, \( H \) the hardness of the material \( A_r \) and \( A_p \) is the real contact area and ploughed area i.e. the area deformed when the surfaces move. \( F_f \) is the friction force. To estimate \( A_r \), 

\[ A_r = \frac{F_N}{H} \quad (2) \]

Where \( F_N \) is the normal load applied in between the surfaces and \( H \) is the hardness of the softest material.

In the case of the friction between the layshaft and gearwheel, it is a bit more complicated than the two circumstances described above. The material and the production method of the two components is roughly the same, which may influence the friction while the contribution from the abrasive part becomes smaller.

During the hard machining, there is also a risk for a so-called white layer formation occurring from heat affection of the material nearest the surface. This might happen if the cooling between the working tool and the machined part is not efficient enough, the martensitic structure in the absolute surface of the machined part can transform from a martensitic structure to an austenitic which will lead to a change in the surface hardness. This will also decrease the shear strength of the surface which will affect the adhesive part of the friction. This transformation will also occur under the nominal phase transformation temperature for austenite [6].

Because the white layer will only affect the outmost \( \mu \text{m} \) of the material, the surface will have a soft coating laying on top of a hard material. The shearing will occur on the top layer while the harder main material will still be carry the main load.

The layshaft-gearwheel interaction becomes even more complex because of the Loctite added to the layshaft surface before the press fitting of the gearwheel. The purpose with the added Loctite is to create a better adhesion between the layshaft and gearwheel and the \( Ms \) between the two parts are increased with 4.6 kNm when used [7].

1.2 Environmental Effects
One of the reason for changing the hard machining process is to minimize the environmental impact. Since hard machining methods using no or less cooling fluid are favourable, since this will remove the processes of purchasing, handling and recycling these fluids. This would make the hard machining process more environmentally friendly.

1.3 Purpose
To improve the productivity of the layshaft manufacturing process, Scania in Södertälje, Sweden, are aiming to replace the current hard machining method for a new and faster process. During torque tests of layshafts produced with the alternative hard machining methods the torque at which the gearwheel started to slide the layshaft was lower than for the current one even though the layshaft was inside the tolerance span regarding surface roughness.

Today, the roughness requirement is based on experience from the current manufacturing method, and how it should be performed to achieve the required performance. This means that the requirement in itself does not give a sufficient description of how the surface should look, but is instead use only as a mean for controlling the process. If the manufacturing method is to be changed, it is therefore necessary to revise the requirement, so that it is certain that it still leads to the required
function. Ideally, the requirement should be "method neutral", and sufficiently describe a functional surface, regardless of the manufacturing method.

The purpose with this study is therefore to investigate if there is any surface parameter who will have any relation with the $M_s$. In addition, investigations of the surface characterisation of the different hard machining methods and the surface contact between the layshaft and gearwheel are made to see the differences between the hard machining methods.

1.4 Aim
The aim with this study is to find a way to know that the product requirements are fulfilled as long as the surface roughness requirements are achieved, but also to investigate differences between the hard machining methods.

2. Theory
2.1 Gearbox
To be able to understand the layshaft role in the gearbox, an explanation of the gearbox function is needed.

The purpose of a gearbox is to transform the engine outgoing engine speed to different and more widely range of speeds out to the driving wheels in the case of a vehicle. This speed transformation accomplished towards a number of different shafts and gears.

A schematic picture of the gearbox is seen in Figure 2. In principle a manual gearbox contains three shafts and a different number of gearwheels depending on the number of gears in the gearbox. The gearwheels can either be fixed to the shaft or have the possibility to move. The input shaft (yellow) connected to the engine and connects to the layshaft (purple) by gearwheels. On the layshaft, gearwheels for the different gears are placed and are in contact with other gearwheels on the mainshaft (green). All the gearwheels are fixed on the input shaft and layshaft while the gears mounted on the mainshafts can rotate and are locked by the gearbox synchronizing.

Figure 2 - A simplified picture of how a gearbox work with the input shaft in yellow, layshaft in purple, mainshaft in green and the revers in red. All complete with synchronizers and gearwheels.
2.2 Process Methods

In this study, layshafts produced by a number of different hard machining processes are investigated. The axial ($z$-direction), radial ($r$-direction) and tangential direction ($\theta$-direction) for the layshaft is shown in Figure 3.

![Figure 3 - Cylinder to show which different directions who is possible for a cylinder to have in this case.](image)

2.2.1 Grinding

In ceramic grinding, a multi-edge tool usually made from alumina ($\text{Al}_2\text{O}_3$) with geometrical undefined cutting edges are used to remove the metal chips [8]. The grinding method explained here is peripheral plunge grinding when the shaft is turning in the $\theta$-direction and will have a grinding wheel who will turn in the opposite direction. This process will produce a lot of heat so the using cooling fluid needs to minimize the risk of microstructural changes such as white layer in the surface.

Grinding will, different from the hard turning create a surface who are more irregular [9]. This because of the undefined geometry of the cutting edges in the grinding wheel. There is also possible to use other grinding wheels such as CBN (Cubic Boron Nitride) grinding wheels which has a higher thermal conductivity and are harder than the ceramic grinding wheels made of alumina [10].

2.2.2 Tape Finishing

In Figure 4 a schematic picture of tape finishing is shown. A finishing tape is in contact with a rotating work piece. At the contact point both the workpiece and the tape is moving in the same directions but in different speeds. The surface roughness of the work piece after finishing and the material removal is depending on the roughness of the tape. During the process that tape can be oscilated to create a cross hatch pattern [11].

![Figure 4 - Schematic figure of tape finishing [11]](image)
2.2.3 Hard Turning

Hard turning is defined as turning on a workpiece with a hardness who exceeding 45 HRC but it is regularly performed on workpieces with a hardness of 60 HRC or harder [10]. The turning process is similar to the one used in ordinary soft turning. That means that a round workpiece is fixed in the z-direction. A one point cutting tool is then removing material from the r-direction of the workpiece. The cutting tool moving over the rotating workpiece surface in the z-direction [12].

Hard turning is a fast, economic and environmental friendly process because of the short process time, small and easy replaceable wearing parts and that it is working without any cooling fluids, [13], which are possible because the chips from the cutting removing the heat from the workpiece [14].

The turning process will however create a surface on the workpiece that will have a higher smoothness along the θ-direction than in the z-direction because of the one point cutting tool who are moving over the surface.

2.2.4 Rotational Turning

Rotational turning, seen in Figure 5, is a combination between the milling and the turning process. The setup is similar to the turning process, but instead of a one point cutting tool a wider tool is used. This wider tool will go from a point A to a point B and cut of material from the part while the part is spinning [15].

This will make this process better suited for wider and planar cylindrical surfaces. This method will also, compared to hard turning, need shorter machining time and have a longer tool lifetime [13].

![Figure 5 - Picture of the rotational turning process [16].](image)

2.3 Material

2.3.1 Metals Structure

During the hard machining of metals, material is removed which creates deformation in the material. This high load may have an impact of the material properties near the surface because of the machining.

Metals are built up by atoms organised in different crystal structures such as FCC and BCC. These different structures will give different material properties due to differences in slip directions between the crystals structures i.e. how the atoms in the metal structure can move compared to each other. When these crystal structures are not aligning with each other a boundary will form. These boundaries will create grains in the metal, all with different slip directions.
There are however, irregularities in the crystal structure called dislocations. The dislocations will hinder movement between the atoms in their slip directions which will make the material hard and more brittle. During deformation of a metal, the dislocation density will increase. When the metal is heated, dislocations will act like nucleation point for new grains, which will make the grains in a deformed area smaller than in a less deformed area [17].

Hardened steel will have a martensitic structure which is formed when an austenite (FCC) phase in steel is quenched and are harder but also more brittle than the ferritic and austenitic structures. This because carbon atoms will be included in the structure and creating a BCT structure instead of a ferritic (BCC) structure and hinder slip directions for the atoms.

The high temperatures which can be achieved in the hard machining process together with interaction with the environment can create a so called white layer formation where the martensite in the hardened material transforms to austenite and a high content of retained austenite will be found in the material and the hardness will be decreased. The retained austenite in the white layer may formed even if the surface temperature is below the nominal ferrite-austenite phase transformation temperature in the Fe-C phase diagram [6].

2.3.2 Surface Roughness

Even if the surface of a material seems to be completely smooth, there is always some roughness of varying degree. This roughness will look different depending on the machining method used to profile the surface. To be able to explain and to compare and categorise different surfaces a number of surface parameters are used.

There are three types of surface roughness parameters that measuring amplitude, spacing and hybrid parameters. A single line scanning the surface by a profilometer achieves these parameters, calculated through the surface profile (P-profile). The P-profile is then divided to one roughness profile (R-profile) and one waviness profile (W-profile). All profiles are seen in Figure 6.
From the R-profile R-parameters is obtained. $Ra$ is one of the most commonly used roughness parameter, often for its ability to obtain stable values. There is however variety of different amplitude surface parameters for example the maximum profile peak height or valley depths, $Rp$ and $Rv$, the total height of the profile, $Rt$, the maximum height of the profile, $Rz$ and the skewness of the assessed profile, $Rsk$. A spacing parameter are the mean spacing of profile elements, $RSm$ while the root mean square slope of the assessed profile, $Rdq$ is a hybrid parameter and the kurtosis of the assessed profile is a functional parameter [18] [19] [20].

Other parameters who are measure the total profile height and the peak height and valley depths. Two surface roughness parameters who have a relation with the friction are skewness and kurtosis of the assessed profile, $Rsk$ and $Rku$. $Rsk$ measures the asymmetry of the height distribution. It is an important parameter as it gives information about the morphology of the surface. Positive values indicate that high peaks are spread on a regular surface and negative values towards that the surface has scratches and pores. $Rku$ is measure the sharpness of the profile [20]. These parameters can also be obtaining from the $P$ and $W$-profile but then as $P$ and $W$-values. Histograms surfaces with different $Rsk$ and $Rku$ values are shown in Figure 7.
3. Method

3.1 Layshaft

Production layshafts was hard machined with four different methods. From these four methods the layshafts are produced with different surface roughness’s both at Scania CV AB at Södertälje, Sweden, at different subcontractors or Scania production sites. From these four methods, layshafts with different press-positions surfaces was manufactured.

Production gearwheels were picked and matched to the layshafts to obtain a difference of the fitting of ± 4 µm between the studied shafts. The gearwheel diameter is smaller than the outer diameter of the layshafts press position. The gearwheels are pressed on to the layshafts with Loctite in the same manner as in the ordinary production with the pressure force needed to get the gearwheel into position measured.

The layshaft-gearwheel package was then torque tested in a test rig to investigate at which torque the gearwheel started to slide on the layshaft. The geared side of the layshaft was placed into a hub connected to an engine and the gearwheel was fixed in the tangential direction as seen in Figure 8. Between the layshaft and gearwheel, an extensimeter was mounted to measure the movement of the gearwheel. The torque was increased until the gearwheel started to move towards the layshaft.

The torque test was made in two batches with standard layshaft used as reference in each batch. In the torque test, a minimum of three layshafts with the same press-position surface was tested. With
the help of the torque test thirteen layshafts was selected, including one reference layshaft from each batch, for further investigation. These two layshafts were in the \textit{Ref} group seen in Table 1. To extend the surface measurement ten layshafts from batch two was also included in the study. These layshafts were from the same groups as the thirteen layshafts selected for further studies.

Thirteen layshafts were divided into ten different groups based on where they were produced and on the hard machining method used. In the \textit{CBN M} and \textit{SLA} groups, there are two layshafts. For those groups some layshafts behaved different in the press fitting and torque test and were selected for further investigations.

Information regarding batches, methods and manufacturing are presented in Table 1. For the hardness and microstructure analysis one layshaft was taken from the production line before any hard machining had been performed to be used as a reference of how the microstructure and hardness changes during the hard machining.

\begin{table}[h]
\centering
\begin{tabular}{|l|c|l|l|l|}
\hline
Layshaft Name & Batch No. & Machining Method & Group & Manufacture \\
\hline
A & 1 & Ceramic grinding & Ref & Scania \\
B & & Tape finishing & Tape Pol. & Scania \\
C & 1 & Rotational turning & Rot. Tur. & Scania \\
D & & Ceramic grinding & Ker & Scania \\
E & & Ceramic grinding & Ref & Scania \\
F & 2 & Ceramic grinding & Ker M & Subcontractor \\
G & & CBN grinding & CBN M & Subcontractor \\
H & & CBN grinding & CBN M & Subcontractor \\
I & & CBN grinding & CBN F & Subcontractor \\
J & 2 & CBN grinding & CBN R & Subcontractor \\
K & & Ceramic grinding & Cat & Subcontractor \\
L & & Ceramic grinding & SLA & Scania Argentina \\
M & & Ceramic grinding & SLA & Scania Argentina \\
N & Non & - & Scania \\
\hline
\end{tabular}
\caption{Information regarding the layshafts included in the study.}
\end{table}

\subsection*{3.2 Sample Preparation}
A ATM Brilliant 255 cutting machine was used for the cutting. A cut was made in the gearwheel which was then removed from the layshaft. Pieces from the layshaft press-position named A1 and A2, shown in Figure 9, were then cut off from the layshaft together with a piece from the gearwheel. The A1 and A2 press-positions were halved to slices of three cm. From the outer press-position the slices are named A1:1, A1:2, A2:1 and A2:2.
Pieces from A1:1 and A2:1 were then cut out from the slices with a thinner blade. Similar pieces were also cut off from the gearwheel piece. The pieces for use in hardness test and microstructure analysis is casted into Bakelite, ground and polished to achieve the required surface for hardness and microscope. Before the microstructural analysis, the samples were etched with a 2% nital solution for 10-20 seconds depending on the sample. Smaller pieces were cut from the slices for SEM analysis.

### 3.3 Experimental

#### 3.3.1 Hardness Measurement

To establish the hardness of the material, a Vickers hardness test was conducted on the Bakelite cast cross-section samples from the A1 and A2 positions and from the gearwheels. To measure the hardness as close to the surface as possible, a load of 100 g was used and the first indent was made 10 µm from the cross-section surface.

Five sequences with sixteen indentations on each one was made on the samples with a KB 30S Vickers indenter using HV0.1 following a prearranged pattern shown in Figure 10. The hardness measurements are following the Swedish standard for Vickers hardness except for the two indentations closest to the surface [21]. These two indentations have been placed nearer to the surface than allowed in the standard with the purpose to see the hardness closest to the surface. A mean value of the indentations at every depths was calculated from the five sequences to establish the hardness of the sample.
3.3.2 Microstructure Analysis
The samples from the hardness test were etched and used for the microstructure analysis. The samples were analysed and pictures were taken with a light optical microscope (LOM) in five, ten, twenty and hundred time’s magnification. Microstructure analysis was conducted on both A1, A2 and on gearwheel samples.

3.3.3 Surface Measurement
To analyse the surface roughness of the layshaft and the change of surface after the torque test a Mahr MahrSurf GD25 profilometer with a 2 µm tip, a scanning distance of 5.6 mm and a measuring distance of 4 mm is used and is shown in Figure 11. The A1 position was assumed to represent an unchanged surface. This due to the smaller radius than the gearwheel and therefore no contact with the gearwheel have occurred.

Before the measurements, the measured surface was cleaned with an alcoholic based washer fluid in order to remove lose Loctite remains and other kind of dirt on the sample surface which can interfere with the result. Surface measurements was conducted on three locations around the layshaft sample were measurements in both axial and tangential directions were made. In the same manner the gearwheel samples were measured but only on a smaller area and not around the whole gearwheel inner surface.

Analysis of the surface profiles, both individually and the fitting between the layshaft and the gearwheel, was conducted using Matlab scripts. Because no measurements were conducted on the gearwheel from layshaft A and D, the gearwheel from layshaft E was used for the analysis.

To evaluate the fitting between the layshaft and gearwheel assumptions are made for the pressure between the surfaces, and the hardness of the gearwheel and layshaft surfaces. The pressure between the two surfaces assumed to pressure equivalent to the fitting for these layshafts and gearwheels. For the hardness assumption the result from the hardness measurements are used and then calculated to GPa by the definition of Vickers hardness \( HV \) seen in Eq. (3) [22].

\[
HV = \frac{1.854P}{d^2} \left[ \frac{kgf}{mm^2} \right]
\]  (3)
Where \( P \) is the applied load in \( kg \), \( d \) is the diagonal distance of the indentation, \( F \) is the applied force and \( A \) is the area of the indentation. The pressure (\( \sigma \)) is defined by force divided by area and therefore Eq. (4) is multiplied by gravity (\( g \)) and divided by 1 000 to get the answer in \( GPa \).

\[
\sigma = \frac{g \times 1.854P}{1000d^2} = \frac{F}{A} \quad [GPa] \quad (4)
\]

The gravity is assumed to 9.81 m/s\(^2\). The hardness is then calculated and assumed to 7 \( GPa \) and the same for both gearwheel and layshaft.

The profiles used was the P-profiles where the curvature and slope of the curves was filtered away in order to get the surfaces to align with each other.

### 3.3.4 Surface Visualization

For the SEM analysis samples from A1:1 and A2:1 positions along with the gearwheel was used and with a surface area of approximate 1x1 cm. The samples were washed with ethanol in an ultra-sonic washer machine for five minutes and dried before inserted in the microscope. Pictures of the surfaces was then taken with 500, 2 500, 5 000 and 10 000 times magnification.

### 4. Result

#### 4.1 Torque Testing

The torque test showed that the layshafts from the groups \( SLA \) and \( Cat \) produced by ceramic grinding together with the CBN grinded from group \( CBN \text{ R} \) are the layshafts who has a \( Ms \) that are similar or higher than the reference for all of the layshafts tested in their group. The tape polished, \( CBN \text{ F} \) and rotational turned layshafts together with the ceramic machined layshaft \( D \) has an \( Ms \) values under the requirement. In addition, \( CBN \text{ M} \) and \( Ker \text{ M} \) had layshafts with \( Ms \) both under and over the requirement.

![Figure 12 - The result of the torque testing for the layshaft included in the study.](image)

#### 4.2 Microstructure and Hardness Analysis

The microstructural analysis of the layshafts shown that there is small difference between the A1 and the A2 position for all of the layshafts. There was also only small visual difference of the microstructure between the layshafts hard machined with different methods.

The layshafts have a martensitic structure with a small amount of retained austenite in the carburized surface who proceeds to bainitic structure longer into the material.
The hardness result for the layshafts is shown in Figure 13 and the result is similar for most of the layshafts with a lower hardness in the first indentation point and with an increase of 6-7 percent in hardness to the second point at 0.02 mm. The hardness then decreases again 0.5 mm in the sample and decreases constantly to the last indentation at 1.1 mm.

In Figure 13 it is possible to see that layshaft K and to a certain extent also layshaft M have a hardness of 70 and 83 percent of the hardness of the Ref layshaft and softer then the other layshafts in batch 2 and are for layshaft K in the same size for both the A1 and A2 position. The microstructure of layshaft
K and F in Figure 14 show that the hardened zone is smaller for layshaft K which has a softer bainitic structure nearer to the surface [23].

Figure 14 - LOM pictures of in 5 times magnification of A2 positions of layshafts K and F

In batch 1 the hardness 0.01 mm from the surface of the un-machined layshaft N is around 68 percent lower than the hardness for layshaft A, B and C and are seen in Figure 16. A higher surface hardness is seen in A, B, and C together with J in comparison with the layshafts from both batch one and batch two. The surface hardness of D is also lower than the machined layshafts in the A2 position. The microstructure of layshaft D, seen in Figure 17, shows that the surface has been heat affected and white layer has formed nearly the surface of the sample. The white layer is found in the first few µm from the surface where the remaining 20 µm in from the surface consists of a fully martensitic phase. From 20 µm the microstructure is the same as in the other samples at the same depth. This heat affected zone with white layer has only been found in the A2 position of layshaft D.
4.3 Surface Analysis

4.3.1 Surface Parameters

Small correlations between the surface parameters and $M_s$ was seen in the measurements taken in the axial direction and no visible correlation for the measurements in the tangential directions has been seen in all $R$, $P$ and $W$-values studied, with exception for $R_{sk}$ in the A1 tangential direction and $W_{a}$ in both A1 and A2 tangential direction where the correlation is similar to the axial measurements.
4.3.2 Surface Characterization

The surface structure, investigated with the surface profiles from a profilometer and by SEM images. The tape-finished layshaft B shows a different surface pattern and having a less orientated surface than the layshafts machined with the other methods for the A1 position that can be seen in Figure 19.
From the SEM image there is also possible to see that the A2 surface has a smoother surface than the surface from the A1 position. This can be seen on the profiles and $R$-parameters of the surface where $R_z$ together with $R_t$, $R_p$, $R_{ku}$ and $R_{dq}$ is lower and $R_{sm}$ is higher on the A2 surfaces compared with the A1 surfaces. All together, these parameters indicate that the A2 surface have flatter and lower peaks that are longer from each other.
The layshaft with the largest difference between A1 and A2 is layshaft D where the A1 surface is 40 to 75 % rougher than the A2 surface for the Ra, Rz, Rt, Rp and Rv as well as for the corresponding P and W-values. For the simple roughness amplitude parameters and Rz layshaft C, F, G and partly M have a large difference between A1 and A2 surface in the tangential direction but here the A2 surface is rougher than the A1. The measurements also indicate a much larger waviness in the axial A2 position for some of the layshafts.

The differences between A1 and A2 positions for layshaft L show that the A1 position is rougher in tangential direction while it is smoother in A2, which also are seen in the roughness parameters analyzed except for the axial P-parameters and for Psk and Wku in the tangential direction. This layshaft are the only one showing this pattern.

No correlation between the difference between A1 and A2 positions and the performance of the layshafts has been found.

4.3.3 Layshaft-Gearwheel Interface
The Matlab simulations show that all of the boundaries between the layshaft and gearwheel have an area with no contact between the two surfaces. The distance between the two surfaces is depending on the surface roughness of the layshaft, which can be seen in Figure 21, for layshaft I with a Ra-value of 0.10 µm and Figure 22 were layshaft E with a Ra-value of 0.70 µm is shown.
This correlation can be seen in the histogram for the respective layshafts. The layshafts with a rougher surface will have a larger distribution of the distance between the two surfaces and have the peak in the histogram, i.e. the distance between the surfaces that is most common, at higher distances compared with the layshafts with smoother surface, which have a smaller interval and distances. Therefore, the peak for layshafts with a lower Ra-value will be higher and more pointed as it is for layshaft I in Figure 21.

A higher periodicity will also influence the distribution of distance between layshaft and gearwheel. With a high periodicity and a large Ra-value, the distribution is more evenly spread over a larger range of distances as in the case of layshaft L seen in Figure 23. In addition, the histogram for layshaft L indicates that two maximums are present, one at 1 µm and a second one between 4 and 5 µm.
The CBN grinded layshafts will also have a higher distribution of contact points than the other methods. For the CBN machined layshafts, a trend where the contact distribution is increasing with lower Ra-values. A similar trend has not been seen for the other layshafts independent from which hard machining method used and the contact distribution for these layshafts are about the same.

5. Discussion

5.1 Hardness and Microstructure

Layshaft $D$ is the only layshaft that has a heat affected surface from the machining with a white layer formation as a consequence. The $Ms$ for this layshaft is lower compared with other layshafts with similar surface parameters. White layer consists of martensite that under the heat affection has transformed to austenite [6]. Austenite has a lower hardness and is easier to shear because of the FCC structure instead of the BCT crystal structure in martensite. The roughness of $D$ is also higher than for the gearwheel, which means that a rougher and softer surface will be in contact to a smoother and harder. This will lead to that the abrasive contribution to the friction will be smaller and the friction will rely more on the adhesive contribution.

One possible explanation to why a phase transformation has occurred on the layshaft $D$ surface is that it was attempted to see how low the surface roughness could be with the ceramic grinding used for the reference layshafts and the process was therefore not stable, which can explain why the A2 position was effected more than the A1 were no affection from heat was seen. The grinding disc was also not fine enough to grind so smooth surfaces, which resulted in that the cooling required for machining of the reference layshafts was not enough when finer surfaces wanted to be reached.

The hardness measurements showed that more layshafts than $D$ are softer near the surface even though $D$ was the only one where a heat affected zone was discovered. This softening near the surface was also smaller than the softening for $D$, which could be seen further in from the surface. This softening in the layshafts without visible heat damage probably depends on the indentations, being placed to near the surface. On some of the indentations the indentation mark is not square (rhombic) which indicates that the small amount of material between the indentation and the material edge cannot hold the load from the indentation and it will collapse which will end up in a hardness that appear softer than it really is. Another, more probably explanation to the indent shape is a rounding of the edge of the steel sample which emerge from the polishing because of the difference in hardness.
between the Bakelite and the steel and therefore a difference in how easily material can be removed during the process.

The difference in hardness further into the material seen in layshaft $K$ and $M$ is from a difference in hardening depths between the layshafts. This difference comes most likely from that the layshafts has been hardened in different batches where the hardening conditions and the hardenability might differ between the samples.

A small correlation between $Ms$ and the surface roughness within the CBN machined group has been seen if layshaft $G$ is excluded due to it behaviour at the press fitting. It is possible to see that the layshafts with the smoothest surfaces have a lower $Ms$ than two rougher ones. The correlation is not linear and the two rougher ones ($H$ and $J$) are both close to the reference layshafts while the finer $I$ have a $Ms$ 15-23 percent lower than the reference. The CBN machined $H$ and $J$ are also the only layshafts studied further that have similar $Ms$ as the reference layshafts. The only difference seen for layshaft $G$ is the lower hardness in the A1 position, but nothing other has been seen that explain why layshaft $G$ differed from the other in the press fitting. Black circular areas were present in the microstructure of $G$, which might be pearlite, but this has not been investigated [23]. That this only occurs on the A1 position makes it hard to believe that it would be the factor that makes the layshaft behave differently in the press fitting.

5.2 Surface Parameters and Characterization

The surface roughness parameters showed no or only weak correlations with $Ms$. A correlation can neither be seen in the profile and waviness parameters studied. Not even for the skewness and kurtosis parameters that have shown has a good correlation with the friction between surfaces in studies [24] [25]. Both of these studies however used polished and very smooth counter surface instead of a real surface used in this study. Other surface parameters used to evaluate frictional forces such as $Rz$ and $Rp$ and their corresponding profile and waviness parameters, do not showing a better correlation with $Ms$ than the other surface parameters evaluate [18].

By using a counter surface, the problem gets more complicated in the case of friction between the two surfaces. It will for example be much more difficult to predict the real contact area when also the counter surface will have a topography and there for much harder, to not say impossible to calculate the contribution from the adhesion part in the definition of friction. The fitting of the two surfaces along with the possibility that the peaks from the two surfaces will hook up to each other will also have to take into consideration. The influence of Loctite and the hardness of the two surfaces will also increase the complexity of the problem. The complexity with all the factors involved may be a reason why no strong correlations between $Ms$ and the surface parameters have been seen in this study.

Compared with other layshafts with similar surface roughness in the study layshaft $C$ has a lower $Ms$. Similar tendency has been seen for the CBN layshafts ($G$, $H$, $I$, $J$) where the smoothest layshafts has the lowest $Ms$ and the roughest the highest. While all the CBN layshafts have approximate the same hardness in the surface, $C$ is harder. As discussed above the hardness will have an impact on the abrasion part of the friction where a hard and rough surface will dig into the softer one. Nevertheless, if the surface, as in the case with $C$, is finer and harder than the counter surface the contribution of friction from the abrasion part will be smaller and finally the friction will only depend on the adhesion part. This may be the reason why smoother surfaces seem to show a lower $Ms$. Even when the difference in hardness between the surfaces is small as in this case the surface parameters shows that a ploughing effects still exists but it will be smaller if the smoothest of the surface also is the hardest.
The surface of the layshafts in the SLA group (layshaft L and M) distinguish from the other as the surface have characteristics that reminds of a hard turned surface even though has been grinded with a ceramic disc [13]. This surface pattern is the most common pattern on the SLA layshafts but varies over both layshafts and press positions. A possible explanation for this surface pattern are that it has been made in the grinding disc during sharpening and then been transferred to the layshaft. The choppy shape of the torque-slip curve for layshaft M have probably occur from the extensimeter.

In the torque test the gearwheel of the SLA layshafts started to slip at lower torque. The movement stopped after a slip of around 0.05 mm and then kept its position until the Ms was reached. Similar movement was also seen in a smaller extent for some of the other layshafts, but not in the same extent as for the SLA layshafts analysed. The torque slip curve is shown in Figure 24. This makes it reasonable to believe that resistance against movement has only been dependent of the Loctite, which can hold up to 25-30 percent of the total torque [7]. The waviness is lower for the SLA layshafts, which indicates a more even height of the surface, which will favour the friction. The main difference for the SLA layshafts is a three to four time’s larger distance between the peaks than for the other layshafts and gearwheels in the study. This may result in that a smaller amount of surface peaks from the gearwheel will be in contact with the layshaft peaks and therefore the contact area will be smaller. The reason why the SLA layshafts have a Ms near the Ref layshafts may be, along with the other layshafts, a lower and mostly negative skewness on the A2 position than A1, which according to literature will indicate scratches in the surface [20]. This mean that a contribution from the abrasion part in the definition of friction is present and give reason to believe that the gearwheel has dig in to the peaks in the layshafts after the first slip and thereafter generate more friction which will increase the Ms for the layshaft. When the load in the torque test is cyclic, after the slip has occurred, more torque is needed to move the gearwheel towards the layshafts which support the idea that an abrasive contribution has to occur even due to the small difference in hardness between the parts. Of course, both the skewness and the kurtosis is sensitive to single peaks in the surface but the results are showing similar behaviour of the skewness and kurtosis for a majority of the layshafts tested.

![Figure 24 - The torque slip curves for the layshaft E (left) and L (right).](image)

The band polished layshaft B is the only one machined with oscillation and will therefore have a more unclear direction in the surface pattern then the other layshafts but there is nothing in the result who
indicate a difference behaviour compared with the layshafts who has a more directional orientation in the surface pattern.

5.3 Layshaft-Gearwheel Gap

The modelling of the gap between the layshaft and gearwheel was made to illustrate how the contact between the two items was made. Only rough filtration of the P-profiles was made to try to get a model that was as near the reality as possible. The measurements, based only on a 5.6 mm long profile and no attempts of best fitting of them was made.

Because the Loctite along with the contact points are having an impact on the Ms the distance distribution of the gap between the two items was studied. The contact and thereby the friction is located on only a few contacts points. The applied load in this model was set to the lowest required to get a correct fitting and will increase with the increase of load but the most of the surfaces will not be in contact of each other. If there only are a small amount of contact points the load on each point will be higher and the peaks will therefore be easier to deform than if more peaks are in contact with each other and there will be a larger distribution of load.

The Loctite is depending on the roughness of the surfaces to work properly. Studies has shown that the optimal surface roughness of the surface were an adhesive is applied is with a Ra around 1.5 and that the bonding will decrease if the surface roughness is higher or lower than that [4]. A theory is that at very smooth surfaces as the one for layshaft C, the Loctite are pushed away when the rougher gearwheel is pressed on the layshaft, rather than hide in the valleys of a rougher surface.

As seen in the result the layshafts with a rougher surface are also having a distribution of the gap distance over more distances compared with the layshafts with a smoother surface, which can be seen in Figure 25. This may be one reason why the layshafts with smooth surfaces has a lower Ms than the rougher ones. At smoother surfaces the distance between the surfaces becomes so small that the Loctite due to its viscosity cannot wet the surface in the gap in an efficient way and less Loctite to hold the surfaces together. Histogram of the distance ranges can be seen in Figure 26.

![Figure 25 - Diagram showing the relationship between the surface roughness and the distribution of distances between surfaces.](image-url)
The CBN machined layshafts are showing a higher Ms than the other layshafts with similar surface roughness. In Figure 26 there is possible to see that the distribution of distances in or very near contact is higher than for the non-CBN machined layshafts. This indicates that the CBN machined layshafts will have more contact with the gearwheel and therefore, theoretically, have a higher friction from the increased contact area. The waviness for the layshafts in the CBN groups is lower than for the other layshafts. The waviness of the CBN layshafts are also the one most similar to the waviness of the gearwheel, which theoretically should give a higher contact area, and therefore, higher friction than if the difference in waviness between the two surfaces would be large.

Figure 26 - Histograms of the gap distribution between layshafts and gearwheel. Ms given in percent with layshaft E as reference.

The CBN layshafts is a better hard machining method regarding the cutting speed and productivity but it needs, similar to the ceramic grinding, a cooling fluid to avoid thermal damage on the workpiece. On this point the rotational turning and band polishing are better methods because the cutting process is working without any cooling fluids. Nevertheless, as seen Ms for those two methods are lower than the required limit of not lower than the reference layshafts. There might be another result if the real torque of gearwheel in the gearbox was used instead of the used requirement. The fact that the temperature in the gearbox during normal use is higher than room temperature can also effect the result. But there is however no reason to believe that a small movement in the tangential direction of the gearwheel towards the layshafts should do any big harm to the gearbox. The fact that the torque of the gearwheel increases as the load cycles are increased also indicate that even if slip will occur in the gearbox it will require more load and torque to get a second slip.

5.4 Further Studies

Even when no correlation between the studied surface parameters and Ms can be seen, there is possibility that there is a correlation. Roughness parameters as the mean height of the profile, Rc, Pc and Wc, Wd are not included in this study but can be used to evaluate the adhesion performance and friction force [18]. In addition, the average slope of the profile, Δα and the core roughness depths, Rk, has an impact on the friction [24]. There is also possible that the surface (S) parameters can have a correlation.
The influence of Loctite is another area where further studies is required. In this study the influence of Loctite was assumed to be the same as in the Loctite product sheet but studies have shown that the bonding strength depends on both the surface roughness and the fitting between the items [4] [7] [26]. The surface roughness is higher in these studies than on the layshafts and also conducted with a very smooth surface which are not the case in this study. The impact of the gearwheel surface from the press fitting and torque testing has not been investigated in this study.

Tests of layshafts produced with different hard machining methods would be tested in real gearbox under real working conditions to evaluate this study.

6. Conclusion

The purpose of this study was to investigate layshafts hard machined with different methods concerning the surface characteristics with the aim to find a way to predict the $M_s$ for the gearwheel when torque is applied.

The study shows:

- There is a weak or no correlations between the surface parameters and torque of slip, $M_s$.
- Layshafts with a harder and a smoother surface than the gearwheel surface has a lower $M_s$ than those with softer and rougher surfaces.
- There is no difference in the surface microstructure between the methods studied.

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8. List of References


