Monitoring of the Triboconditioning process

An investigation with Acoustic Emission

Daniel Strömbergsson
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Luleå University of Technology
Department of Engineering Sciences and Mathematics
Luleå University of Technology

Master thesis

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Author:

Daniel Strömbergsson

Supervisor:

Assoc. Prof. Pär Marklund

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Preface

The work presented in this master thesis has been carried out at the Division of Machine elements at Luleå University of Technology as a part of a development project lead by Applied Nano Surfaces. I would like to thank my supervisor Associate Professor Pär Marklund and Stephan Schnabel at LTU for important and valuable discussions. At ANS I would like to especially thank Emil Edin for supervision and help with the REA- and KamKalle test rigs, and Jonas Lundmark for help with project set-up and through discussions scoping the work. Also thanks to the SKF Condition Monitoring Center in Luleå, Per-Erik Larsson and Kent Olofsson for providing a monitoring system without charge, the access to the software and a lot of help with the set-up and optimization of the system.

Daniel Strömbergsson, Luleå, June 2015
Abstract

Applied Nano Surfaces has from laboratory studies developed a new finishing process, called triboconditioning, which combines a mechanical burnishing with coating the surface with tungsten disulfide. At present they are beginning the work to integrate the process into OEMs, for example Scania and Volvo Cars, production lines. As a step in this direction the idea of being able to monitor and evaluate the results of the triboconditioning process live as components are going through the process was proposed as an investigation area. This would ease the identification and discard of faulty components in a finished batch compared to spot testing. Also such a system could, in the best case, potentially observe early warning signals as to when the process results is starting to decline.

A screening of monitoring methods similar to the, from the start, proposed Acoustic Emission has been performed. This resulted in the selection to use an Acoustic Emission system to perform monitoring tests of the process. Such a system was provided from SKF Condition Monitoring Center, together with access to the SKF condition monitoring software.

To eliminate potential time related issues and dependencies it was decided to perform the monitoring on test series of the triboconditioning process in the laboratory at ANS, and to repeat previous test series with earlier investigated process results. To test runnability issues the burnishing tools were induced to wear and then used to perform treatments with set standard parameters.

The main correlation that could be drawn from the AE signal behaviour to the process results was that it clearly showed the point where the treatment was finished, and no more improvements of friction or surface composition could be expected by letting the process time continue. Signal behaviour indicating tool wear which had affected the process results was distinguishable, however no early signal behaviour correlating to the start of tool wear before it affects the process results were found.
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V
1 Introduction

The phenomena of wear is something that exist everywhere in the modern world, every machine and application that uses some kind of mechanical operation experience wear. The total cost of wear in the developed countries is estimated by Rabinowicz to upwards of 6% of the respective GNP [1].

Priest and Taylor presents figures of the effect of friction in the combustion engine and where the available energy in the fuel is used. 15% of the total 88% energy in the fuel that is lost is dissipated as mechanical losses where most consists of frictional losses, occurring at sliding or rolling contacts. Based on this actions performed on the sliding or rolling contacts resulting in 10% less frictional losses should decrease fuel consumption by 1.5% [2]. This percentage might not seem much, though applied to the petroleum consumption in Europe of 9.2 million m$^3$ per year [3] the implications of such an improvement becomes more clear.

Applied Nano Surfaces (ANS) has from research done at the Ångström Laboratory at Uppsala University, developed a finishing process which in laboratory tests show great promise to reduce friction and wear in sliding or rolling contacts. This by combining a burnishing operation and the chemical formation of a solid lubricant layer on the burnished surface. Tungsten when allowed to react with sulfur form tungsten disulfide which shares a lot of its tribological properties with molybdenum disulphide, after graphite the second most common solid lubricant. An explanation of the ANS process can be seen in Figure 1.

![Figure 1. Illustration of the ANS process [4]](image)

Burnishing will occur on the workpiece and cause flash temperatures in the contact between the workpiece and the carbide tools, which will initiate a chemical reaction with the tungsten and sulfur additives in the process fluid. This will create a tribofilm which fills in the microscale valleys left after the burnishing.
The focus of recent research has been on applying the process in OEMs manufacturing lines of components with sliding contacts, e.g. camshafts and followers from Scania and Volvo.

1.1 Purpose

As a part of the application of the triboconditioning process to component manufacturing lines ANS wishes to investigate the possibility to integrate a monitoring system, to be able to evaluate the results during the process with a non-destructive method. This to replace alternative common methods which include spot tests of friction and wear after a batch of components treated with the finishing process. Acoustic Emission was initially meant to be used as monitoring method, to such a degree that equipment had already been sourced, but before stating the work a step back was taken to allow a screening of similar methods and make a properly motivated choice.

The main goals of the thesis is:

- To investigate suitable process monitoring methods and make a motivated choice.
- Perform monitoring tests by repeating previous test series on the triboconditioning process, and setting up new test series of parameters correlating to runnability issues.
- Identify behaviours from the test data that can be related to results of the process and any eventual runnability issues.

The monitoring tests will be performed by repeating tests of the triboconditioning process in a test station at ANS, this will give test runs of parameters with known expected friction and surface composition results to identify correlations with the monitoring signal behaviour.
2 Theory

This section will present theoretical fields relevant to understanding the principles of the triboconditioning process, and some screened methods of process monitoring.

2.1 Tribology

The word tribology is derived from the Greek word for “to rub”, Tribos. Tribology is by van Beek defined as “The science and technology of interacting surfaces in relative motion, including friction, wear and lubrication” [5].

2.1.1 Friction and wear

Friction is the resistance towards movement between two object sliding or rolling against each other, see Figure 2. The resisting force of friction in relation to the normal force acting in the contact between the two objects defines the coefficient of friction (C.O.F.), \( \mu \).

\[
\mu = \frac{F_{\text{fric}}}{F_{\text{norm}}} \tag{2.1}
\]

Figure 2. Explanation of friction

In steel on steel contacts the C.O.F. will be as high as 0.8 and with bronze on steel 0.4. If these contacts are lubricated the C.O.F. are lowered to ~0.15 [5]. This occurs because the lubricant will partly or fully separate the surfaces, the lubricant regime goes from boundary to mixed to full film lubrication.

Wear can be divided into four fundamental mechanisms: abrasive wear, adhesive wear, corrosive wear and surface fatigue.

Abrasive wear occurs in a contact between two objects with different hardness, the asperities of the harder material will sink into the softer. The relative velocity between the two will cause a ploughing of the softer material by the asperities [5], an explanation on the micro scale can be seen in Figure 3.
Adhesive wear occurs when interacting asperities in the contact experience strong adhesive bonding, causing micro-welds [5]. Material can under continuous movement between the surfaces, transfer from one object to the other. The bonding between these particles and the surface is not always strong enough and will cause free wear particles to form in the contact.

These wear mechanisms can, according to van Beek [5], be reduced by the respective actions presented in Table 1.

Table 1. Actions for reducing wear [5]

<table>
<thead>
<tr>
<th>Reducing adhesive wear</th>
<th>Reducing abrasive wear</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Have one or both surfaces be a non-metal</td>
<td>• Combination of hard materials, less than 10 % difference ensures small penetration depth</td>
</tr>
<tr>
<td>• Carburising or nitriding</td>
<td>• Low roughness, possible by brushing or burnishing, resulting in a large asperity summit radius</td>
</tr>
<tr>
<td>• High hardness, difference by factor 3 to 5 between hardness values</td>
<td></td>
</tr>
<tr>
<td>• High roughness</td>
<td></td>
</tr>
<tr>
<td>• Solid or liquid lubricant, strong oxide film</td>
<td></td>
</tr>
<tr>
<td>• Thin top layer of low shear strength</td>
<td></td>
</tr>
</tbody>
</table>

Analytical calculations of friction and wear is based in large part on contact mechanics and central to this field is the Hertzian contact formulation, the line contact formulation below in its entirety is taken from van Beek [5].

The effective modulus of elasticity, \( E' \), is described as:

\[
\frac{1}{E'} = \left(\frac{1 - v_1^2}{2E_1} + \frac{1 - v_2^2}{2E_2}\right)
\]  

(2.2)

Where \( E_x \) and \( v_x \) is the elastic modulus and Poisson’s number for the respective bodies. The effective radius is derived from the effective radii of the two bodies:

\[
\frac{1}{R'} = \frac{1}{R_x'} + \frac{1}{R_y'}
\]

\[
\frac{1}{R_x'} = \frac{1}{r_{1x}} + \frac{1}{r_{2x}}
\]

\[
\frac{1}{R_y'} = \frac{1}{r_{1y}} + \frac{1}{r_{2y}}
\]

(2.3)
The mean contact pressure, $p_m$, is written:

$$p_m = \frac{1}{4} \left( \frac{\pi}{2} \right)^2 \left( \frac{F}{l} \right)^2 \left( \frac{E'}{R'} \right)^2 \tag{2.4}$$

Where $F$ and $l$ gives the applied force over the length of the contact. The max Hertzian pressure, $p_{max}$, is then given by multiplying the mean pressure with the factor $\pi/4$.

$$p_{max} = p_m \times \left( \frac{\pi}{4} \right) \tag{2.5}$$

### 2.1.2 Solid lubricants

As seen in Table 1 one of the ways to reduce adhesive wear is to add a thin top layer of what is known as a layered material, shown in Figure 4, with weak bonds between the layers and thereby a low shear stress. After a run in this allows the layers to organise parallel to the surface in the direction of motion and easily slide over each other [5], which results in a low C.O.F. of 0.1-0.2.

![Figure 4. Layered graphite [6]](image)

The most widely used dry lubricant is graphite, which is made up of hexagonal planes of carbon. Though the necessity of water vapour to weaken the van der Waals bonds between the planes makes the use of graphite restricted. Another widely used material group is disulfides, mostly in the form of molybdenum disulfide ($\text{MoS}_2$). These are constructed similarly and uses the same principles as graphite as a lubricant, but do not require water vapour and work best in vacuum or a dry atmosphere [7].

Tungsten disulfide ($\text{WS}_2$) is used as an alternative to MoS$_2$ and is, compared to graphite and MoS$_2$, more applicable in high temperature operations because of its higher temperature range before oxidation.

### 2.2 Triboconditioning

The ANS triboconditioning process utilises a burnishing operation to plastically deform the surface and lower the surface roughness. Flash temperatures in the contact between the tool and workpiece will initiate the chemical reaction between the process fluid additives,
which forms the WS$_2$ coating [5]. The burnishing tools is mirror polished bearing rollers made out of carbide steel, which by its high hardness ensures the deformation of the cast iron substrate of the samples. The process fluid consists of a synthetic oil as base with extreme pressure additives consisting of tungsten and sulfur.

The chemical reaction is not proven but a highly probable chemical pathway has been proposed [8]:

\[
\begin{align*}
\text{Sulphidation:} & \quad RS_nR' + \text{Fe} \rightarrow \text{FeS} + \text{RR'} \\
\text{Tungsten reduction:} & \quad \text{WO}_3 + \text{Fe} \rightarrow \text{FeWO}_3 \\
\text{Ion substitution/exchange:} & \quad \text{FeWO}_3 + 2\text{FeS} \rightarrow \text{WS}_2 + 3\text{FeO} 
\end{align*}
\]

Previous work focuses on optimizing the process parameters [9], composition of process fluid [10] [11] and compositions as well as thickness of coatings [7].

2.3 Monitoring methods

As the thesis work was set up it was decided to step back and decide the monitoring method before work had started, due to this a screening of the intended method of acoustic emission together with similar methods of process monitoring is presented in this section.

2.3.1 Acoustic emission

Acoustic emission (AE) is by Gou and Amulla defined as [12]:

“...transient elastic waves due to the rapid energy release from a localized source within a material when subjected to stress. AE sources can be dislocation movements, deformation, inclusion fracture, and crack propagation. The AE non-destructive technique is based on detection and conversion of these high frequency elastic waves to electrical signals.”

In mechanical applications AE-signals occurs due to friction and wear, the elastic waves originates from the breaking and removal of asperities and plastic deformation of the underlying material. The monitoring and quantifying is done by comparing certain behaviours on the given signal spectra to pre-defined reference values and behaviours.

AE-signals occurs at a wide frequency span, from 50 kHz up to 2 MHz [13]. The data is collected with highly sensitive sensors of a piezo electric material, converting the elastic waves to a voltage signal when deformed. These signals and trendline values sampled over time can be of two different types [14], examples shown in Figure 5 and Figure 6:
Theory

- **Burst signals**, which could indicate the sudden breakage of asperities and formed wear particles [15].

![Figure 5. A typical burst signal](image)

- **Continuous signals**, this is used when evaluating the wear in a contact and when trying to identify the critical point of accelerated wear when the behaviour of the signal changes.

![Figure 6. A typical continuous signal](image)

The analysis can be done continuously on the complete raw data, though the amount of collected data during the process monitoring can become unmanageable, up to Gigabytes/min and even more. By looking at the whole frequency span a lot of interesting information might be difficult to identify or lost, instead frequency bands can be identified which covers the interesting parts of the spectra and filters away noise.

By setting a threshold on how strong certain burst signals have to be to register as a warning of an AE-event, the formation of wear particles larger than an allowed size can be
monitored. The threshold is also used to eliminate the noise in the signal by performing a test run to identify the noise level and place a threshold just above [12].

2.3.2 Spindle torque

By monitoring the drive control current of the electric motor driving the spindle in a lathe the torque required to perform the operation can be monitored, this method is called spindle torque (ST) monitoring. This has proven to be a very sensitive process monitoring method, and practical because of the already built in connectors in CNC-lathe motors which makes the only equipment needed regular connecting wires and a data collecting box [16].

The current is passed through a built in resistance in the motor and the corresponding voltage can be sampled. The relationship between the measured voltage and the actual torque is described with the nominal values of torque and voltage given by the manufacturer [16].

\[ T = U_m \times \frac{T_{nom}}{U_{nom}} \]  \hspace{1cm} (2.7)

An example of a given signal when measuring spindle torque to monitor burr size at drilling operations on sheets of Al-alloyed steel to be used in the aerospace industry, can be seen in Figure 7 a) and the cutting operation part of the ST signal from a) can be seen in b) [16].
a) The full signal spectra

b) The cutting operation in a) of the signal spectra

Figure 7. An example of a ST signal [16]

From the shape in b) 5 different parameters could be identified in relation to burr height, each parameter had a threshold which if broken correlated to a higher burr height from the drilling operation than allowed. This shows that from an easy measurement a lot of complex information can be attained from an ST signal.

2.3.3 Contact resistivity

Contact resistance (CR), \( R_c \), is defined as the resistance experienced by a current which is passed through a contact between a workpiece and a cutting tool. By measuring the voltage over this contact, which will fluctuate dependant on the resistance in the contact, the process can be monitored [17]. This relationship follows Ohms Law:

\[
R_c = \frac{U_c}{I_c} \tag{2.8}
\]

By introducing the specific contact resistivity \( r_c \), which is experimentally defined between the contact components resistances, a relationship between the CR and the contact area can be formulated [18].
Monitoring methods

\[ R_c = \frac{r_c}{A_c} \quad (2.9) \]

This can give an indication to the state of the tool in reference to wear condition etc. Through an analysis the relationship between the voltage and the interesting parameter can be formulated, certain behaviours which differs from the reference behaviour can be related to different parameters and process results.
3 Measurement concept

The first step in setting up the measurement concept is choosing a measurement method. This choice was done by setting up a matrix of the advantages, disadvantages and uncertainties for each investigated method, which can be seen in Table 2. This method is often used as a first step of evaluation concepts, but due to the small amount of alternatives found in the screening the one that is deemed best at this stage is the one chosen.

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantage</th>
<th>Disadvantage</th>
<th>Uncertainties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic emission</td>
<td>• Signals up to ~2 MHz</td>
<td>• Complicated mounting and position placement of sensors</td>
<td>• Will there be enough elastic waves created by the process to monitor</td>
</tr>
<tr>
<td></td>
<td>• Wide array of options on tools for data processing</td>
<td>• Challenging to integrate into existing production processes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Previously used in burnishing operations</td>
<td>• Specific for each tribosystem</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Availability of equipment and software</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spindle torque</td>
<td>• No specific equipment, as opposed to AE</td>
<td>• Sampling speed determined by data collecting equipment</td>
<td>• Torque data at burnishing might drown in big lathes</td>
</tr>
<tr>
<td></td>
<td>• Equipment and set-up is the same for every case</td>
<td>• Raw data have to be processed manually</td>
<td>• Not a widely used method in research</td>
</tr>
<tr>
<td>Contact resistance</td>
<td>• No specific equipment, as opposed to AE</td>
<td>• Sampling speed determined by data collecting equipment</td>
<td>• No similar case have been found were the method is used</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Raw data have to be processed manually</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Not always compatible to run currents through machines</td>
<td></td>
</tr>
</tbody>
</table>

AE is the only method where there is more advantages than disadvantages and uncertainties. The disadvantages of AE listed are more relevant in future work, for the work presented in this report a set tribosystem with good access to sensor-mounting nullifies the disadvantages listed. This compared to the ST and CR methods which both have more disadvantages and uncertainties than advantages. Especially the fact that there is no
knowledge about what happens with the chemical process, which in itself is not fully understood, when an electrical current is added from the tool through to the workpiece discards the CR method as an alternative.

From this comparison the chosen measuring method is Acoustic Emission, of the investigated methods it is the one who provides most potential data and ease of which the analysis is performed. Even though AE measurements requires a lot more advanced equipment than the other methods this is provided from the SKF Condition Monitoring Center in Luleå.
4 Method

This section presents the AE equipment used, the test rigs and equipment to perform the triboconditioning test series. Also presented is previous work which was repeated and the complete test series which was investigated.

4.1 Acoustic emission equipment

The AE measuring equipment provided by SKF Condition Monitoring Center consisted of their Multilog IMx-W monitoring system, interface and cable assembly, two AE sensors and the @ptitude Observer software. An overview of the architecture of the monitoring system can be seen in Figure 8.

The IMx-W, also named Windcon, is primarily designed for monitoring vibrations in wind turbines [20]. The Windcon has 16 analogue DC and two digital input channels in which all can be used simultaneously.

The AE sensor type used is SKF’s CMSS 786M Accelerometer and Acoustic Emission Sensor [21]. The sensor has an accelerometer to measure vibrations and a piezo element to
measure AE with an sensitivity band of 100 to 500 kHz. The sensor were mounted by studs with an ¼” thread on the burnishing tool indicated as position 2, see Figure 9. This position were chosen because of the proximity to the operation contact and that it was the position with the minimal amount interfaces in between the sensor and the source which the generated waves had to propagate through. To see if vibration signals at a lower frequency which propagates through the tool and the holder could provide an adequate signal, mounting position for the sensor were placed further back on the tool holder, indicated as position 1. This will also give an indication to the limitations of the AE measurements at later stages when it have to be implemented on actual production processes.

![Figure 9. Explanation on sensor mounting positions](image)

The raw AE signal from the sensor is processed by a SKF CMON 2504 Interface card, which is needed to extend the functionality of the Windcon to include AE signals in addition to vibration [22]. The connection between the sensor, the Windcon and the interface card is made by the CMSS-ONL-2504 cable assembly. This allows the Windcon to monitor repetition frequencies from the AE-signal which is picked up by the sensor, so it is not the absolute raw AE-data which is monitored but it yields a spectra from which conclusions surrounding peaks and amplitudes potentially can be drawn.

The @ptitude Observer software is used to manage and analyse data collected by the monitoring systems both live and historic. Each different measuring point can be defined, and both the repetition frequency data spectrum can be extracted and a variety of signal trends and trendlines can be calculated. The data is stored by the monitoring system on a database which provides access to the data from any computer which have the software installed.

### 4.2 Measurement method

The AE measurements were performed on tests of the triboconditioning process in the test rig at ANS, named the REA-rig and can be seen in Figure 10. As the lathe rotates the load is applied and controlled through the spring to the tools on either side of a 100 by Ø22 mm cast iron test sample. Two electric motors each rotating a disk with swing arms mounted
Method

to the tool holder package will cause the tools to oscillate axially over the test sample resulting in a treated band of 18 mm.

Figure 10. Overview and close up of the REA process test rig at ANS

To get a foundation on which to build the analysis of the measurements on an old test series with evaluated results was repeated, this on experiments performed for another thesis work at ANS investigating load and time parameters influence on frictional performance and composition of the treated surfaces.
From this other parameters, which relates to issues that could occur when the process is implemented in a manufacturing process, can be varied to investigate if the behaviour of the signal distinctly changes. This will give an indication if the chosen method is suitable as a monitoring method on the implemented process at a later stage. If faults can be identified by the operator or the software the process can be shut down as the process results reaches a critical allowed level instead of performing spot-tests afterwards and having to discard whole or parts of component batches.

4.3 Evaluation methods of coating

To evaluate the process treatments performed in the test rig at ANS tests of the C.O.F. are performed. This is done in the ANS lab with their Kamkalle friction test rig seen in Figure 11, where a roller from a rolling bearing is pressed by a loaded spring against the test sample mounted in a lathe. Force measurements at C in the radial direction, corresponding to the normal force in the contact, and at B in the peripheral vertical direction, corresponding to the friction force gives the C.O.F. as explained in sec. 2.1.1.

![The friction test rig in the lab](image1)

![The friction test rig explained with B and C indicating load sensor positions](image2)

Figure 11. The Kamkalle friction test rig
Each test takes 15 min and consists of two accelerations up to 200 rpm and decelerations back to 0 rpm in the friction test rig lathe.

The results of the process treatments was also evaluated using an optical X-ray fluorescent (XRF) spectrometer, which investigates the composition of the surface by exciting electrons and analysing the emitted light as the electrons go back to equilibrium. This measurement is done to get a tangible performance result of the chemical reaction which occurs during the process. The measurement will be performed to a certain depth which is greater than the thickness of the WS$_2$ layer which are created with the process. Therefore the measurements will largely consist of the cast iron substrate and the percentage tungsten indicated cannot be used in itself, but can be used as comparison between treatments.

4.4 Previous work

Simultaneously as this thesis work another was performed at ANS by Frida Lemel, which investigated the content of tungsten and its correlation with the tribological properties of components treated with the triboconditioning process [23]. To investigate parameter effect on the resulting tribological properties and composition the load and process time parameters of the triboconditioning process was set as variables. Tests of the C.O.F. was performed according to the set-up presented in 4.3 for each treatment in both series, extensively repeated to minimize measurement faults. The resulting graphs is presented in Figure 12.
a) Varied load

Average value of coefficient of friction
process time 5 min and varied load

b) Varied process time

Average value of coefficient of friction
load 3kN and varied process time

Figure 12. C.O.F. results of series with varied load and process time [23]
With the XRF-spectrometer the compositions of each treatment could be investigated, these results are compiled in Table 3.

<table>
<thead>
<tr>
<th>Varied load</th>
<th>% Tungsten</th>
<th>Varied time</th>
<th>% Tungsten</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 kN</td>
<td>0.25</td>
<td>0.5 min</td>
<td>0.08</td>
</tr>
<tr>
<td>1</td>
<td>0.36</td>
<td>1</td>
<td>0.15</td>
</tr>
<tr>
<td>1.5</td>
<td>0.43</td>
<td>2</td>
<td>0.33</td>
</tr>
<tr>
<td>2</td>
<td>0.63</td>
<td>3</td>
<td>0.52</td>
</tr>
<tr>
<td>3</td>
<td>0.66</td>
<td>4</td>
<td>0.65</td>
</tr>
</tbody>
</table>

When converting these loads to Hertzian contact pressure according to eq.(2.2)-(2.5) the relevant input data is compiled in Table 4 and the resulting maximum pressures is presented in Table 5.

<table>
<thead>
<tr>
<th>Input data</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of elasticity, cast iron (test sample)</td>
<td>$E_1$</td>
<td>180 GPa</td>
</tr>
<tr>
<td>Modulus of elasticity, tungsten carbide (tools)</td>
<td>$E_2$</td>
<td>700 GPa</td>
</tr>
<tr>
<td>Poisson’s number, cast iron</td>
<td>$\nu_1$</td>
<td>0.26</td>
</tr>
<tr>
<td>Poisson’s number, carbide</td>
<td>$\nu_2$</td>
<td>0.18</td>
</tr>
<tr>
<td>Sample radius</td>
<td>$r_{1,x}$</td>
<td>11 mm</td>
</tr>
<tr>
<td>Contact length (tool diameter)</td>
<td>$l$</td>
<td>10 mm</td>
</tr>
</tbody>
</table>

Only the radius of the sample, $r_{1,x}$, in eq.(2.3) will have a value, the rest is flat surfaces and thereby an infinite radius.

<table>
<thead>
<tr>
<th>Load</th>
<th>Max contact pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 kN</td>
<td>0.47 GPa</td>
</tr>
<tr>
<td>1.0 kN</td>
<td>0.66 GPa</td>
</tr>
<tr>
<td>1.5 kN</td>
<td>0.81 GPa</td>
</tr>
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<td>0.94 GPa</td>
</tr>
<tr>
<td>3.0 kN</td>
<td>1.15 GPa</td>
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These values can be used when comparisons with other cases in future work, where different test setup is used. Though the load values is easier to grasp and more logical spanned and will be continued to be used through the thesis report.

4.5 Test series

As a repeating parameter the load was chosen, as the friction measurement results proved over a wider span than the process time [23], which would be the alternative. Also the friction results proved to be wider spread, this should ease the analysis of the AE behaviour as potential difference should be more pronounced.

To find the breaking value of the load where the process results start to decline have in previous work been found to be higher than the limit of the test rig itself, by performing the process at max load over a longer period of time a breaking point might be found. This to
try to identify signal behaviour correlating to overload which can be used at the set-up of the process on a new component manufacturing line.

As a step to investigate if AE can be used as a warning system for when the process start to fail, tool wear was proposed as an investigated parameter. To induce stages of tool wear the triboconditioning process was performed in the test rig for an extended period of time on a shaft of hardened steel (AISI 1040 hardened to 55 HRC), and a piston pin sample with DLC coating. These runs were performed on the same set of tools, thereby the stage of tool wear named DLC 15 min has already been through 2 hours of wear induced by the hardened steel shaft. Between each inducing run the triboconditioning process was performed with standard parameters of 3 kN and 5 min on regular samples. As a last step the process was performed on a DLC coating until coating failure, which also created a large wear particle on the tool, as described in sec. 2.1.1. Images after each wear operation can be seen in Appendix A.

All test series described above is compiled in Figure 13 to get an overview of the complete test series performed. To avoid complications of a single test to the overall result each test was performed at least twice unless direct complications demand more.

![Figure 13. Performed test series](image)

The entire test series described above and the numbering of each performed test with added comments surrounding complications will be appended in Appendix B.
5 Results

The trendline values for each tests, in the different series shown in Figure 13, will be presented in its entirety in Appendix 0, whereas this section will discuss general behaviour and correlations to the triboconditioning process and its results.

5.1 Initial test results

Before the formulated test series in sec. 4.5 were performed initial tests to optimize the software and gain experience using the test and friction test rigs were performed.

In addition to the software optimization the different sensor mounting positions were investigated this stage, with the result shown in Figure 14. The signal peak on the left corresponds to a 5 min test with the sensor mounted on the tool and the peak in the right to a test with the sensor on the tool holder.

The additional three interfaces from the tool to the tool holder mounting position will dampen the AE and vibration signals by a factor of 2.5 to 3 through the whole signal. From this it was decided to only perform the main measurements with the sensor positioned directly on the tool.

5.2 Test series results

From the results of the initial tests an general reoccurring AE signal shape could be distinguished, this was also observed when the measurements of the actual test series began. The observed shape is seen in Figure 15, the signal can be sectioned into three distinct parts depending on its behaviour.
From this sectioning a probable hypothesis of correlation to the triboconditioning process is proposed:

1. The initial spike occurs as the tools is pressed against the sample and the first burnishing deformation of the largest asperities.
2. The second section correspond to the main part of the asperity deformation where the surface roughness is smoothed out.
3. At the last stage the load has been distributed over a to large area to deform the surface any more, though the chemical reaction initiated in the contact might still occur.

A reoccurring shape on the vibrational signals picked up by the accelerometer in the sensor can also be observed. Though the overall strength of the signal varies depending on the position on the sample, towards the edges the signal is strongest while the middle treatment signal is weakest. A hypothesis is that this behaviour originates in the test rig lathes centerline alignment between the chuck and tailstock, which was measured on the chuck to be off center by 0.05 mm. Partly due to this, and partly due to the lack of clear correlation between the signal shape and process, no conclusions from the vibrational signal has been drawn.

5.2.1 Repeated test series
When examining the signal of each test some conclusions can be drawn. The initial spike does not seem to correlate to any logical parameter in the test set-up. The strength of the RMS signal spike, when a distinct spike can be observed, has a span between 0.15 to 0.21 RMS at random. This behaviour can be observed in Figure 16, where two tests with a load of 3 kN is followed with 3 tests of 2 kN.
Results

Figure 16. Monitored tests of 3 and 2 kN

Though while no conclusion surrounding the spike can be drawn from the figure above, the signal settles down consistently at around 3 min into the test. This behaviour is consistent with the other tests performed, with some outliers. When comparing this behaviour to the friction results in Figure 12 b) there is mild to no improvement between the 3 and 4 min long treatments. These findings and correlations support the hypothesis that as the AE signal decrease to a lower and smoother level the treatment is complete with only marginal improvements if any when it is allowed to run for a longer period of time.

The signal will decrease and smoothen out to the same level, regardless of the applied load. The difference the magnitude of the applied load can do to this signal is not significant enough to be detectable with this set-up.

Process results were evaluated with friction and composition measurements which can be compared to the results in Figure 12 and Table 3, these results are shown in Figure 17 and Table 6. Time limitations restricted enough repeated tests to eliminate error sources and position dependency on the treatment. The similarities with previous work proves that the repetition test series was successful and trustworthy conclusions on the monitoring results can be drawn.
Figure 17. Friction measurement results

As stated in sec. 4.3, the percentage values below is not absolute because of the XRF spectrometer and can only be used as comparison between similar treatment results. The standard deviation of the tungsten measurements was 2σ-0.03.

Table 6. Measured tungsten in treatments

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<td>0.66</td>
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</table>

5.2.2 Extended time/load series

Initial attempts to see if the triboconditioning results could be influenced negatively, if the process is allowed to run at max load for an extended period of time, yielded no workable results at an reasonable timeframe. Tests at both 10 and 15 min relative to the regular process time of 3-5 min showed no distinct difference in friction results. Friction tests at treatments of 5, 10 and 15 min can be seen in Figure 18.
Results

In Figure 19 the trendline signal of the three treatments can be compared.

![Trendline signals for the extended series](image)

**a) 5.5 kN and 5 min treatment**

**b) 5.5 kN, 10 resp. 15 min treatment**

Figure 19. Trendline signals for the extended series

As seen there is no distinct difference between the three treatments. Instead the signal continued the same behaviour for as long as the process were performed. It was because of this decided to discard this test series as it does not have a potential to develop either the monitoring system or the triboconditioning process in itself.

5.2.3 Wear test series

When looking at the AE signal and comparing treatments with unworn tools and treatments with tools worn against a hardened steel shaft no distinguishable difference can be made. Examples of two treatments with unworn tools against two treatments with tools worn for 2 hours can be seen in Figure 20.
Test series results

a) Treatments with unworn tools

b) Treatment with tools worn for 2h against a hardened steel shaft

Figure 20. AE trendline signal of treatments with unworn and worn tools

When the carbide tools were worn against a piston pin with a DLC coating for 15 min a distinct change in AE signal can be observed, as shown in Figure 21. As the case when comparing between treatments with tools worn against hardened steel for different amounts of time, there is no distinguishable difference between treatments with tools worn against the DLC coating for 15 and 30 min.
Results

This increase in amplitudes of the signal is even more pronounced in the comparison with the failed treatments when total tool failure had occurred, as can be seen in Figure 22.

To get a relatable result of the tool wear treatments a number of friction tests were performed on each treatment and compiled into Figure 23. To get point of reference both an untreated sample was tested as well and friction tests done in other series with fresh tools was included. To show the results of total tool failure, which in turn resulted in total treatment failure, a friction test on a failed treatment is also included.
As seen there is no distinguishable difference between the treatments with different stages of tool wear, though the C.O.F. is visibly higher than the treated reference with unworn tools.

When compiling the results of the tool wear series there is a visible difference on the friction results as the tools wear down which does not become visible on the AE signal after some significant tool wear.

5.3 AE monitoring performance

This section presents an overview of the results from the AE measurements and their correlation to the triboconditioning process. This gives an indication to the performance and potential of an AE monitoring system when the process is to be adapted to industrial use.

Initial tests show that sensor position, proximity to the operation and material interfaces in between, is very important for a good result from which a sound analysis can be made. Each interface will dampen the signal and the analysis is made on small signal differences, focus should therefore be to avoid these as much as possible.

The main potential use of AE as a monitoring method in this case is its ability to clearly indicate the point when the process is finished. Which can, as opposed to an initial test series and from these results determine process parameters, ease the start-up and implementation of the process on a component production line. With alarm levels in the software, complications related to the substrate which could lengthen the process can warn if specific components in a manufactured batch has not been thoroughly treated and have to be extracted from the batch. As opposed to spot tests on a manufactured batch which could either not catch these faulty components, or if chosen as a test component can cause a whole batch to be seen as faulty.

When investigated no early signs in the AE signal could be observed when the tools were worn down before it affected the result of the finishing process. Instead behaviour
changes did not start until the tools had experienced significant wear, though did not affect the process results distinguishably more than lightly worn tools.

As a summation AE is a suitable solution as a monitoring method, though without the ability at this stage to detect early warning signals that the process results is starting to fail. The ability to, with advanced alarm levels, backtrack potential problems and identify singular faulty components in a manufactured batch is a large advantage.
6 Discussion

The choice of using acoustic emission as a monitoring method proved to be a good choice, it has in this case yielded a large amount of data which easily could be analysed. AE can often be labelled as being a simple, cure all for process monitoring but this work has shown that a lot of work goes in to setting up and optimizing the system. Even then no apparent early signals which warned that the process was soon to fail could be observed. Compared to the alternatives which should be easier and not as time consuming setting up, the analysis of the data has been more direct. Especially live analysis as the process was running compared to the alternative of using LabVIEW with the other monitoring methods.

Seeing as the Windcon system and the software have been used to monitor a completely different type of operation than intended and the span of the software made it impossible to investigate all set-up possibilities. This could increase the potential of AE to a higher level than the thesis work presented here has shown. Another system which monitor the raw AE signal instead of the repetition frequency in this case could yield more reliable information from the spectra at each measurement point. In this work no reliable conclusions from the spectra was drawn when it was not clear how much information was lost or muddled together in the repetition frequencies.

The limitations on the set-up and strength of the components on the process test rig affected the possibilities of test series which could be performed. As previously stated the test rig was the limitation on the load parameter, the required overload to negatively affect the process results was not possible due to the components of the test rig failing. The set-up of the test rig made it impossible to remove the tools to properly quantify the induced wear marks at each treatment, as the tools had to stay at the exact same angular position when performing the treatments. That also made it impossible to induce the wear on the tools outside of the test rig. A proposed test series to investigate ageing of the process fluid was discarded partly because of the test rigs inability to easily change process fluids between treatments. A system to solve this exist but is not operational and had to be installed by ANS, and it was suspected that the synthetic base oil could perform most of its purpose without the added EP additives and with no visible difference to the AE signal. This created a lot of uncertainties surrounding a workable result and contributed to the discarding of the process fluid ageing test series.

Both the measurements done in the friction test rig and the XRF composition measurements needed more repeated measurements of each treatment to minimize different sources of error. The time consumption to perform the measurements, each run of friction measurements takes 15 min and set-up time while each XRF measurement takes 30s and set-up time, was the limitation of these measurements. The standard deviation of the composition measurements performed with the XRF spectrometer was indicated at each measurement but not noted, it was a consistent value of $2\sigma$-0.03.
6.1 Future work

Continued work could be taken in a few different steps, both the system’s ability as a monitoring concept has to be further investigated and its integration possibilities in a manufacturers production lines has to be developed. An AE system either more generic or specially developed as process monitoring system could clarify more behaviours correlating to the process results. Further ahead the set-up of alarm levels on both the spectral data and trendline behaviours is a large part in the development of the monitoring system and its applicability on the triboconditioning process. The use of the REA test rig in this thesis work has eliminated one of the bigger problems in using AE to monitor the process. The process tools to be used in an actual component manufacturing process is a lot more complicated and sensor choice and mounting is more demanding. Compared to the case in this work shown in Figure 9, these tools often do not have easily accessible, planar surface without a number of material interfaces to the operation tools to be used as a sensor mounting position. The type of sensor also have to be evaluated, the CMSS 786M sensor used here is most likely to large and bulky to mount on process tools in a CNC-lathe.

Because of the ease of which a ST-system is set up in these types of operations, and the unknown fact if anything can be seen and correlated to the process with such a system it would be of interest to investigate outside of a laboratory environment.
7 Conclusions

- Acoustic emission show potential to be a useful monitoring method of the triboconditioning process.
- The signal shows when the treatment has finished and no further improvements on lowering the coefficient of friction can be made and the tungsten content on the surface has been saturated.
- Warning signals related to tool wear can be observed, though not as early as to show before the process results have been affected.
- Further work concerning sensor position outside a laboratory environment, investigation of signal behaviour during other potential runnability problems and procedures of setting the alarm levels has been proposed.
References

8 References


Appendix

9 Appendix

A Wear marks ................................................................. A-1
B Test series spread sheet ......................................................... B-3
C Test series figures ................................................................. C-5
A Wear marks

1h resp. 2h against Hardened steel shaft

15 resp 30 min against DLC coated piston pin
Failed tool after an additional 20min against a DLC coated piston pin
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Extended load/time series
Test series figures

C Test series figures
Test 1033,1035

Test 1012-1014
Test series figures

Test 1021,1022,1036

Test 1037,1038
Comparison between 1017, 1018 and 1019, 1020

Comparison between 1019, 1020 and 1021, 1022, 1036
Comparison between 1022, 1036 and 1037, 1038