INTERNSHIP REPORT: EVALUATION AND ANALYSIS OF A NEW ALLOY FOR ELEMENT MATERIAL IN CVT

Abstract

To increase the power density of the CVT, higher forces must be transferred through the CVT elements, which requires the use of an alternative material with improved fatigue properties. This study compares the tribological behavior of the new material with the current material and evaluates its possible use as element material in CVT.

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TABLE OF CONTENTS

1  Introduction ...................................................................................................................... 1
   1.1  Background .................................................................................................................. 1
      1.1.1  Bosch CVT ............................................................................................................ 1
      1.1.2  Competitors ......................................................................................................... 3
   1.2  Motivation .................................................................................................................... 4
      1.2.1  Current state of the art and its future ................................................................. 4
      1.2.2  Task description .................................................................................................. 4
2  Theoretical Knowledge ....................................................................................................... 5
   2.1  Material science background ..................................................................................... 5
      2.1.1  75Cr1 and 100Cr6 ............................................................................................... 5
      2.1.2  Microstructure .................................................................................................... 5
      2.1.3  Heat Treatments .................................................................................................. 6
   2.2  Contact Dynamics ....................................................................................................... 9
      2.2.1  Microstructure Role in Contacts ......................................................................... 9
      2.2.2  Friction and Wear ............................................................................................... 9
      2.2.3  Stribeck Curve .................................................................................................. 11
3  Empiric Data ...................................................................................................................... 13
   3.1  Equipment ................................................................................................................... 13
      3.1.1  Tribometer .......................................................................................................... 13
      3.1.2  75Cr1 and 100Cr6 Test Samples ........................................................................ 14
      3.1.3  Discs .................................................................................................................... 19
   3.2  Tests ............................................................................................................................ 20
      3.2.1  Run-in ................................................................................................................ 20
      3.2.2  Stribeck Curve Tests ......................................................................................... 23
4  Analysis ............................................................................................................................. 26
   4.1  Data ............................................................................................................................. 26
      4.1.1  Wear .................................................................................................................... 26
      4.1.2  Stribeck Test Results ......................................................................................... 29
5  Conclusions ....................................................................................................................... 31
   5.1  Friction ....................................................................................................................... 31
   5.2  Wear ............................................................................................................................ 31
5.3  Answer to motivation & Future of Investigation ................................................................. 31

6  APPENDIX .......................................................................................................................... 0

6.1  Appendix A - Heat Treatments ......................................................................................... 0

6.2  Appendix B - Tribometer ................................................................................................. 2

6.3  Appendix C – Drawings .................................................................................................... 7
1 INTRODUCTION

1.1 BACKGROUND

1.1.1 Bosch CVT

The CVT was first conceptualized in 1490 by Leonardo da Vinci, and first built by Milton Reeves in 1879. The CVT was made suitable for application in cars by Hub van Doorne in the late 1950’s, and further improved over the years. In 1995, the VDT company was acquired by Robert Bosch GmbH which kept designing and producing CVT transmissions for cars.

The CVT improves the conventional working principle of gear trains and gear systems and is currently used in more than 100 different models of personal vehicles. CVT stands for Continuous Variable Transmission. The CVT is an automatic variable transmission that makes use of conic pulleys and a belt instead of conventional gears. This report will focus on the CVT application engineered by Bosch Transmission Technology B.V.

Instead of making use of gears with a fixed number of teeth, the CVT is composed of two variable pulleys connected by a belt. Each pulley consists of one fixed and one adjustable conic sheave, which can move along its axis of rotation. As the conic sheaves move closer to each other the belt is forced into a larger radius. Increasing the radius of the belt in one pulley would effectively change the speed ratio between both pulleys.

The belt (referred to as push-belt) is the element that connects both pulleys together. The push-belt is composed of ‘elements’ and ‘loops’, while the elements carry the power through the pulleys and bare all load, the loops keep the elements from detaching. Contrary to conventional belts, the push-belt does not pull, but pushes the driven pulley. For this, a solid link has to be created between both pulleys. At the same time, the belt has to be flexible enough to turn around the pulley. The engineered solution is a set of loops that hold together hundreds of elements. The size of the belt and number of elements in each belt varies for each application.

On traditional vehicle gear transmissions, the transmission of power is determined and limited to the relation of teeth within the gears. In such mechanical systems, only a fixed number of gear ratios are available. Usually these ratios are engineered to serve a purpose in the most efficient way. Often, gear systems need to fulfill a wide range of speeds and several gears and combinations of gears are used.

The CVT offers an ‘infinite’ number of speed ratios between an upper and lower limit, enabling a seamless transition between speed ratios. A seamless change of gears offers many mechanical
advantages for power transmission. Avoiding gear selection and gear coupling implies that there is no torque interruption during gear change, speed ratio can be adjusted continuously and the engine can operate at the most fuel efficient point.

The difference between a conventional gear-driven transmission and a CVT is apparent by comparing both systems in a wheel force vs vehicle speed graph.

![Wheel force vs vehicle speed graph. Blue: gear transmission. Red: CVT](National%20Research%20Council)

While each gear (blue) is only useful for a short band of the vehicle’s speed, a CVT transmission (red) covers all speeds. No gear selection is needed and the system works seamlessly through the complete vehicle speed range. Additionally, the CVT curve matches the maximum acceleration curve, which is the operating point at all speeds where more power is transmitted to the wheels.

In order to perform a speed ratio change, the CVT relies on an electro-hydraulic control system which based on current speed, torque demand and other factors, is able to select the optimal speed ratio between the pulleys.

Having this control over the engine speed implies that not only a more efficient and comfortable driving experience can be achieved, but also an increase in acceleration rates is possible over conventional gear systems.
1.1.2 Competitors

A broad range of CVT designs exist and are currently used in a wide range of applications. From the automobile industry in form of automatic transmission systems to aircraft electrical power generators. For this, multiple different forms of CVT are used, depending on the application. Regarding automatic transmissions for vehicles, another solution worth mentioning in this report is the chain-like element manufactured by LuK.

Due to the nature of the working principle and how the industry has adapted to continuous variable transmissions, it is the case that either a belt or a chain component can fulfill the same application. The fact that both components are interchangeable increases the rivalry between manufacturers, as car manufacturers don’t have to issue major changes to their designs based on which component is decided to be incorporated in a given car model. 
1.2 Motivation

1.2.1 Current state of the art and its future
Currently, the market share involving CVT car production is shared between a small number of manufacturing companies. The current trend of the market is to increase the use of this kind of transmission as it offers an increase in efficiency. Such efficiency increase translates to less combustible usage which is beneficial to the user in an economic manner and an overall improvement by making use of less fossil fuels.

Regarding the aspect of fossil fuels, new market trends will require automobile systems to be more efficient in the near future. For this, new designs of CVT solutions are currently being engineered and tested in order to comply with upcoming market needs.

Another requirement for future designs will be an increase of power density. Such design improvements include a reduction in the dimensions of the whole transmission system. Reducing the radius of the pulleys will increase the loads the elements have to withstand. These requirements unveil the need to make use of different materials.

As with other complex mechanical systems, finding the middle ground between positive and negative mechanical properties has to be achieved. A suitable material for new designs should present a compromise between friction, wear and fatigue resistance.

Another aspect regarding the automobile industry also worth to ponder upon is the rise of electric powered cars. Although the trend is relatively new and there is still a big internal-combustion engine market share, it is thought that electric vehicles will soon overtake a large share of the automobile industry market.

1.2.2 Task description
This report will focus on an empirical comparison between the current steel used for the push-belt’s elements by Bosch and a new alloy that has the potential of improving the characteristics of the transmission system. This task includes literature study on friction, and wear. Creation of a plan for tribological properties evaluation. Design and manufacture samples. Evaluation of performance, and the characterization of materials and surfaces.

A literature study is performed to gain insight on material science and how the material behaves. Then, making use of a universal tribotester, tests are carried out in order to study the mechanical behavior of both steels, placing attention on wear, friction and fatigue resistance. The study also aims to gain understanding in run-in procedures and run-in effects.
2 THEORETICAL KNOWLEDGE

2.1 MATERIAL SCIENCE BACKGROUND

2.1.1 75Cr1 and 100Cr6

The current steel used for the construction of the push-belt’s elements is a steel known as 75Cr1. This steel alloy is composed of several chemical elements that will be discussed further on. The steel to be tested, which is believed to have improved mechanical properties is known as 100Cr6. As 75Cr1, 100Cr6 is a high strength chrome steel used for bearing applications, tools, and other high demanding uses. The chemical composition of a steel defines its behavior. Knowing a material’s composition gives insight on the material as it can be used as an indicator of its mechanical properties.

<table>
<thead>
<tr>
<th>COMPOSITION</th>
<th>C</th>
<th>CR</th>
<th>MN</th>
<th>SI</th>
<th>NI</th>
<th>MO</th>
<th>AL</th>
<th>CU</th>
<th>S</th>
<th>P</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>75CR1</td>
<td>0.7-</td>
<td>0.3-</td>
<td>0.6-</td>
<td>0.25-</td>
<td>0</td>
<td>0.03</td>
<td>0.1</td>
<td>&lt;0.025</td>
<td>&lt;0.025</td>
<td>2.03-</td>
<td>2.68</td>
</tr>
<tr>
<td>100CR6</td>
<td>0.93-</td>
<td>1.35-</td>
<td>0.25-</td>
<td>0.15-</td>
<td>0.1</td>
<td>0.05</td>
<td>0.3</td>
<td>&lt;0.015</td>
<td>&lt;0.025</td>
<td>3.27-</td>
<td>4.04</td>
</tr>
</tbody>
</table>

Table 1. Chemical composition of 75Cr1 and 100Cr6

Comparing both steel’s chemical composition, 100Cr6 is a higher alloyed steel. 100Cr6 contains a higher percentage of Carbon and Chromium than 75Cr1, along with other elements 75Cr1 doesn’t include. It is known that, frequently, a higher alloyed steel has better mechanical properties regarding improved wear resistance, higher hardness and improved fatigue resistance. For the application for this study, a material with improved fatigue and wear resistance is sought. The reason 100Cr6 steel was proposed for this application is because of its improved fatigue resistance over 75Cr1.

It is worth mentioning that a compromise between properties has to be achieved. Not only the material has to be hard enough to withstand operating conditions, but it also has to be suitable for the blanking process the elements undergo when they are manufactured.

2.1.2 Microstructure

The microstructure of a steel describes how its internal components are arranged when the material forms. The microstructure of a material strongly influences its physical properties such as strength, hardness, corrosion resistance and wear resistance. The microstructure of a material depends on many factors, but it mainly depends on chemical composition and forming conditions.

Many elements and structures compose steel, but it is worth to mention the role of carbides in a steel’s microstructure. Carbides are defined as compounds composed of carbon and a less electronegative element. In the current case, the carbide to analyze is cementite, with formula Fe₃C. Carbides are in part responsible for a steels hardness, as they are harder than surrounding
structures. Harder carbides will yield a harder steel. The volume fraction of carbides within a steel will then play a determinant role in a material’s hardness.

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>CEMENTITE VOLUME FRACTION</th>
<th>CEMENTITE HARDNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>75Cr1</td>
<td>0.11</td>
<td>787</td>
</tr>
<tr>
<td>100Cr6</td>
<td>0.145</td>
<td>922</td>
</tr>
</tbody>
</table>

*Table 2. Cementite volume fraction and hardness for both steels [Bosch]*

As it can be seen from ‘Table 2’, not only 100Cr6 includes a higher volume fraction of cementite, but its cementite formations are expected to be harder than 75Cr1. This is a good indicator that 100Cr6 steel will present higher hardness than 75Cr1.

2.1.3 Heat Treatments

Heat treatments are used to give the materials the desired microstructure and phases in order to have the desired mechanical properties. Changing the microstructure of steel by applying heat is a broad practice in industry. The studied heat treatments in this section are hardening, carburizing, and tempering.

The temperature and times needed to harden steel vary depending on its composition. For this, different composition steels will require different hardening temperatures and times. For the application concerning this study, the steel is first pressed into the desired form during blanking. The piece is then hardened, which gives the steel a martensitic structure. The current hardening method performed by Bosch is optimized for the desired 75Cr1 steel properties.

Heat treatments are based on heating a materials and then cooling it down in a controlled fashion in order to keep a specific microstructure inside the material. After hardening, it is common to temper the material. During the tempering process, the metal is heated at temperatures below its critical point. The goal of this process is to reduce the hardness of the steel to the desired hardness and increase its toughness. The amount of hardness reduction depends on steel, tempering temperature, cooling time, and other factors which will not be addressed in this report.

Carburization happens during the hardening process. During this process the material is hardened in a carbon rich atmosphere. Some of the surrounding carbon will bond into the metal surface increasing its carbon percentage. The amount of carbon percentage increased depends on the initial composition of the steel. This is described on the material’s phase diagram.
Figure 5 describes the phase diagram of 75Cr1 and its carburizing ability. We can see the steel has a 0.73% of [C], which could be potentially increased to ~1% [C] at austenization temperature (~850 °C). The higher the austenization temperature, the more carbon could be present in austenite, which would result in a more carburized surface. In case of applying higher carbon content gasses during carburizing, the carbon content in austenite will remain constant, but the amount of carbides at grain size will increase, which will increase surface hardness.

Figure 5. Phase Diagram of 75Cr1 [Bosch]
In the case of 100Cr6, figure 6 describes its phase diagrams and carburization ability. In the case for this material, during carburization the carbide fraction increases while depletion of Cr and Mn take place in Austenite. This yields a lower hardness martensite fraction that is compensated by a higher number of carbides and higher carbide hardness. Also, in case of extended carburization at higher carbon content atmosphere, the carbon content in austenite will remain constant but carbon will be incorporated into the carbides.

As stated above, both steels present similar but different properties regarding microstructure and heat treatments. As it escapes the scope of this report, more information regarding heat treatments can be found in Appendix A - Heat treatments.
2.2 CONTACT DYNAMICS

2.2.1 Microstructure Role in Contacts
As seen in the previous chapters, the microstructure of a material defines its mechanical properties and behavior. For this, it is important to gather enough insight within a material’s inner structure in order to be able to predict and understand its behavior.

For what is aforementioned, the microstructure of the 100Cr6 steel when transformed into martensitic phase should perform better than the current 75Cr1 steel, as it shows higher hardness values and better fatigue resistance.

2.2.2 Friction and Wear
Wear in contacts can vary greatly depending on the properties and characteristics of the contact. Wear occurs by the plastic displacement of the contact surface and the detachment of particles from one or both surfaces, for which friction and wear are related.

Friction is defined as the resistance that one surface encounters when moving over another. For this, it can be seen that the higher the friction, the higher the stress put on a surface, and the higher the loads that the surface has to bear will be. Nonetheless, a great number of factors influence in both friction and wear. As a result, a whole branch of engineering is created to study the mechanics of interacting surfaces in relative motion, called tribology.

This investigation has focus on the contact of two different steels at relative motion in an oil rich environment. There are four types of wear worth to be mentioned even if considered out of scope for this investigation.

**Abrasive Wear**: Abrasive wear takes place when two different hardness rough surfaces slide with each other. The principal wear mechanisms occurring is the loss of the softer material due to hard particles from the harder material plowing through it.

Within abrasive wear there are two main classifications: Two-body and three-body abrasive wear. Two-body abrasive wear takes place when two bodies slide and the rough imperfections of the harder materials ‘plow’ through the softer material.

Three-body abrasive wear occurs when hard loose particles are within the contact. These particles can originate from the wearing-off of the surfaces, or from a third material in the surroundings (dust).

Abrasive wear can be reduced by several factors, such as decreasing contact load, sliding distance or reducing third body particles. Increasing surface hardness reduces abrasive wear, but compromises the integrity of the other surface as wear could be developing there instead.
This wear mechanism is typically identified by the presence of deep grooves on the softer material in the sliding direction. Abrasive wear is the main wear mechanism present in industry and the prominent wear type present in this investigation.

**Adhesive Wear:** Adhesive wear occurs when strong adhesive bonding between interacting asperities causes micro-welding of the surfaces. Transfer can be either temporary or permanent. Very high levels of friction and heat develop in this kind of wear.iii

Adhesive wear can be reduced by improving hardness and strength of the contact or changing the chemical nature of the surface.iv

This type of wear is not present in this investigation.

**Fatigue wear:** Fatigue wear is caused by cyclic loading during friction. Fatigue occurs if the applied load is higher than the fatigue strength of the material. The result of fatigue wear is severe plastic deformation. Cyclic loading can lead to the formation and propagation of cracks under the stressed surface, which will be destroyed. Cracks propagate from the surface to subsurface regions. This results in separation and delamination of the surface.v

This type of wear is not present in the performed study, but is worth mentioning as fatigue wear is one of the key properties to be improved, as currently used designs suffer from this kind of wear.

**Corrosive-Chemical wear (Tribochemical wear):** Corrosive wear occurs when the surfaces are exposed to corrosive elements. This type of wear can take place in lubricated and unlubricated environments. In this kind of wear, a protective layer is generated on the surface by a tribochemical reaction. During sliding, this protective layer is removed and fresh metal is exposed to the environment. A new layer of protective film is created in its place. Lubricating oils contain additives that enhance the wear behavior of contacts by forming protective films.

If the removal of the protective layer is slower than its growth, only protective layer is removed and subsequently replaced. If the removal of the protective layer is faster than its growth, some amount of bulk material will be removed along with the protective layer. This defines a spectrum of different states of wear, mild or severe.
At its initial state, the oxidation rate is fast and an oxide film on the steel is developed. When the oxide film develops to 2-3 nm, the oxidation rate slows down and the formation of oxide film continues by diffusion of oxygen into the metal.\textsuperscript{vi}

### 2.2.3 Striebeck Curve

The Striebeck curve defines the behavior of a given lubricated contact on different lubrication regimes with dependence to speed, load and viscosity of the lubricant. Oil lubricated contacts show a range of behaviors depending on slip speed and load. This is partly due to the effect of oil in the contact. Oil does not only form a protective layer over the surfaces but it also acts as a third body between both surfaces, keeping both surfaces separate. This effect can be commonly explained as a form of aquaplaning.

The Striebeck curve describes a curve between friction in the y-axis and the Hersey number in the x-axis, usually represented in logarithmic scale. The Hersey number is a dimensionless parameter that combines the slip speed, the dynamic viscosity and the load, following Equation 1:

\[
\text{Hersey Number}[-] = \frac{\text{Slip Speed [rev/s]} \times \text{Dynamic Viscosity [N} \times \text{s/m}^2]}{\text{Load [N/m}^2]} \tag{1}
\]

Although the Striebeck curve typically takes into consideration the dynamic viscosity of the lubricant and load, it is also possible to represent the behavior of the contact only with relation to slip speed.

The curve is divided into three lubrication regimes, named Boundary Lubrication, Mixed Lubrication and Hydrodynamic Lubrication.\textsuperscript{vii} During a test these regimes vary mainly with a change of slip speed and/or load while keeping viscosity constant.

**Boundary Lubrication:** This is the lubrication regime with a smaller film thickness within the contact. In this phase, contact between both surfaces takes place. The roughness of both surfaces define the amount of friction in this phase. The amount of flow of lubricant plays little to no part in the friction and wear behavior.\textsuperscript{viii}

**Mixed Lubrication:** As slip speed increases, a hydrodynamic pressure buildup occurs in the contact. This increases the lubrication film thickness in the contact. In this lubrication regime load...
is carried by both hydrodynamic pressure and contact pressure. In this phase friction decreases as there is less surface to surface contact.

**(Elasto)Hydrodynamic Lubrication:** On higher speeds the hydrodynamic pressure increases, which creates a lubrication film thick enough to effectively separate both surfaces. On this phase the load is carried by the hydrodynamic layer on its own.\textsuperscript{x}

### 2.2.3.1 Oil Temperature

Temperature within contact affects directly the viscosity and chemical properties of the lubricant.

As oil temperature increases, the viscosity of the oil decreases. At too high temperatures, the oil viscosity will not be enough to generate sufficient hydrodynamic pressure to carry the load. This means that a elasto-hydrodynamic lubrication regime could possibly not be achieved or only achieved during very high slip speeds. If the oil temperature is too low, its high viscosity will not allow the oil to flow into the contact, which would restrict lubrication.

Temperature also determines the exact chemical behavior of the oil within the contact. Oil is composed of a wide variety of additives that enable certain properties of the lubricant, such as anti-wear additives and rust and corrosion inhibitors. These additives are activated at different temperatures. Some additives such as cold-flow improvers and high-temperature thickeners are added to extend the temperature range of the oil.\textsuperscript{x}

### 2.2.3.2 Load

Load is one of the factors that greatly influences wear and friction rates along with slip speed. Within the contact, load is carried by the surface asperities in Boundary Lubrication, and by the hydrodynamic pressure on the elasto-hydrodynamic lubrication regime. A higher load will require a higher hydrodynamic pressure and will cause higher wear rates and higher friction in boundary lubrication.

The effect of the applied load is taken into consideration in the Hersey number.

### 2.2.3.3 Speed

In lubricated contact, slip speed is one of the major contributors to wear and friction. As slip speed is increased, the speed at which surrounding oil is introduced into the contact is also increased, and a pressure buildup occurs within the contact surfaces. This pressure build-up generates the hydrodynamic layer that defines the elasto-hydrodynamic lubrication regime. Nonetheless, lots of factors influence the characteristics of the hydrodynamic layer and its calculation is not trivial.
3 Empiric Data

3.1 Equipment

3.1.1 Tribometer

To conduct this study, experiments were performed in Rtec’s Multi-Function Tribometer. A Tribometer is an instrument capable of performing tests in order to measure tribological quantities. The instrument used has multiple possible setups, which enable it to carry on a wide spectrum of tests. On this report we will focus only on the used methods and setups for this study.

The followed setup is commonly referred as “Pin on disk”. This setup consists of a stationary “pin” (a steel sample) under an applied load in contact with a rotating disc underneath it. The load on the sample is applied vertically through a spring. The sliding speed of the contact is controlled by the rotating speed of the disc and the distance from the sample to the center of the disc. The lubricant is added on a liquid container which can also heat up. Thermocouples are placed in the liquid container and directly inside the oil surrounding the steel sample. This gives control over load, slip speed, and temperature.

Friction is a key property to be measured in order to validate 100Cr6 as a new material. Friction is the force resisting a relative motion between two surfaces. In order to measure this force, the steel sample is located at the end of a 3D sensor, which is able to measure frictional force in both X and Y direction. The coefficient of friction can then be calculated by Equation 2:

\[
Cof = \frac{\sqrt{Fx^2 + Fy^2}}{Fz}
\]  

(2)

Where Fx and Fy are the forces measured in X and Y direction, and Fz is the load on the sample.

As soon as the machine was put to use, some issues where observed with its behavior. Vibration and sensor problems were encountered and studied. Understanding and fixing these issues took a significant amount of time. As these complications are not directly part of the task, more information on encountered issues can be found in the Appendix B - Tribotester issues.
3.1.2 75Cr1 and 100Cr6 Test Samples

The design used on the CVT belt changes within application and use. For this, there is a need to use a ‘universal’ testing method which will not be dependent on the elements shape or size. By creating samples of known size and shape for both materials, the geometric effects of the surface do not play a role in the contact’s behavior, and the material’s properties are easily identified.

For this investigation, the formed samples are shaped in a way to get a square-shaped contact between both surfaces. The samples are manufactured from the same strip material that is used to create the elements for the CVT, thus, the sample material is as closely related to the element material as possible. Samples are cut out of the strip material by EDM (Electrical Discharge Machining). This manufacturing method offers high tolerance manufacturing even for high-strength materials and a good surface finish.

Figure 12. Sample face and step representation. Profile [Top] and iso-view [Bot]

Figure 13. Unworn Sample
A sample can be divided into two areas, the ‘face’ of the sample and its ‘steps’. While the ‘face’ will be the surface in contact with the rotating disc, the ‘steps’ will remain untouched. This method keeps the ‘steps’ in pristine conditions, and serve as a measuring surface to measure the amount of ‘face’ material that worn off.

The height difference between the face and the step is of 150μm for 75Cr1 samples and 100μm for 100Cr6 samples.

The effective surface area of the face is of around 1.8mm$^2$. The exact surface area varies between samples.

As aforementioned, the 75Cr1 and 100Cr6 samples where subject to the same heat treatment. As a result, both samples have similar hardness, although the 100Cr6 material shows a slight increase in hardness. This is possibly because of its ability to accept more carbon content during carburizing.

<table>
<thead>
<tr>
<th>Sample Material</th>
<th>HV Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>75Cr1</td>
<td>694</td>
</tr>
<tr>
<td>100Cr6</td>
<td>704</td>
</tr>
</tbody>
</table>

*Table 3. material hardness measurement*

This effect can be seen within the microstructure of the elements. The following figures (figures 14-18) show the surface microstructure of both 75Cr1 and 100Cr6 samples after hardening.
75Cr1 Surface microstructure:

Image 14 shows the microstructure of the surface of the 75Cr1 sample. In order to take this picture, a sample was cut in half exposing its interior to see its inner structure. The effects of the carburizing process can be seen on the material surrounding the surface of the sample and penetrate the surface around 10µm. The formation of carbides (white spots) on the surface is clear.

*Figure 14. 75Cr1 surface microstructure. 1000x magnification.*
100Cr6 Surface microstructure:

The carburizing effects on 100Cr6 don’t penetrate more than 10µm beneath the surface but there is a higher formation of carbides near the surface. By designing an appropriate carburizing process for this steel, its effects could be augmented.

Surface comparison

Upon comparison the higher formation of carbides in 100Cr6 is clear. 100Cr6 shows presence of more and smaller carbides, and a higher volume fraction of carbides than 75Cr1. Darker structures can also be seen in 100Cr6, as more carbon is absorbed during carburizing.
Information regarding the material can be gathered upon inspection of the 75Cr1 and 100Cr6 core material microstructure in figures 17 and 18. The first difference between both microstructures...
is the lack of well-defined martensite structures in the 100Cr6 structure. Martensitic structures can be easily identified by their needle-like structure appearance. They are clearly visible in the 75Cr1 steel while no so apparent in 100Cr6 core structure.

The 100Cr6 steel could be hardened further, for this it doesn’t show its martensite structure at its maximum state. Another factor affecting this is that each steel has a different temperature from which austenite transforms into martensite. While 75Cr1 austenite transforms at 300ºC into martensite, it doesn’t do so in 100Cr6 until the 200ºC mark. For this reason, martensite didn’t form up to such extend in the 100Cr6 steel.

Comparing both core structures we can also see that the 100Cr6 steel has more carbide formations than the 75Cr1. Not only at surface level but also in core material structure. Carbides are formed at grain boundaries and as mentioned in previous sections in this report, they play an important role defining the hardness of a material. Although both materials have similar hardness in their current state, we can see again that 100Cr6 has the potential to improve hardness when heat treated properly.

3.1.3 Discs
The role of the discs in the contact is also significant. The discs are made out 20CrMo55 steel. This is the same material used in the CVT conical pulleys and will recreate the conditions of the machine while in operation.

The discs are 60mm in diameter and hold a randomized pattern in their top surface which will be used to grind down the samples during the run-in procedure. The randomized pattern is not completely random as it varies along the disc’s radius. For this reason, it is possible that the observed wear and properties of the contact at one specific radius is not replicable at another radius.

![Figure 19. Test disc with visible pattern and 3 worn test tracks](image)

For this reason, after performing some initial tests with the disc for the first time, it was decided to perform the Strubeck curve tests and following tests at the same radius in order to reduce variables. Thus, the disc is divided into ‘test tracks’.

Disc drawings can be found in the Appendix C – Drawings.
3.2 Tests

3.2.1 Run-in

The run-in process is defined as the initial surface and subsurface conditioning process, generally used for sliding or rolling contacts. During this step a pristine surface will be worn down and adapted to the contact surface. Running-in prepares the surface and material for its application.

When two surfaces initially meet, it is never the case that they fit in perfectly. Instead, small areas on each surface (hills) are in contact with each other. Initially these small areas are loaded with a high surface pressure. As a consequence, these areas undergo elastic and plastic deformation which translates into wear and loosing of material (see section 2.2.2). The resulting surface offers a higher surface area in which to distribute the load. This mechanism of adaptation is active until both surfaces are sufficiently worn down and the load can be distributed evenly throughout the contact surface. When the contact surface is homogeneously worn down, creating a proper contact between surfaces, it is considered to be run in. Running-in reduces the roughness of a surface and ensures a better contact and sliding. Ultimately, a run-in is successful when friction stabilizes.

Unfortunately, running in the samples in a consistent manner is not trivial. The run in procedure greatly affects the surface life and load bearing capacity. How this works is not completely understood and would require an entire study just on this matter. Studies of running-in are relatively rare in literature and running in procedures are often developed by trial and error.

Running-in surfaces for tribological testing is necessary as the contact behavior is constantly changing until the run-in is complete. This is expected as the surface itself is changing until it is completely adapted, which defines the end of the run-in process. For this, until a sample is not run-in enough, its tribological behavior will change and any test performed on it will yield inconclusive results.

Figure 20 describes the effects of running-in of a contact through changes on its Stribeck curve. These changes vary from one lubrication regime to another. In the case of boundary lubrication (BL), the friction coefficient lowers. This is expected as if the surfaces are being polished, roughness lowers and friction drops. The mixed lubrication (ML) regime phase is shifted to the left as a result of lubricant having better access to flow into more polished surfaces. This effect is
similar to how worn down car tires are subject to slip on wet roads. The major difference between both cases described in figure 20 is in the behavior of the hydrodynamic lubrication regime after run-in.

In the low contact pressure case (Figure 20, left), the hydrodynamic lubrication regime gradually works at lower friction values as the run in completes. On the other hand, on a high contact pressure scenario, the hydrodynamic lubrication regime gradually works at higher friction values.

**Performed run-in.**

It is though that for the run-in to be successful, the maximum loads have to be higher than the loads the contact will bare during its application. This way, the surface adapts under higher loads and will remain unchanged during application. The run-in procedure used for the tests is a combination of different loads and speeds that alternate between high and low values.

Figure 21 describes the followed run-in procedure. Before the run-in, a 100N load is applied at low sliding speeds to prepare the surface. During the first phase, load is alternated between 100N and 300N in 2 minute intervals while the sliding speed is of 0.15 m/s (rotating disc speed = 64 rpm, at radial position x=22 mm). There are 10 load alternations during this phase, which takes 40 minutes to complete. The second phase consists of the same load alternation, but sliding speed is 0.85 m/s (rotating disc speed = 637 rpm, at radial position x=22 mm). There are 5 alternations and the second phase takes 20 minutes to complete. Total duration of the test is 60 minutes.

![Figure 21. Run-in procedure at position x=22mm. Load (Blue line) and rotary speed (green line)](image)
The effects of the run-in are visible during the running-in process itself. Looking at a friction vs time graph of the running-in procedure (figure 22), the behavior of the friction coefficient can be an indication of the state of the surface.

![Friction vs Time during a run-in.](image)

Figure 22 represents the graph created by a sample while performing a run-in procedure (run-in procedure can be seen in figure 21). The first spike of the graph (marked by the left red circle) indicates the start of the first load step. The high steps represent high load conditions while the low steps represent low load sliding conditions. It is observed that the friction at low loads (100N in this case) varies more than the friction at high load conditions (represented by a red dotted line). The second major change in friction is due to speed changes. In the second part of the test, rotation speed increases to 637 rpm, which generates lower friction values for both high and low conditions.

The indicators visible in this graph are the spikes at the beginning of each load change (red circles). When the surface is not adapted, a change in speed or load will generate a momentary transition flow condition that stabilizes with time. As the surface adapts, this effect lessens; it can be seen that at the end of the process this behavior is no more and we can conclude that friction has stabilized.

Another indicative of the sample’s state is the downward trend of friction during the test (red dotted line). This trend soon stabilizes. If this trend continues, it means that the sample is still not in a stable condition and thus friction will not remain stable. Any Strubeck curve test performed at this point will have inconclusive results.
Effects of running-in a sample.

Upon microscope inspection the effects of the running can be observed. Figure 23 represents two different samples. The top sample did not receive a complete run-in as not sufficient wear took place. Also, the sample was slightly tilted over the disc, this is why one side of the sample is more worn out than the opposite side. The bottom sample did receive a complete run-in and is ready to perform a Stribeck curve test.

Although, many factors influence the effect of the run-in procedure. Specifically, the roughness of the disc plays a major role. As the sliding area of the disc is much bigger than the sliding area of a sample, the disc will wear down much less than a given sample. During tests, it was the case where either a sample experienced too much wear, destroying the sample beyond-use, or low amount of wear took place. Again, this mechanism could not be studied further, but it is believed the main cause for this is the wearing down of the large surface of the disc.

3.2.2 Stribeck Curve Tests

As aforementioned in the previous Stribeck Curve section (section 2.2.3), Stribeck curve tests study the evolution of the friction coefficient of a contact as load and sliding speed change. The designed tests try to involve different speeds and loads in order to graph a significant Stribeck curve.

Although the Hersey number takes into consideration the dynamic viscosity of the lubricant and load, it is also possible to represent the behavior of the contact only with relation to slip speed alone. This simplifies the test procedure by eliminating parameters that will not be studied at the moment and this method will be followed in the performed tests.
Figure 24 represents the test procedure for a Strubeck curve. The test is divided in two phases. During the first phase, 100N load is applied and speeds range from 0.001 m/s to 1 m/s and back to 0.001 m/s. This is then repeated with a 250N load.

<table>
<thead>
<tr>
<th>Step</th>
<th>Load [N]</th>
<th>Speed [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>0.001</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>0.05</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>0.5</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>0.5</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>0.05</td>
</tr>
<tr>
<td>7</td>
<td>100</td>
<td>0.001</td>
</tr>
<tr>
<td>8</td>
<td>250</td>
<td>0.001</td>
</tr>
<tr>
<td>9</td>
<td>250</td>
<td>0.05</td>
</tr>
<tr>
<td>10</td>
<td>250</td>
<td>0.5</td>
</tr>
<tr>
<td>11</td>
<td>250</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>250</td>
<td>0.5</td>
</tr>
<tr>
<td>13</td>
<td>250</td>
<td>0.05</td>
</tr>
<tr>
<td>14</td>
<td>250</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Table 4. Steps of a Strubeck curve test.
Notice that speeds increase and then decrease going through the same values. This is intended as it will serve as a validation for the results. This is visible in figure 25, which describes the friction coefficient during a Strieber curve test. In the first phase (100N) it can be seen how the regions with same sliding speed match (green dashed line). This is a good indicator which means the contact is stable during those conditions.

![Figure 25. Strieber curve friction coefficient results. Friction vs Time (s)](image)

On the other hand, during the second phase at high load (250N), the regions with same sliding speed do not match so clearly and a slope can be seen during the high speed step (red dashed line). This means that at those conditions (250N, 1m/s) the contact is not stable and thus its indicated that the run in procedure was not sufficient for this sample. These indicators can be used to know if a sample is fit to do a Strieber curve test or if the test was carried out successfully. In the case of figure 25, the sample was not fit for the test.

In order to graph a Strieber curve from a coefficient of friction vs time graph, the most stable points have to be used. For this, we will use the points at the end of each step, marked with red spots in figure 26.

![Figure 26. Strieber curve friction coefficient results. Friction vs Time (s)](image)
4 ANALYSIS

4.1 DATA

4.1.1 Wear

One of the major drawbacks in this investigation was the variable wear rates each sample experienced. The reason for this is thought to be the effect of the polishing of the disc surface. Wear rates depend on sliding speed, load, surface roughness, material hardness and oil temperature. Making constant these variables throughout testing is not as straightforward as it may seem. As mentioned above, disc roughness changes along the radial direction of the disc. This means that the encountered roughness at one position is not replicable at another radial position. For this, once a running track is polished to certain amount and significant wear will no longer take place, recreating the contact conditions is not trivial. Switching to a new test track implies that a different surface roughness is encountered by the surface.

As mentioned above, wear is also dependent on load. The findings of this investigation show that either too much wear was present or no wear was present at all. The effects of load on the wear rate are clear. For this, it’s convenient to link load to surface pressure on the contact.

The most notorious case of wear experienced in this investigation was undergone by a 75Cr1 sample whilst testing run-in procedures, which was worn down completely.

![Figure 27.75Cr1 Sample 2 completely worn down.]

Although its accelerated destruction doesn’t give us much insight on the wear mechanism, it is interesting to compare its initial and final scenarios, which give us limits to what the materials is able to sustain. It’s worth mentioning that once the sample was worn down to this level, no more wear was observed. This is explained by the increase in surface area to bear the load.

<table>
<thead>
<tr>
<th>Pristine Conditions</th>
<th>Worn-down Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Area</td>
<td>1.783021 mm²</td>
</tr>
<tr>
<td>Load</td>
<td>300 N</td>
</tr>
<tr>
<td>Surface Pressure</td>
<td>168.25 N/mm²</td>
</tr>
<tr>
<td>Wear Rate</td>
<td>82.893 µm/km</td>
</tr>
</tbody>
</table>

Table 5. Conditions of the sample before and after wearing down.
Comparing both surface pressure before and after wearing down, we can set the limits of the material. A surface pressure of 82.5 N/mm² will not generate significant wear in a sample. Looking at figure 26 we see that the sample was worn down to the steps, increasing its surface area. In order to get a 82.5 N/mm² surface pressure in a new sample, not more than 150N should be applied, and only low wear will take place. This means that applying 150N on a sample will generate little to no wear.

**Wear comparison of both steels**

Comparing two samples of different material that underwent the same run-in conditions, both in a fresh disc track, a comparison of wear rates is possible.

<table>
<thead>
<tr>
<th>Material</th>
<th>Load N</th>
<th>Distance m</th>
<th>Wear um</th>
<th>Wear rate um/km</th>
</tr>
</thead>
<tbody>
<tr>
<td>75Cr1</td>
<td>300</td>
<td>962</td>
<td>5</td>
<td>5.197505</td>
</tr>
<tr>
<td>100Cr6</td>
<td>300</td>
<td>962</td>
<td>2</td>
<td>2.079002</td>
</tr>
</tbody>
</table>

It is observed a reduced wear rate in 100Cr6 steel. Other samples are not to be compared as they underwent different conditions. Several reasons of why the 100Cr6 material experiences less wear than the 75Cr1 are theorized. Wear is related to the chemical reaction occurring on the surface and the protective layers formed between the oil and the steel, the chemical composition of 100Cr6 could give it a better wear resistance in these conditions. The increased amount of carbides observed in section 3.1.2 may also be increasing the wear resistance of the material. Many factors affect wear in this conditions, for an in detail reasoning of the wear mechanics, a detailed investigation should be performed on this matter.

Figures 28 and 29 show both materials samples after the run-in procedure. It can be seen that the 100Cr6 sample did not wear out as much as the 75Cr1.
In the case of other samples, a very different wear rate was measured within the same disc track. This makes apparent the relation of a fresh disc track with high wear rates.

The disc also shows signs of wear after its use. Although a complete polished surface is not achieved, a significant effect is observed along the track. The disc contains grooves in ‘random’ directions which always encounter the sample with a +/- 20° angle. Some of these grooves are too deep and are never polished.

Figure 30 represents a test track after its use. Overall, the test track is worn down to -5µm. Still, the test track is not as homogeneous as expected. A contour of the track is plotted in figure 31, where a decrease in height with the rest of the disc is observable. The test track (in between the red and green marker) presents lower height but also hills and valleys.
4.1.2 Stribeck Test Results

Temperature effects in Stribeck curve measurements are not greatly significant from 40°C to 100°C. Based on the performed tests, we can see (figure 31) that there is some change in friction at both temperatures. At 100°C (blue line) the viscosity of the lubricant is less. So, friction is generally a bit higher (at this combination of speed at 100N loads) as the lubricant can’t create such a separation layer as at 40°C. These effects will vary depending on the temperature range and will require a whole study on its own. It is possible that wear is also affected by temperature differences.

Figure 32. Stribeck curve temperature comparison between 40°C and 100°C
Putting the temperature effects of viscosity aside, a series of Strubeck curve tests are performed between 75Cr1 and 100Cr6 samples. These tests are all equal and test the samples at two loads, 100N and 250N. For a detail description of the tests, refer to section 3.2.2. The resulting graph (figure 32) contains the results for these tests.

![Figure 33. Comparison of Strubeck curve tests of both steels at 100N (Blue) and 250N (Red) loads.](image)

In figure 32 we can see both steels perform equally in the Strubeck curve tests. No apparent difference between both materials is observable. The biggest observable difference is the effect of load on the contact.
5 CONCLUSIONS

5.1 Friction

As figure 32 (section 4.1.2) shows, there is no difference in friction coefficient between both steels at these loads/speeds. As the 100Cr6 steel shows a similar friction than 75Cr1, it is still candidate to be used as element material.

A material with too high friction could damage the pulleys while a material with low friction would require more operating force and will cause an overall loss in performance.

5.2 Wear

Wear was observed to be reduced for the 100Cr6 steel compared to 75Cr1. Lower wear rates are beneficial but could compromise the integrity of the whole system. If the lower wear rates are caused by the ‘other’ surface getting worn down (in our case, the disc surface) then a major problem could arise if the pulleys get worn down instead of the elements.

For a conclusive answer regarding wear, a better study should be performed, focusing on sample and disc wear rates.

5.3 Answer to Motivation & Future of Investigation

Overall, the 100Cr6 material presents improved mechanical properties. The ability to be hardened to a higher state, reduced wear, better fatigue resistance and similar friction to the 75Cr1 steel. All these properties are beneficial for the application, and the 100Cr6 steel should perform positively in the CVT as element material. Nonetheless, it is not clear the amount of improvement the material would bring. A more thorough study should be performed on wear and fatigue resistance.

This study serves as a first contact with the Tribometer, samples and discs. The effects and procedures for running-in samples should be studied further in detail (also beneficial for real-application purposes). The behavior of the discs, disc surface, disc properties and how it affects samples should also be studied. Ultimately, this study can be recreated to generate more data and confirm the observed findings.

Another aspect this study did not address is the contact between elements and loops in the CVT. It may be that the use of 100Cr6 brings negative consequences for the integrity of the loops and this effect should be studied further.
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6 APPENDIX

6.1 APPENDIX A - HEAT TREATMENTS

Commonly in industry, steels are heat treated in order to change their properties, both during manufacturing and after manufacturing. As seen in section 2.1.3, the heat treatment a steel receives to achieve certain properties varies from one steel to another, as it is dependent on its phases and microstructure factors.

Different heat treatments yield different microstructure and phases within the same material. In the case of unhardened 100Cr6, following each path described in figure 34 will yield a different phase in the material. Each phase has different properties. In the present study, 100Cr6 samples where heat treated by the same process as 75Cr1, which yields a martensitic structure in both steels.

![Figure 34. 100Cr6 heat treatments and resulting phases.](image)

In figure 34 it can be seen how the cool down rate affects the microstructure. This process is represented in Time-Temperature-Transformation diagrams. The TTT diagrams for 75Cr1 and 100Cr6 are displayed below in figure 35 and figure 36 respectively.
These diagrams (Figure 35 and Figure 36) show the relation between time and temperature and show the final phases of the material. An estimation of the final hardness (in HRC) is also given for 100Cr6 in Figure 36.
6.2 Appendix B - Tribometer

All tests performed in this study made use of Rtec’s Multi-Function Tribometer. This is the first time that such machine is used and little was known about its operation and behavior. This hardware uses a complementary software named RtecViewer which plots the resulting measurements.

This machine serves as test bed and measuring instrument. As mentioned in section 3.1.1., the sample is vertically placed on a holder resting over the top surface of a rotating disc. A vertical load is applied on the sample to create surface pressure in the sample-disc contact point. The disc rotates at a known angular speed, which is used to calculate the real sliding speed in the contact point based on the radius from the disc center to the contact point. The sample and disc are inside a closed chamber with enough lubricant to ensure lubricant flow in the contact point. This chamber can be heated up to perform tests at different temperatures.

This measuring instrument showed some behavioral issues which at first prevented the study to continue and effort was put on fixing these issues before reliable Stribeck measurements could be done.

Unleveled disc.
It was soon observed that the rotating disc was not rotating properly. Upon inspection of friction graphs, a pattern could be seen between the friction and disc angular position. It was discovered that the set of rotating disc bed and disc were not achieving a leveled rotation.

Indicators:
- Periodic oscillations could be observed in the FZ and COF measurements.
- Such oscillations matched rotation speed.

![Figure 37. Rtec software measuring vertical force (Yellow) and disc angle (white).](image-url)
Having a direct correlation in measured force oscillations and rotating speed, the machine was disassembled to measure and level the rotating disc bed. The results of the measurement are graphed in figure 38.

![Perimeter Height Graph](image)

**Figure 38. Rotating disc bed height [left]. Set-up for height measurement [Right]**

To fix this issue, a thin shim was used to level the bed, but the height alterations are so small that by adjusting the screws the disc height vastly changed.

Unfortunately, this issue was not fixed and small vibrations could not be eliminated. These vibrations take place during testing and measuring and should be taken into account. Still, their effect was kept small by using the inner tracks of the disc, as height difference is higher on the outside regions.

As the disc does not rotate completely flat, but has one area which is higher than the rest of the disc, for every rotation there is a load increase and load decrease. This may have a negative effect on the formation of the hydrodynamic layer, especially at high speeds. The effects of this issue could be studied with a testing rig that does not show such height variations.

**X axis and Y axis**

Not an issue by itself but worth mentioning is that axes X and Y do not behave in the same manner. This is because they are not built with the same components. It was observed that the X-axis cannot advance at more than 5 mm/s. It is possible to move the X-axis up to 7mm/s at low or null loads, but is not advised. If the X-axis is programmed to move faster than 5mm/s, then encoder errors will start to appear as the X-axis cannot keep up with programmed tasks. The machine is likely to fail under these conditions.

**Heat issues.**

Once the heat chamber was set-up and all the equipment for testing was ready to use, it was observed that heat changes yield measurement drift in each sensor. The drift of each sensor was seen to be dependent on temperature change and time. The rate of drift for every sensor was not the same.
In order to perform a test on high temperature, the machine needs to warm up the heat chamber. This process takes some time, depending on the goal temperature. After setting the machine to an objective temperature, the sensors will measure a drift while the rest of the machine is warming up.

Temperature changes affects the measurements of at least the following sensors.

- Fz
- Fx
- Fy
- Z Encoder

For example, if the machine is set to a 100 C temperature goal, the liquid holder will warm up in ~1 hour, while the sensors will warm up in ~6 hours. This means that any test performed before the sensors warm up completely is subject to wrong measurements, as the sensors are still changing temperature while the test is being performed.

Figure 39 shows these effects. In this case, the machine was set up with a constant load (100N) and temperature was set to 100 ºC. As the machine warms up, both sensors Fx and Fy show a measurement drift, +3.5N for Fx and >3.75N for Fy. Apparently both sensors reach a steady state after 20000 seconds (5.5 hours).

Figure 39. Loaded test sensor temperature drift. Chamber temp (Purple), Oil temp (red), Fx (blue), Fy (green) vs Time (seconds)
The variations of Fz in this test are 0 as Fz is set to 100N at all times, the machine will adapt to maintain it constant. In order to measure Fz drift, an unloaded test has to be done. In this test, the sample is some distance (micrometers) over the surface of the disc, but there is no contact. No load is applied and the machine is set to warm-up to 100ºC.

![Figure 40. Unloaded test sensor temperature drift for Fz (blue) vs Time (seconds)](image)

In this case, the behavior of Fz is surprising. Although temperature stabilizes after 5000 seconds (1.4 hours), Fz constantly changes value throughout the whole test (until 30,000 seconds (8.3 hours)) achieving a peak negative value of -3.4N.

When the heater is turned off and temperature goes down to 20ºC, the Fz sensor measures a positive drift with a maximum peak of 1N. The shape created by Fz in this case is similar to the warm-up phase, hinting this issue may be explained by hysteresis.

**Possible causes of sensor drifts:**

Some possible causes for the observed sensor drifts are given.

- Sensor heat alteration
  - The warm heat chamber might leak warm air into the sensor, heating the sensor and changing its measurement properties.

- Material expansion
  - Metal expansion while heating-up, material hysteresis and metal contraction while cool-down might cause the observed issues.

**Workaround**

As the investigation of this issue alone would have taken too much time, it was decided to work around it and minimize its effects. In order to minimize its effects, the machine was set up to warm up overnight, which gave the sensors more than enough time to warm up and achieve a constant measurement. The tests would then take place on the following day at the same temperature, thus, avoiding heat gradients.
Software Glitch

It was the case that the machine would sometimes measure inconsistent values from the sensors and the machine would halt for safety reasons. Note that the measured values cannot be real and thus must be a software glitch. These glitches typically look like Figure 41 and may be caused by operating system updates, background updates or data acquisition errors.

Solution

The best solution proven to work was to reboot the computer and tribometer, let any updates run until the computer is idle and run the software again.