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MASTER'S THESIS

Additive Technology for Limited Slip Differentials

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MASTER OF SCIENCE PROGRAMME

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Division of Machine Elements

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Preface

During the last months I have been working on the project that will put the final dot to the degree Industrial Engineering that I began at Universitat Politècnica de Barcelona (UPC) in 1998.

This work has been carried out at the Division of Machine Elements at Luleå University of Technology (LTU) in the north of Sweden. The hardness of the nordic climate has been counterbalanced in excess by the warmth of the people that I have found and that helped me to finish this project which I present to you in the following pages. Especially I would like to acknowledge the support given by my supervisor Rikard Mäki. Also to all the Machine Elements division that have made the realization of the project possible. I do not want to forget either the collaboration from the director of the project, Bager Ganemi.

Also I want to thank the support given by my family without which I would not now be here writing these lines and also to my friends for having been there.

Luleå, Spring of 2004

Rafel Triviño Flores

Prefaci

Durant els passats mesos he estat treballant en el projecte que posarà punt i final a la carrera d'Enginyeria Industrial que vaig començar l'any 1998 a la Universitat Politècnica de Barcelona (UPC).

Aquest treball ha estat desenvolupat a la divisió d'Elements de Màquines de la Universitat Tècnica de Luleå (LTU) situada al nord de Suècia. La duresa del clima nòrdic a estat sobradament contrarrestada per la calidesa de la gent que he trobat i que m'ha ajudant a tirar endavant aquest projecte que us presento en les següents pàgines. Especialment m'agradaria agrair el suport donat al meu supervisor, Rikard Mäki. També a tota la divisió d'Elements de Màquines que han fet possible la realització del projecte. No vull oblidar tampoc la col·laboració del director del projecte, Bager Ganemi.

També vull agrair el suport donat, a la meva família sense la qual jo no seria ara aquí escrivint aquestes línies i també als meus amics nous i de sempre per haver estat allí.

Luleå, Primavera de 2004

Rafel Triviño Flores

Abstract

At the Division of Machine Elements, a research project called 'Wet Clutch Tribology' is being carried out in cooperation with Statoil Lubricants R&D and Haldex Traction Systems AB.

Haldex Traction is a supplier of all-wheel drive systems featuring an electronically-controlled limited-slip wet clutch differential working as centre differential, connecting the drive shaft to the rear axle of the vehicle. The system is used in cars by companies such as Audi, Bugatti, Seat, Volvo and Volkswagen. In order to achieve the desired properties of the system it is important to have transmission fluids that give the 'right' frictional properties in order to transmit torque and suppress vibrations.

The main task of this thesis work is to investigate how different oil additives influence the friction in a wet clutch, in order to gain the ability to optimize the formulation of new additive packages for limited slip differentials.

After several tests, the resulting novel transmission fluid shows good performance, temperature dependence and friction characteristics compared to commercial fluids available today on the market and used in real cars.

Resum

A la divisió d'Elements de màquines es desenvolupa un projecte de recerca anomenat 'Wet Clutch Tribology' en cooperació amb Statoil Lubricants R&D i Haldex Traction System AB.

Haldex Traction és un proveïdor de sistemes per proporcionar tracció a les quatre rodes mitjançant un embragatge diferencial mullat controlat electrònicament que actua com a diferencial central. Aquest diferencial connecta l'eix de tracció amb l'eix posterior del vehicle. Fàbriques com Audi, Bugatti, Seat, Volvo i Volkswagen inclouen aquest sistema en els seus vehicles. Per aconseguir les propietats desitjades és important disposar de fluids de transmissió que tinguin les propietats adequades per transmetre parell i suprimir les vibracions.

La principal tasca d'aquest projecte és investigar com els diferents additius influeixen la fricció en un embragatge mullat. Amb això es pretén guanyar els coneixements necessaris per optimitzar la formulació de nous packs d'additius per embragatges de relliscada limitada.

El nou fluid de transmissió obtingut després de diversos tests presenta bones propietats en quant a dependència de la temperatura i característiques de fricció en comparació amb altres lubricants disponibles al mercat.

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1. The aim of the work

The main task of this thesis work is to investigate how different oil additives influence friction in a wet clutch, in order to gain the ability to optimise the formulation of new additive packages for limited-slip differentials.

2. Lubrication

Tribology may be defined as the study of the lubrication, friction, and wear of moving or stationary parts. The pressure generated on the surfaces in contact leads to formation of a fluid film. When opposing surfaces are completely separated by a lubricant film, fluid film lubrication occurs. As a result, no asperities are in contact.
If two surfaces fit snugly into each other with a high degree of geometrical conformity they are called conformal surfaces, figure 1, otherwise they are called non-conformal surfaces, figure 2. In conformal joints the load is carried over a relatively large area which remains essentially constant while load is increased. On the other hand, in non-conformal surfaces the area increases with the load but it is still smaller than the lubrication area between conformal surfaces.

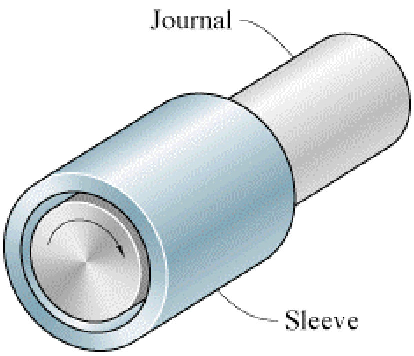


Figure 1 Conformal surfaces [Bernard]

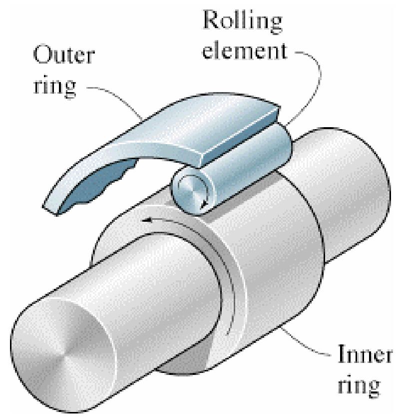


Figure 2 Non-conformal surfaces [Bernard]

There are different types of lubrication regimes depending on the materials and the surfaces in contact.

Hydrodynamic lubrication (HL) is generally characterized by conformal surfaces with fluid film lubrication. A pressure is caused by the bearing surfaces' geometry and their relative motion and the viscosity of the fluid. This pressure can hold a normal load. The magnitude of this pressure is not enough to cause significant elastic deformation of the surfaces.

Elastohydrodynamic Lubrication (EHL) is a form of hydrodynamic lubrication where elastic deformation of the lubricated surfaces becomes significant. There are two types of EHL: Hard EHL and Soft EHL.

Hard EHL relates to materials with high elastic modulus, such as steel. Soft EHL relates to materials of low elastic modulus, such as rubber.

In *Boundary Lubrication* conditions the solids are not separated by the lubricant. Therefore, fluid film effects are negligible and there is considerable asperity contact. The frictional characteristics are determined by the properties of the solids and the lubricant film at the common interfaces. The properties of the bulk lubricant are of minor importance, and the coefficient of friction is essentially independent of fluid viscosity.

Mixed Lubrication conditions are a mixture of boundary and fluid film lubrication conditions. If the pressures in elastohydrodynamically lubricated machine elements are too high or the running velocity is too low the fluid film will be penetrated and mixed lubrication will occur.

The wet clutches work under mixed lubrication at high speed and low pressure and temperature conditions. If there is low speed and high temperature and pressure they work under boundary lubrication conditions.

2.1 Additives

An additive is a substance which is mixed with the base oil in order to improve its performance. There are different types of additives: antioxidants; viscosity modifiers; pourpoint depressants (PPD); detergents and dispersants; antifoam agents; demulsifiers and emulsifiers; dyes; anti wear and extreme pressure additives; friction modifiers and last but not least corrosion inhibitors.
The Haldex Limited Slip coupling needs lubricant to work. It has an important role in order to prevent shudder. The oil is composed of base oil and additives which are of vital importance in order to obtain good anti-shudder properties.

Antioxidants
The function of a lubricant is limited mainly by the ageing of lubricant base stock. The ageing process of the oil can be delayed tremendously by the use of antioxidants.

Viscosity modifiers
The viscosity is a fundamental characteristic of every fluid. There are several applications that require a certain viscosity index (VI). In transmission fluids a high VI is required since high VI means less temperature dependence. Viscosity modifiers are a good help in this task.

Pourpoint depressants
These are closely linked to a series of viscosity modifiers and inhibit the crystallisation of the fluid at low temperatures.

Detergents and dispersants
These kinds of additives prevent agglomeration of waste products into solid particles rather than cleaning up existing dirt as their names suggest.

Antifoam agents

The foaming of lubricants is a very undesirable effect that can cause enhanced oxidation by intensive mixture with air, cavitation damage as well as insufficient oil transport in circulation systems that can even lead to lack of lubrication. These additives prevent the foaming.

Anti wear / Extreme pressure agents

In the case of boundary or mixed lubrication under high load/temperature conditions these additives react. As a result, a protective layer is formed on the surface of the friction materials. It prevents the micro welding that would occur without these agents. Anti wear additives are used in moderate stress conditions while extreme pressure additives are used in extreme stress conditions.

Friction modifiers

They are similar to AW/EP but they work at temperatures where AW or EP additives are not yet reactive. These help to prevent shudder in the wet clutch.

Corrosion inhibitors

These are used in nearly every lubricant to protect the metal surface of any machinery, metalworking tool or work piece from the attack of oxygen, moisture and aggressive products.

3. Wet clutch

A wet clutch is one that works under lubricated conditions. The most common configuration is called a multiple disc wet clutch, figure 3. Basically, one shaft is connected to friction discs while the other shaft is connected to separator discs. A hydraulic piston applies a force normal to the discs engaging them. In this configuration a torque can be transmitted from one shaft to another. When the discs are disengaged no torque is transmitted and shafts can rotate independently from one another.

The most common application for this type of clutch is in automatic gearboxes. More recently we can find wet clutches used as an intelligent differential in electronically controllable automotive transmissions. This work is focused on this kind of application.

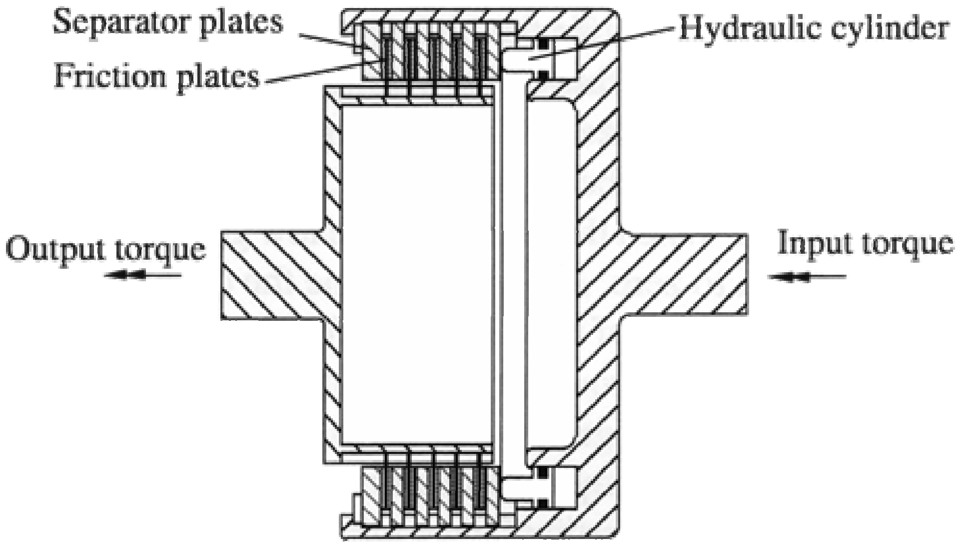


Figure 3 Wet clutch diagram

3.1 Haldex Limited Slip Coupling

The Haldex Limited Slip Coupling is a limited slip differential that distributes drive torque between front and rear axles of all-wheel drive passenger cars. Under normal conditions (good traction) the car is only driven by the front wheels. When the front wheels lose traction a speed difference occurs between the front and rear axle of the car. When this occurs the wet clutch on the drive shaft is engaged in order to distribute drive torque to the real axle.
The unit can be viewed as a hydraulic pump in which the housing and an annular piston are connected to one shaft and a piston actuator is connected to the other, figure 4.
The two shafts are connected via the wet multi-plate clutch pack, normally unloaded and thus transferring no torque between the shafts.

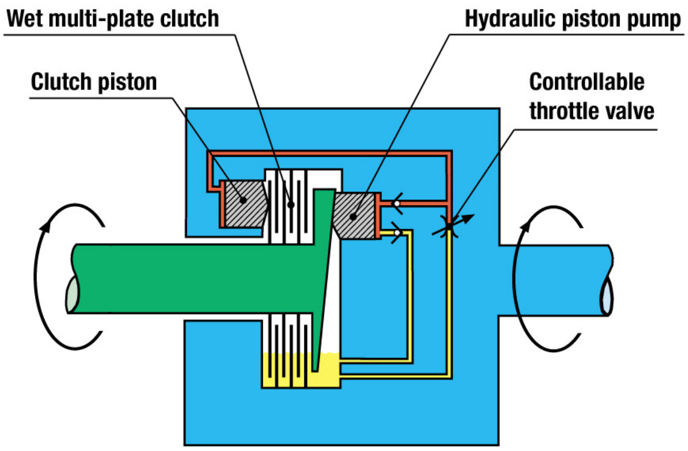


Figure 4 Haldex Limited Slip Differential

When both shafts are rotating at the same speed, there is no pumping action. When a speed difference occurs, the pumping starts immediately to generate oil flow. It is a piston pump, so there is a virtually instant reaction with no low-speed pumping loss.
The oil flows to a clutch piston, compressing the clutch pack and breaking the speed difference between the axles. The oil returns to the reservoir via a controllable valve, which adjusts the oil pressure and the force on the clutch package.
In traction/high slip conditions, a high pressure is delivered: in tight curves (i.e. parking), or at high speeds - a much lower pressure is provided. Figure 5 shows where the clutch is located in the car.

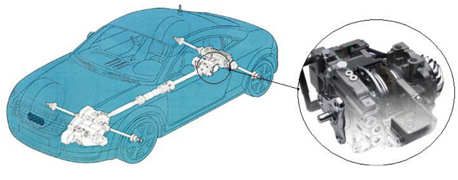


Figure 5 Location of the Haldex coupling inside the Audi TT

4. Noise and vibration

These types of clutches are installed in high performance cars. Therefore no noises are allowed. Noises are caused by vibrations so we have to prevent these. There are two kinds of vibrations: Resonance Vibration and Self-Excited Vibration.

The force acting on a vibrating system is usually external to the system and independent of the motion. However, there are systems for which the exciting force is a function of the motion parameters of the system, such as displacement, velocity, or acceleration. Such systems are called self-excited vibrating systems since the motion itself produces the exciting force [Rao]. In this case when stick-slip appears, the acting force becomes a function of the sliding speed.

The self-excited vibrations are the cause of the shudder. Such vibrations can be avoid by increasing the positive value of δμ/δv [Kugimiya_2]. What this means is that the slope of the friction-velocity curve has to be positive. In figure 6 different typical friction-velocity curves can be seen. According to these oil A will suppress the vibration whilst oil B and C will not since they have negative slope in some parts.

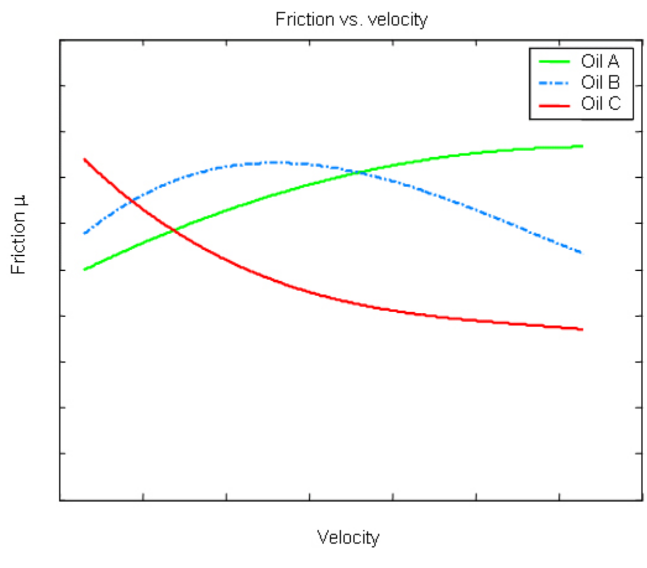


Figure 6 Typical friction velocity curves

A positive slope can be achieved by adding additives to the base oil. In particular the friction modifiers, which can considerably reduce the difference between the static and dynamic coefficients of friction, help in this matter.

It's important to notice that the friction is linearly affected by the temperature. The higher the temperature the lesser the friction. Therefore we can plot the friction at a constant temperature if we subtract the contribution from the change in temperature, figure 7. However the friction velocity curves presented in this work are not compensated.

As the reader can see in figure 8 it is easy to discover shudder behaviour with the apparatus used to perform the tests. In this graph some shudder behaviour can be seen and also how easy it is to detect. Moreover the machine makes loud noises.

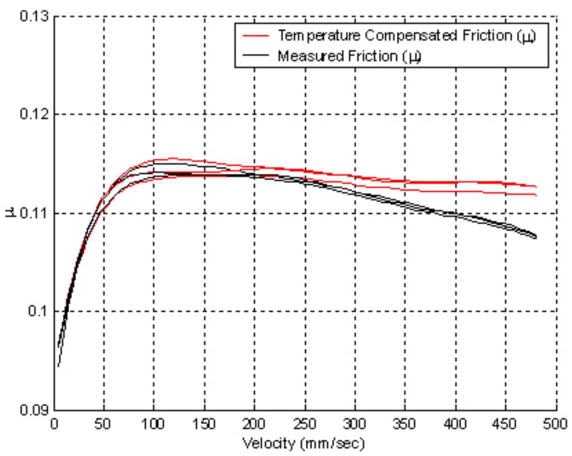


Figure 7 Temperature compensated friction curves from a commercial ATF fluid

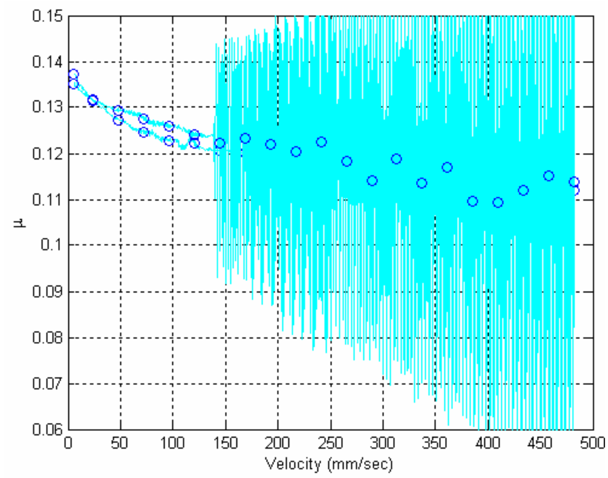


Figure 8 Shudder behaviour registered in a graph

5. Experimental equipment

5.1 The clutch plates

The friction disc is composed of the base disc and the friction material. The base disc is made of hardened steel. Then the friction material, which is sintered bronze, is applied. This material is easier to manufacture than carbon-fibre materials and more resistant to temperature and stress than paper based materials. The separator discs are made of hardened steel. The grooves facilitate oil distribution to the area of contact, and help to lower the temperature in the clutch by enhanced oil flow.

The discs can be seen in figure 9. The outer diameter of the friction disc is 108 mm and the inner diameter is 76 mm. The area of contact when the oil grooves have been accounted for is approximately 2250 mm^2.

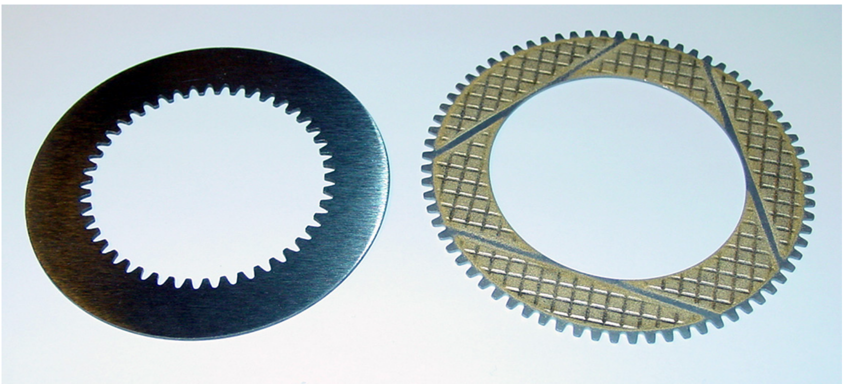


Figure 9 Clutch plates. To the left is a separator disc and to the right a friction disc.

5.2 Limited slip wet clutch test

This test rig was designed by Rikard Mäki to simulate the working conditions of the Haldex wet clutch. In figure 10 a model of the apparatus can be seen. The machine is supported on an aluminium stand (1). The base (2) is a rigid beam of length 1600 mm. The gear box (3) mounted in the base transmits the power between the electric motor (2) and the clutch housing (6) through the coupling (4) and the hollow hydraulic piston (5). The torque transmitted by the clutch is sent through the torsion bar (7) to the torque sensor (8). The torque sensor is able to move in the axial direction thanks to a sliding system (9).

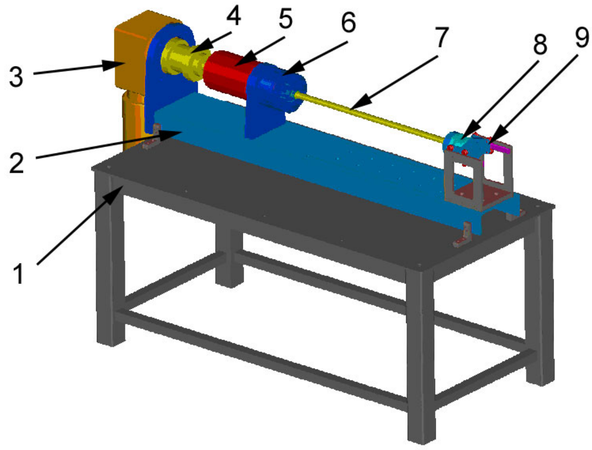


Figure 10 Overview of Limited Slip Clutch Test Rig [Mäki_1]

A closer look at the apparatus can be seen in figure 11. The power generated by the motor (3) is transmitted to a shaft through the torsionally rigid flexible coupling (4). The maximum output torque is 500 Nm and the speed can be varied between 0,5 and 125 rpm (2,5 to 600 mm/s on the mean radius). The coupling is able to permit displacements in the axial direction. The shaft (10) goes through the hollow hydraulic piston to the clutch housing (6). It will transmit the force generated by the piston to the discs that are being tested (11,12). The applied force will reach 20 000 N in this test. The force sensor (13) is placed at the beginning of the torsion bar (7). At the end we can find the torque sensor (8). It is possible to change the torsion bar thus making it shorter or longer. This will change the natural frequency of the apparatus between 100 to 500 Hz.

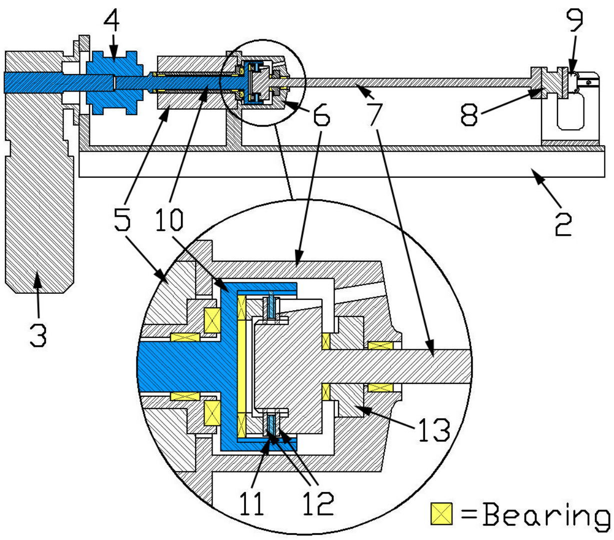


Figure 11 Limited Slip Clutch Test Rig in a schematic view. [Mäki_1]

Different sensors are placed in the machine: 2 thermocouples (one to monitor the plates temperature and the other to monitor the fluid temperature); one load cell to monitor the applied load on the plates and one torque sensor to monitor the torque transmitted by the plates. All the information provided by these sensors, plus the sliding speed and the time is used by a computer to perform the tests and is recorded for further analysis.

5.3 Standard reciprocating friction tester.

The tests were carried out with a reciprocating friction and wear tester, type TE77, from Plint and Partner [Plint]. A schematic view of the apparatus is shown in figure 12. The upper specimen is moved in a reciprocating motion with a stroke length of 2.7 mm. The applied load was varied between 100 N and 200 N and the frequency was varied between 2.5 Hz and 10 Hz.

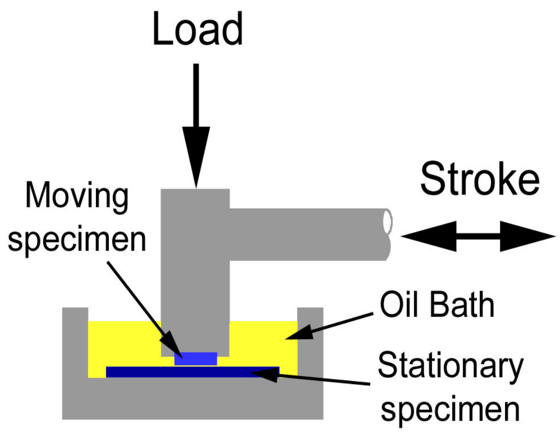


Figure 12 Schematic view of the reciprocating friction and wear tester

The friction force was measured on the stationary fluid holder by a piezoelectric load cell.
The designed friction surfaces are shown in figure 13. The moving friction surface is laser cut from the friction disc used in the clutch. A circular piece with a diameter of 10 mm and glued to the end of a steel cylinder was used for sample mounting in the test equipment. The stationary sample was cut from the steel separator discs of the clutch.

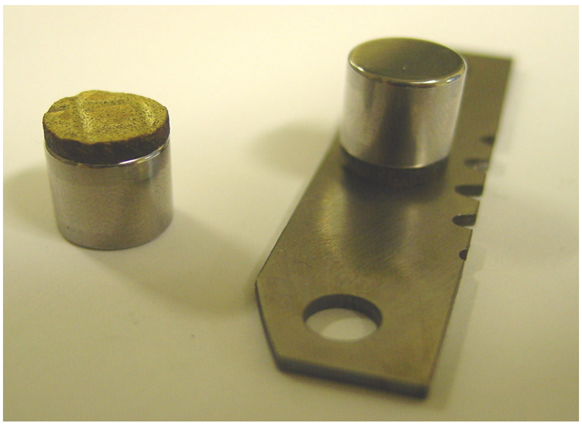


Figure 13 Specimen used in the reciprocating friction and wear tester. Moving specimen to the left, both specimens to the right

6. The tests

Two types of tests were performed. Standard reciprocating friction tests were done to select the oil samples which would be tested on limited slip tests.

6.1 Limited slip tests

Tests are composed of a series of sliding velocity ramps between 1 and 100 rpm. During the ramps the plates are loaded with 20 000N. The lubricant flows at 200 ml/min thanks to a pump. The first ramp is done at an initial temperature of 70°C. Then when the oil cools to 60°C the second ramp series is begun and so on, reducing the temperature by 10°C each time until 30°C is reached. Therefore, 5 series of ramps are run. Before starting the ramps a running-in is done in order to prepare the discs. During the running-in the plates are loaded with 15 000N during 10s, then they are unloaded for ten seconds and then again loaded. The cycle time is therefore 20s. This is repeated for 90 cycles. The usual duration of a whole test is around four hours.

After the test a cleaning operation is performed in the test machine. The clutch housing is disassembled and all the bearings and parts are cleaned separately. A paraffinic solvent is used to remove the oil. Then the clutch housing is assembled without any parts inside and cleaned by pumping in solvent while the shaft rotates at 100 rpm. This operation takes 30 minutes to complete. The used friction plate is always disposed of and replaced by a new one.
However the thoroughness of the cleaning will depend on what we will test afterwards. If we want to test a totally different fluid it’s necessary to change even the separator disc with the thermocouple whilst if we only want to test the same base oil with a different concentration of additives we only need to remove the old fluid and replace it by the new one.

By adding some equipment it is possible to run low temperature tests as well in the machine. The housing and the hollow piston are insulated and cooled by two cooling machines. One blows cooled air and the other pumps cooled methanol that flows through a copper pipe located around the clutch housing. As a result, the ramps can start at -25°C.

6.2 Standard reciprocating friction test

Influence of additives and base fluid composition on coefficient of friction was tested with a reciprocating friction and wear tester, type TE77, from Plint and Partner [Plint]. The applied load was varied between 100 N and 200 N, and the frequency was varied between 2.5 Hz and 10 Hz.
The temperature of the fluid bath was also controlled, and the tests were performed between 25 and 115 °C.
These tests were carried on by Kent Ekholm [Ekholm].

7. Analysing the data

When a test is performed, the data is registered in a file. It contains information about sliding speed, load applied, oil and clutch plate temperatures, torque transmitted and time. All these parameters can be seen in figure 14.

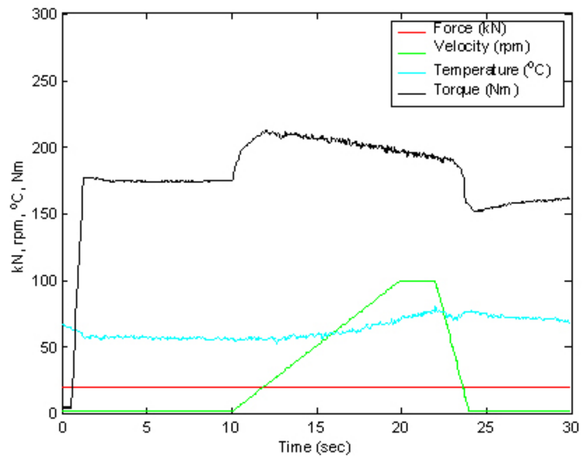


Figure 14 Data registered by the apparatus

The acquired data from the test is analysed and operated with Matlab software. A program plots different graphs extracting data from the files in order to present the results in a friendly way.
The most interesting graph plots coefficient of friction against sliding velocity, figure 15. In this graph it is possible to appreciate the tendency that the analysed lubricant has towards shudder. Each curve begins at the respective start temperature. As it was said before, the higher the temperature the lesser friction so high temperature curves are plotted at the bottom whilst low temperature curves are plotted above. In the case of shudder appearing it is easy to detect as explained in previous paragraphs.

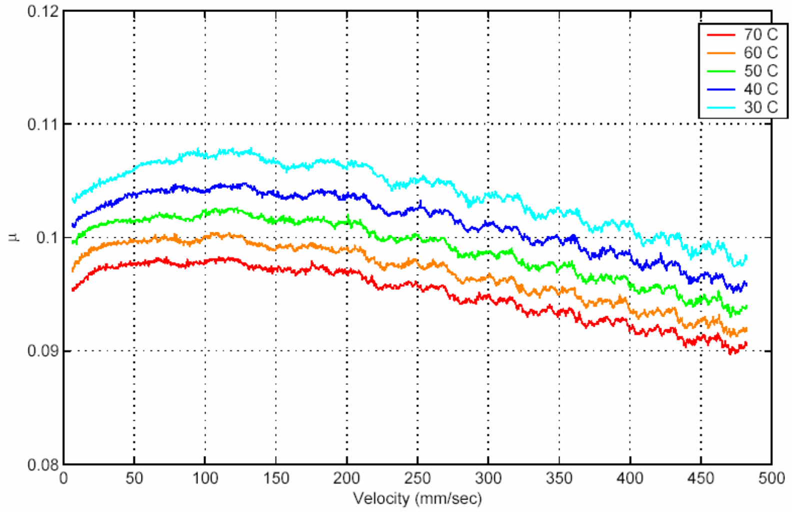
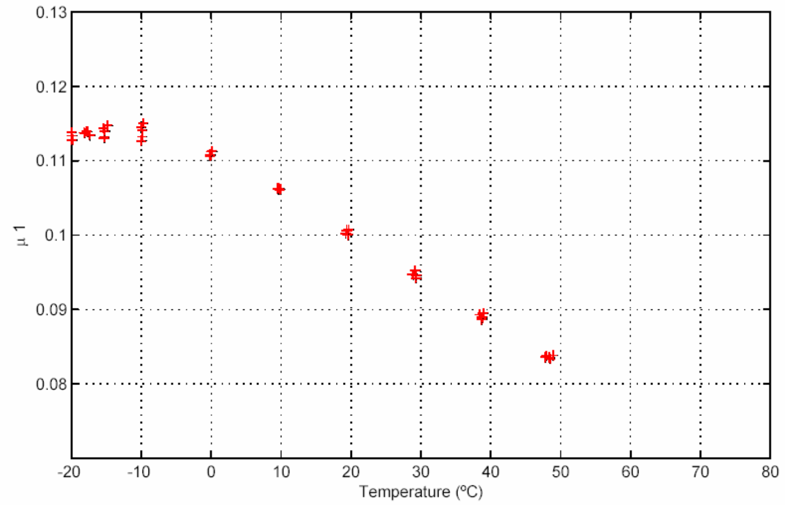


Figure 15 Friction-velocity curves plotted with Matlab

Another useful graph plots coefficient of friction as a function of temperature for 1 rpm and for 50 rpm in order to distinguish the temperature affects on the measured friction parameters, figure 16. It is also useful to describe the torque capacity (μ1) and dynamic friction (μ50) [Mäki_2], [Ohtani].



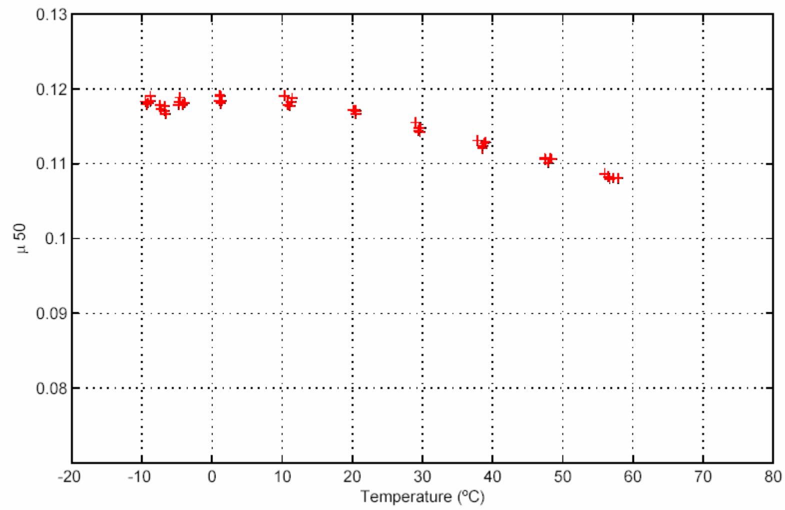


Figure 16 Coefficient of friction trend as a function of temperature at 1 rpm (top) and 50 rpm (bottom).

8. Results

The objective of the testing is to find a new formulation with better performance. In this chapter the evolution process of the formulation can be seen. First single additive testing is shown. Afterwards the additive combination test is described. Finally a new formulation is presented and its performance shown.

8.1 Single additive testing

At the first stage of the project several additives were tested separately in order to study their friction characteristics in the reciprocating test machine. After looking through the results some blends containing friction modifier additives or anti wear additives were selected. These mixtures were tested in the limited slip test rig in order to know their friction characteristics.

8.1.1 Friction modifier

The effect on the friction coefficients due to the additive can be seen in figure 17. The peak for the static coefficient of friction is noticeably reduced when the lubricant mixed with the friction modifier is used.

After this the mixture was tested in the limited slip test rig. The results can be seen in figure 18. This additive can be considered good because there is no sign of stick-slip and the friction velocity curves are quite constant.

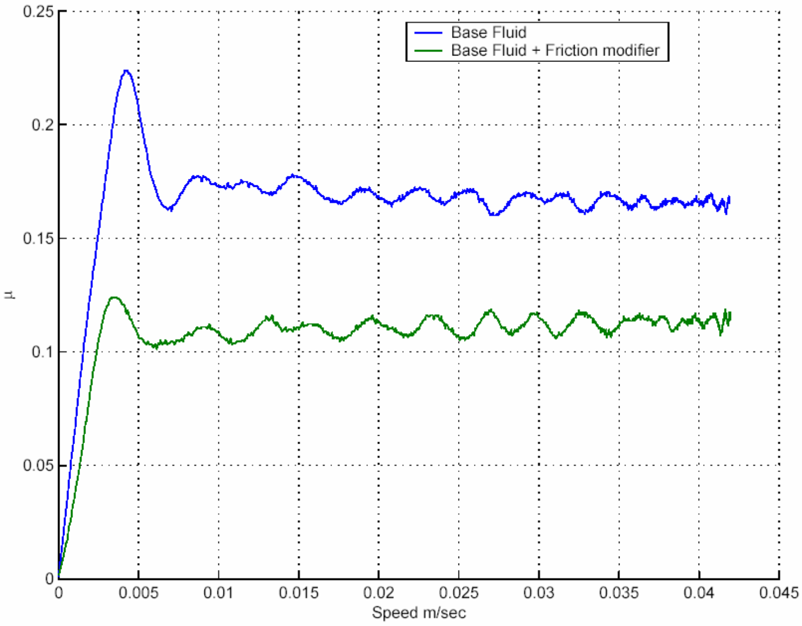


Figure 17 Comparision between base oil and base oil mixed with friction modifier. Experimental conditions: 70°C 150N 6Hz. [Ekholm]

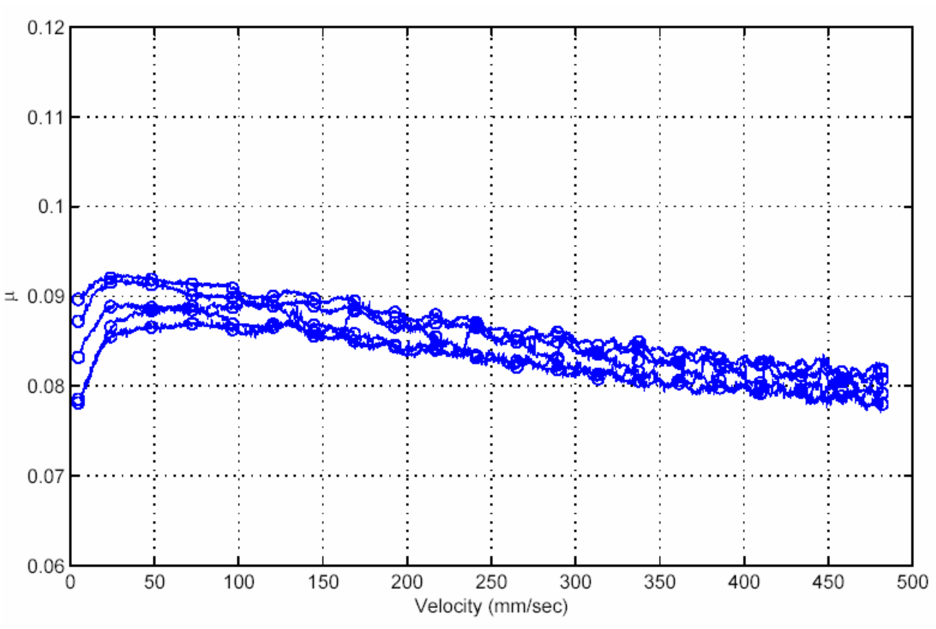


Figure 18 Friction velocity curves for base oil with friciton modifier carried out with the limited slip test rig.

8.1.2 Anti wear additives

In this case two different anti wear additives were tested. The results can be seen in figure 19. They seem correct but when they were tested in the limited slip test rig a big shudder effect appears, figure 20.

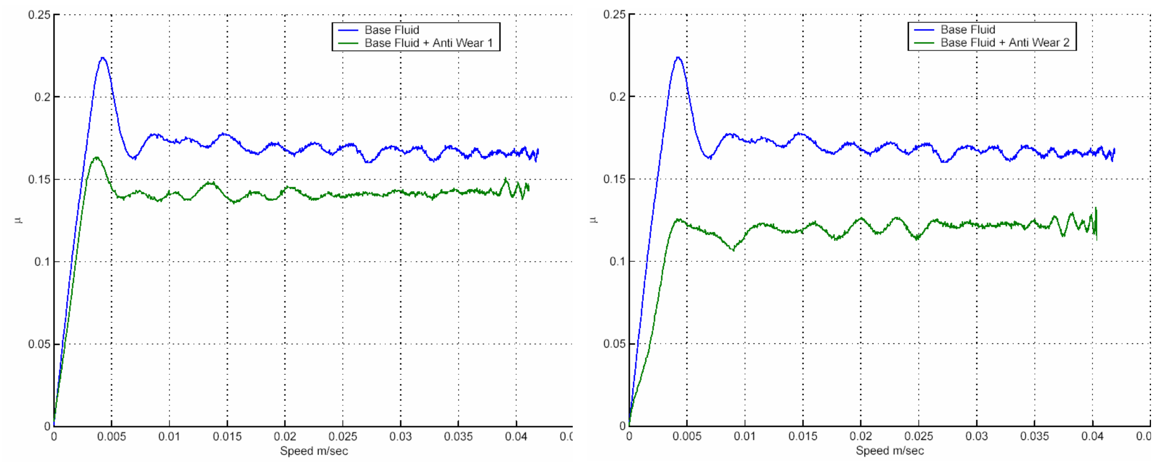


Figure 19 Comparison between base oil and base oil with anti wear 1 (left) and anti wear 2 (right). Experimental conditions: 70°C 150N 6Hz. [Ekholm]

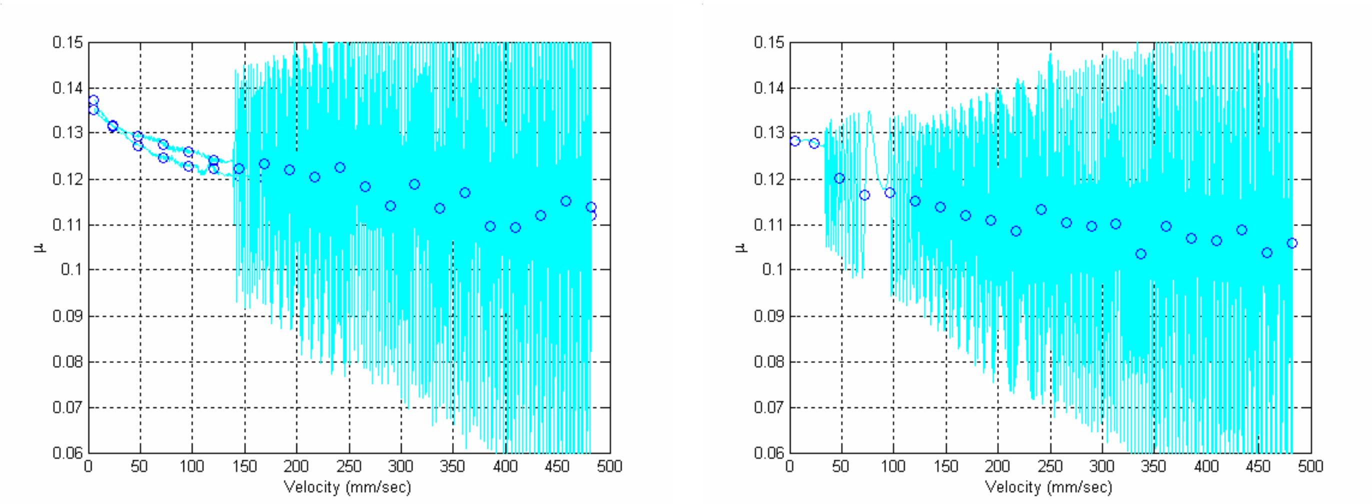


Figure 20 Self-excited vibrations produced in the limited slip test for AW1 (left) and AW2 (right).

8.2 Additive combinations

At the second stage of the project additive combinations were tested in order to reach the final formulation. This stage was divided into 3 steps. At each step one type of additive was introduced. Then a selection was made comparing the curves.

The starter formulation was composed of synthetic base oil with antioxidant, friction modifier and detergent additives. The antioxidant and the detergent have demonstrated not to affect significantly the anti-shudder performance [Kent]. However we need them to prevent oxidation and to avoid the agglomeration of waste products respectively. The friction modifier is the other way around. It improves the anti-shudder performances in the way that without it the oil is not suitable for the application because of the shudder.

In table 1 the composition of the lubricants tested is shown. As the reader could see at the first step, rust and corrosion additive was added. At step two and three anti wear and extreme pressure were mixed respectively.

Designation	Antioxidant	Friction Modifier	Detergent	EP	Rust & Corrosion	AW	Step
Fluid 1A	✓	✓	✓		✓ Type AC A		1
Fluid 1B	✓	✓	✓		✓ Type AC B		
Fluid 1C	✓	✓	✓		✓ Type AC C		
Fluid 1D	✓	✓	✓		✓Type AC D		
Fluid 2A	✓	✓	✓		✓ Type AC A	✓Type AW A	2
Fluid 2B	✓	✓	✓		✓ Type AC D	✓Type AW A	
Fluid 3A	✓	✓	✓	✓Type EP A	✓ Type AC D	✓Type AW A	3
Fluid 3B	✓	✓	✓	✓Type EP B	✓ Type AC D	✓Type AW A	
Fluid 3C	✓	✓	✓	✓Type EP C	✓ Type AC D	✓Type AW A	
Fluid 3D	✓	✓	✓	✓Type EP D	✓ Type AC D	✓Type AW A	
Fluid 3E	✓	✓	✓	✓Type EP E	✓ Type AC D	✓Type AW A	

Table 1 Designation of oils blended during the project

8.2.1 Step 1. Selection of rust and corrosion additive.

At this initial step rust and corrosion additive was added to the formulation. This additive is needed to prevent corrosion in the clutch.

Four different additives were mixed with the initial formulation in order to produce four new lubricants. Each one was tested and curves were compared to each other. Finally it was decided to keep the formulations 1A and 1D for the next steps. As the reader can see in figures 22 and 23, 1A was chosen because of its good friction velocity curves while 1D was chosen because of its good µ1 and µ50 temperature dependence. 1B and 1C were discarded because of their bad friction velocity curves.

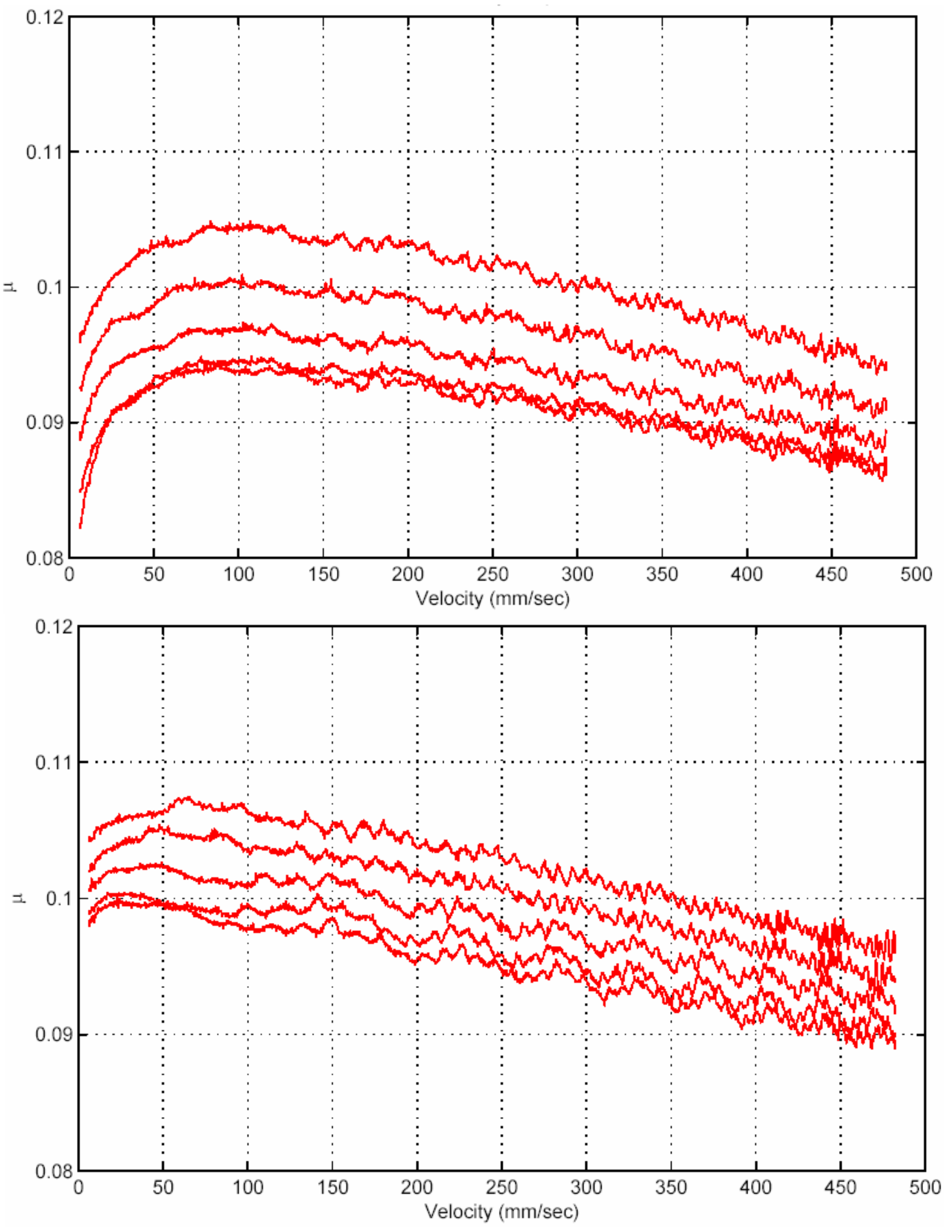


Figure 21 Friction velocity curves from fluid 1A (top) and 1D (bottom).

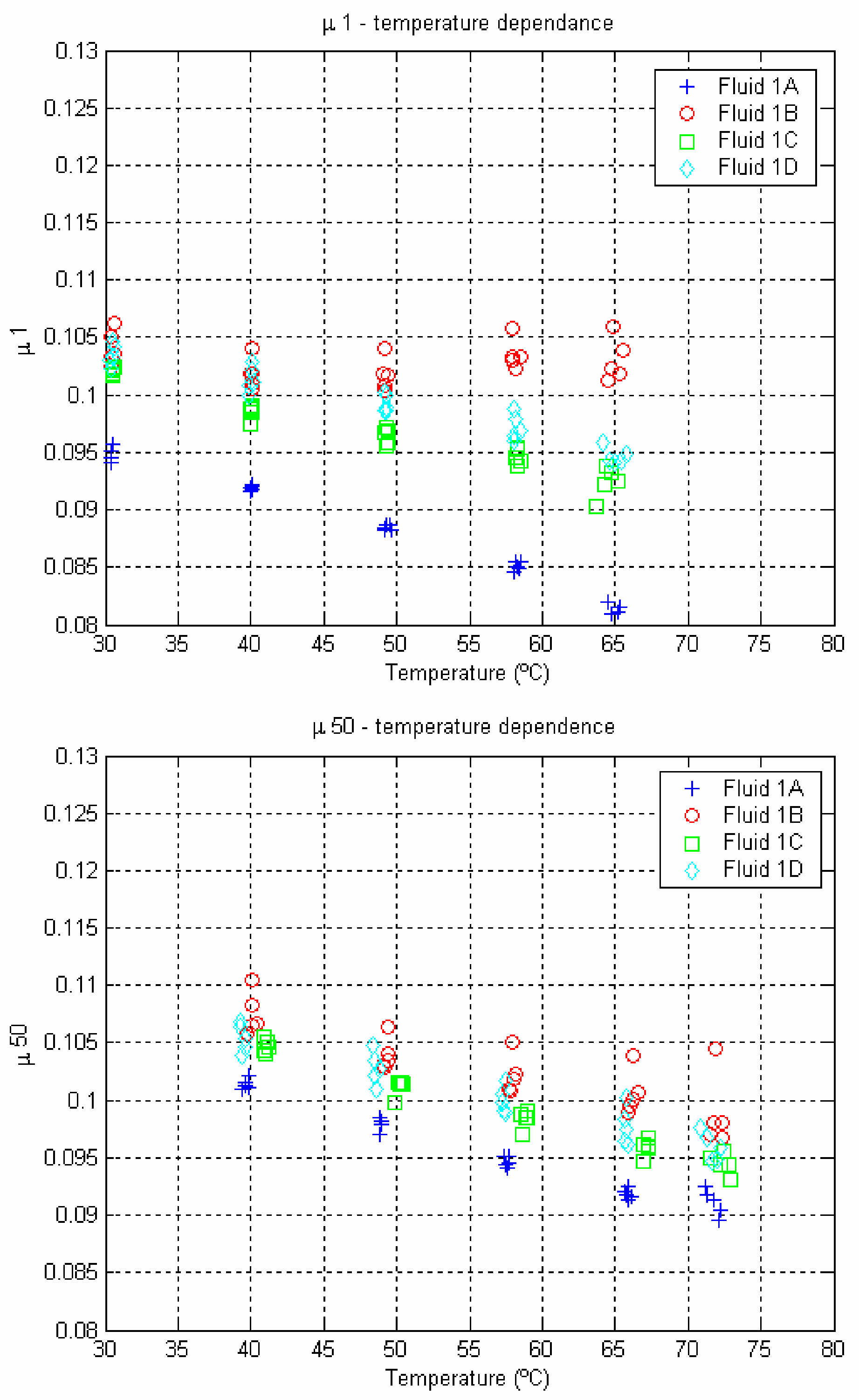


Figure 22 Coefficient of friction at 1 rpm (top) and at 50 rpm (bottom) from fluids belonging to first stage.

8.2.2 Step 2. Addition of an anti wear additive.

At the second step anti wear additive was added to the formulations obtained at the first step. This additive is needed to prevent the wear and micro welding as its name suggests.

This time the two lubricants, which passed step 1, with the new additive mixed in (the same for both) were tested. After looking through the curves just fluid 2B had the required performance. Fluid 2A produced stick-slip, therefore it was discarded.

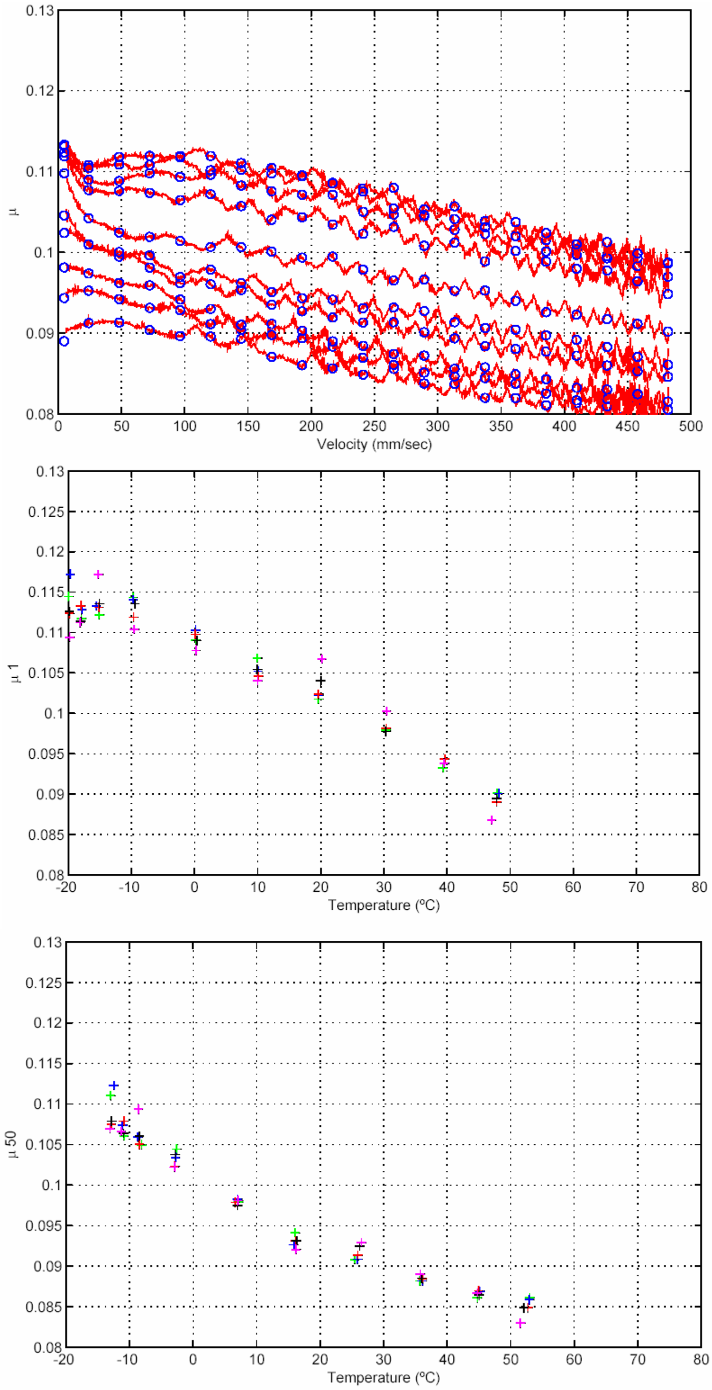


Figure 23 Friction velocity curves (top), μ1 temperature curves (middle) and μ50 temperature curves (bottom) from fluid 2B.

The curves are not very good because at the beginning they don't have the desired shape. Their slope is too negative (figure 23 top). However these are better than the ones from fluid 2A. This time a low temperature test was carried out.

Trend of μ1 (coefficient of friction at 1 rpm) can be seen in figure 23 (middle). The tendency is quite linear.

The same can be said for the trend of μ50, figure 23 (down). However the friction is too temperature dependent.

8.2.3 Step 3. Addition of extreme pressure additives.

At this final step, five different extreme pressure additives were added to the fluid 2B obtained at the second step. There are bearings and cam followers lubricated by this fluid that need this kind of additive.

The five new formulations were tested and their results were studied. Finally fluid 3B passed the test. The others were discarded since they produced stick-slip.

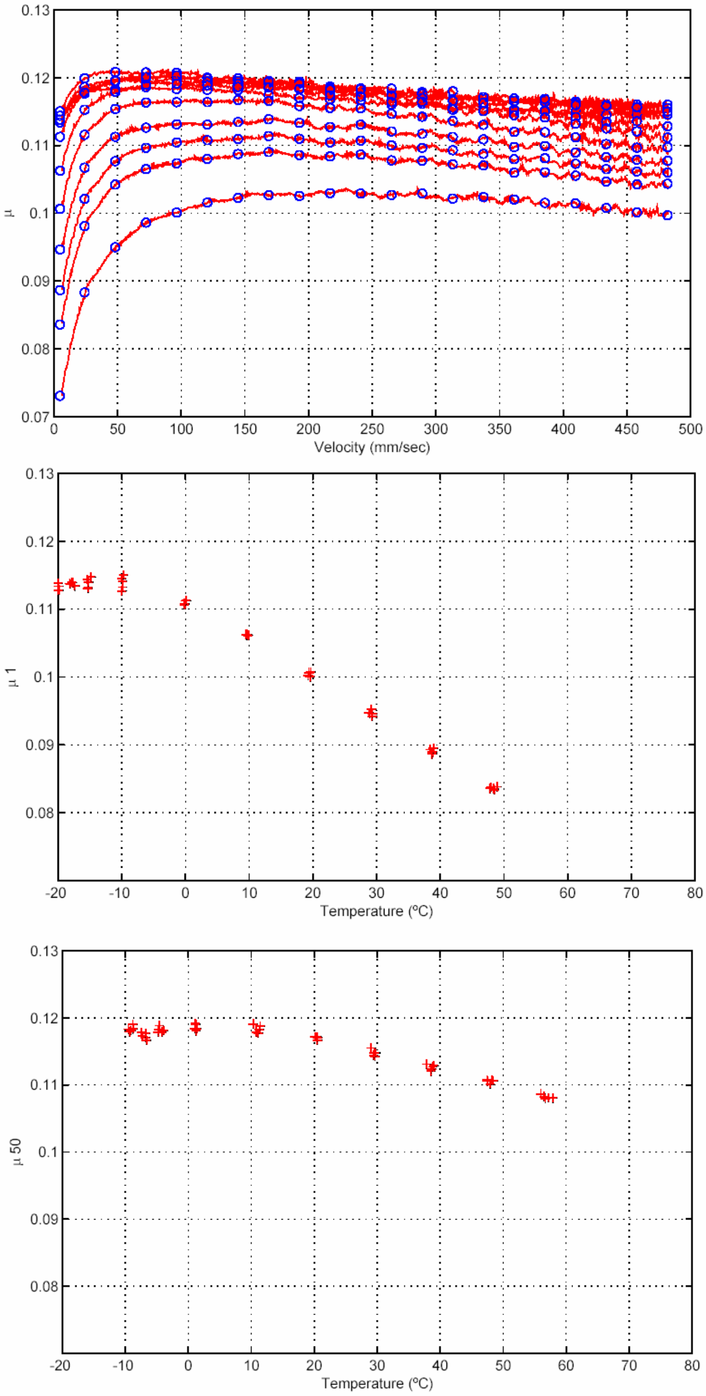


Figure 24 Friction velocity curves (top), μ1 temperature curves (middle) and μ50 temperature curves (bottom) from fluid 3B.

The friction velocity curves shows good behaviour especially at low temperatures where they are quite constant (figure 24 top).

The fluid shows quite constant friction behaviour at lower temperatures. Then it decreases linearly with the temperature (figure 24 middle).

As is it shown in the graph (figure 24 bottom) the fluid has low temperature dependency at high sliding speeds.

Finally a new fluid was formulated containing all the needed additives. Its performance is shown in the next paragraphs.

8.3 Performance of new formulation

Finally the object of the project was reached. A new lubricant suitable for use in limited slip wet clutches was formulated. In the next paragraph, temperature compensated friction curves are presented as well as a comparison between the new formulation and commercial fluids used today in cars.

8.3.1 Temperature compensated curves

The compensation is done in order to know the evolution of the friction as a function of sliding velocity without the influence of temperature. What is done is to subtract the contribution of the temperature at each point. As it was said the friction shows a linear behaviour as a function of temperature.

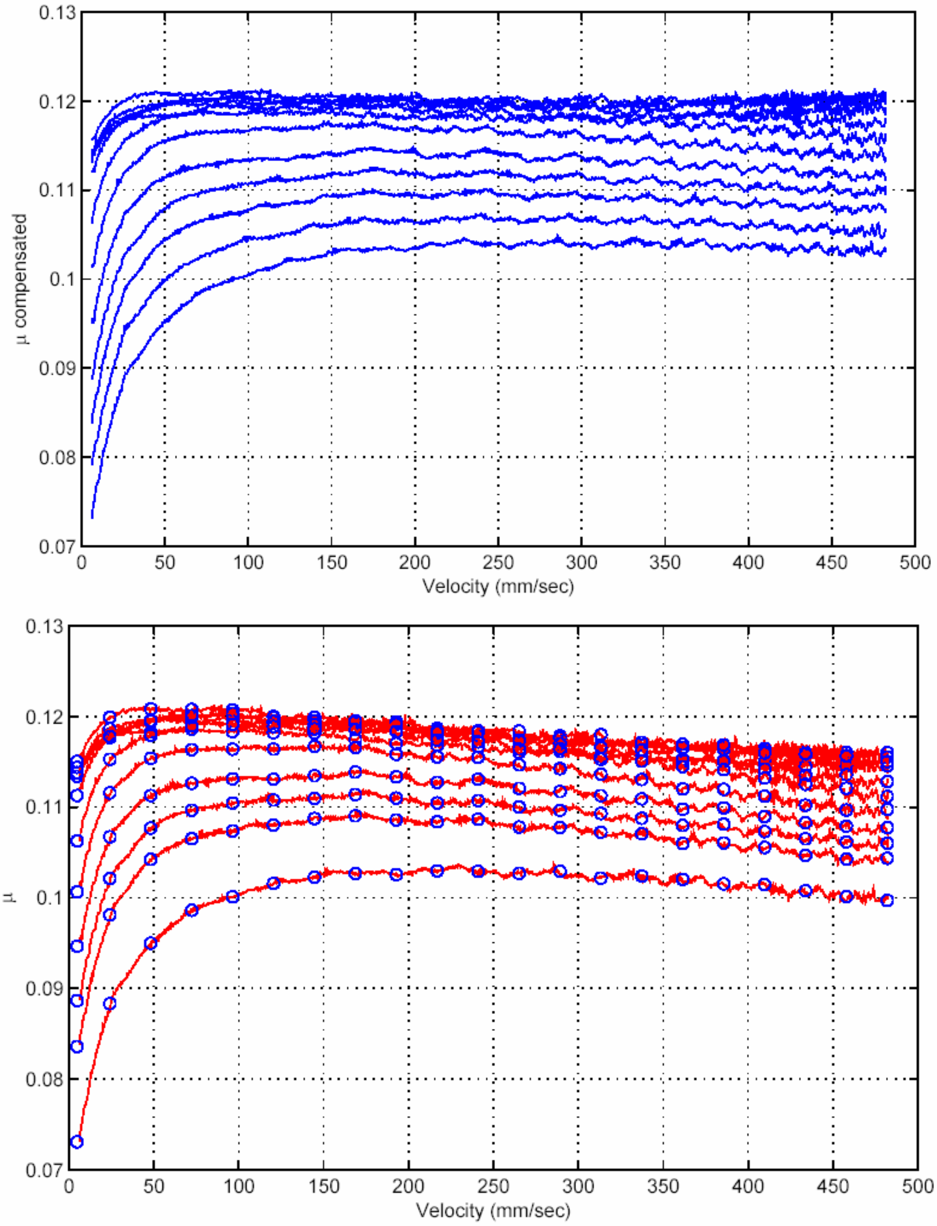


Figure 25 Temperature compensated curves (up) in front of non-compensated curves (down)

Therefore the points can be linearly fitted and the slope can be found. Finally this slope can be used to calculate the compensated friction. However these compensated curves are approximated since only μ50 slope is used. That's because at slow velocities the temperature change is quite small so its contribution to the friction is small as well. It is in high sliding speed this contribution increases. As a consequence μ50 slope can be used as an approximation.

8.3.2 Comparison between fluid 3B and commercial fluid from Statoil

The temperature range on the graph is between 30 and 70 degrees since there is no data from commercial fluid at low temperatures.

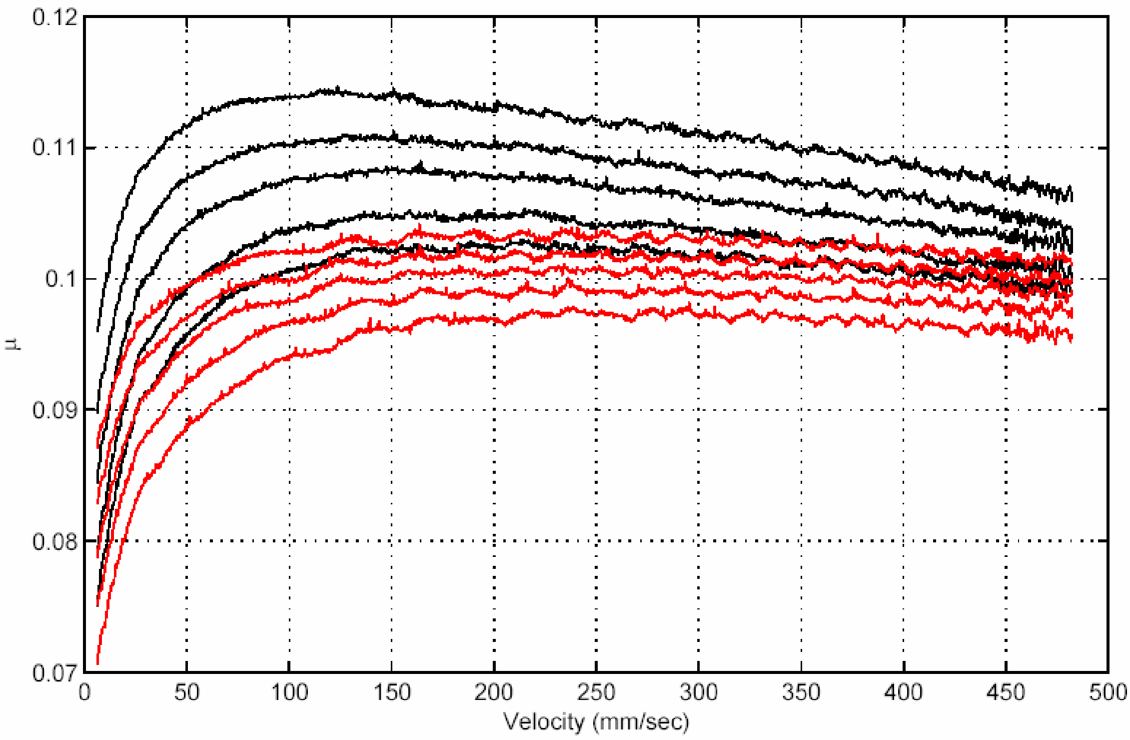
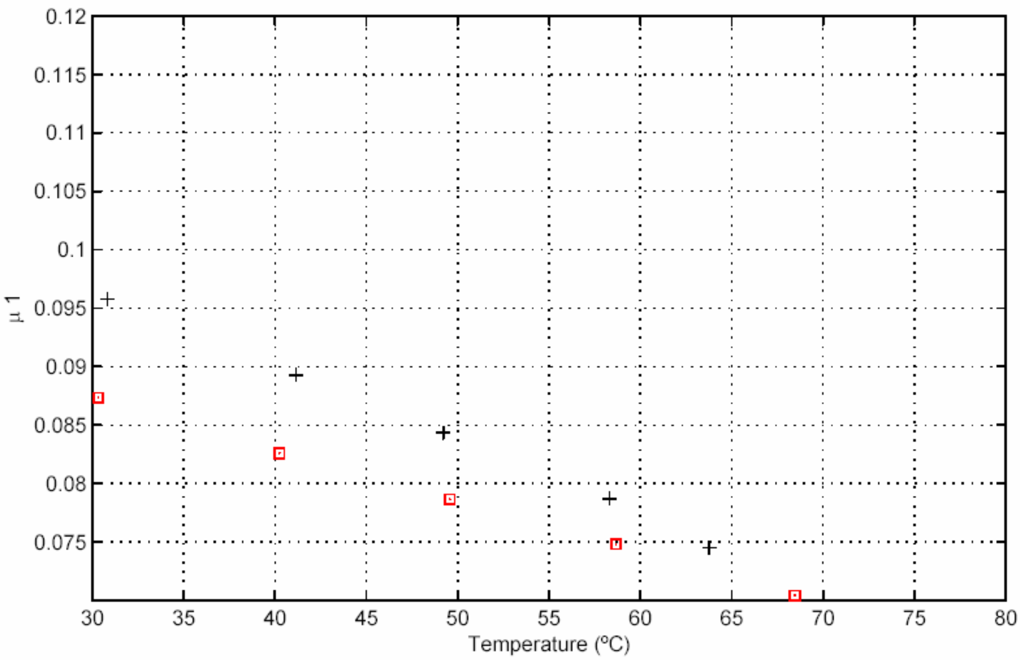


Figure 26 Comparison between fluid 3B (black) and commercial fluid (red)

The friction velocity curve, figure 26, shows that the new formulation has more torque transfer capacity. The drawback is that the slope is more negative than in the commercial fluid. However the best performances of fluid 3B are at low temperature and this data is not represented in the graph.



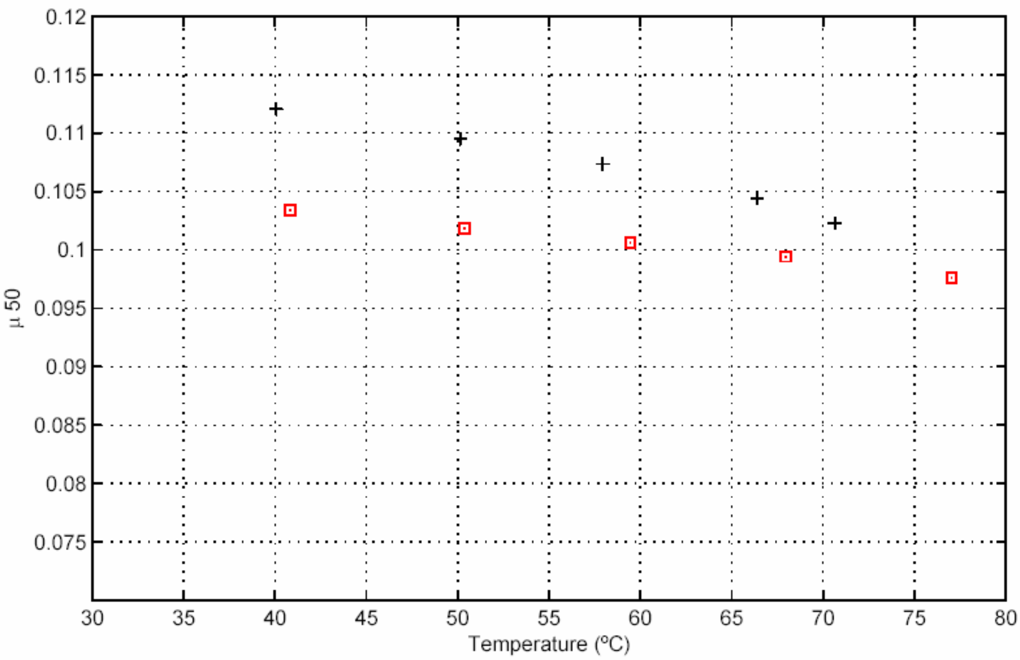


Figure 27 Comparison of coefficient of friction between commercial fluid (squares) and fluid 3B (crosses)

Both fluids have low temperature dependency at high sliding speeds but while fluid 3B has a higher friction at the same temperature the commercial fluid has lower temperature dependence.

8.3.3 Comparison between fluid 3B and commercial additive package blend.

Parallel to this work an additive package was tested. This additive package was manufactured by a third company. It was mixed in the laboratory with base oil (5% concentration) in order to test it. The results contrasted with the new formulation are presented in the next graphs.

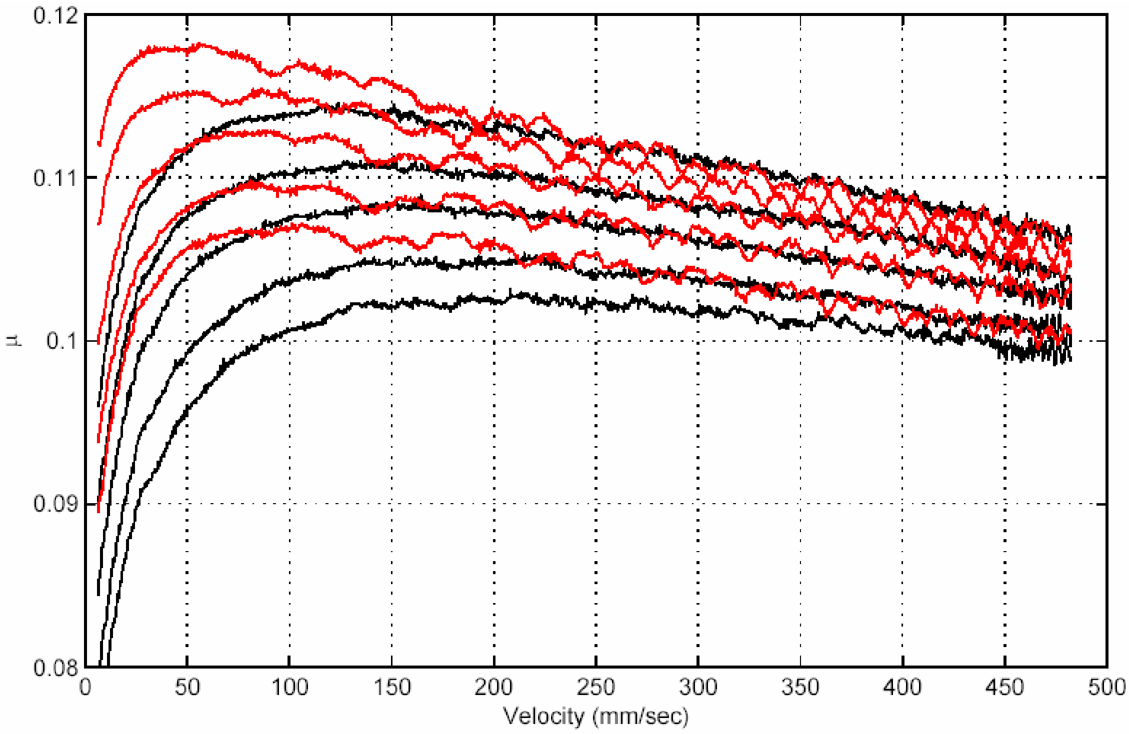
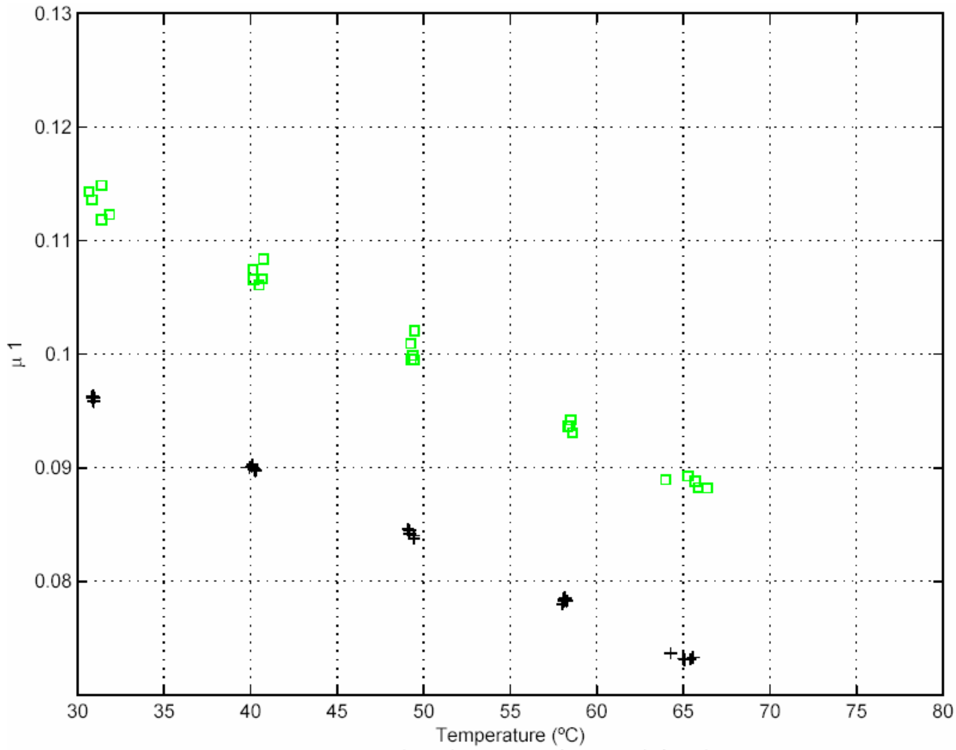


Figure 28 Comparison between fluid 3B (black) and commercial additive package fluid (red)

The additive pack formulation has a grater negative slope in the low sliding speeds zone whilst they behave approximately equal at high sliding speeds, figure 28. It means that the new formulation could be better in suppressing vibrations because of its less negative slope.



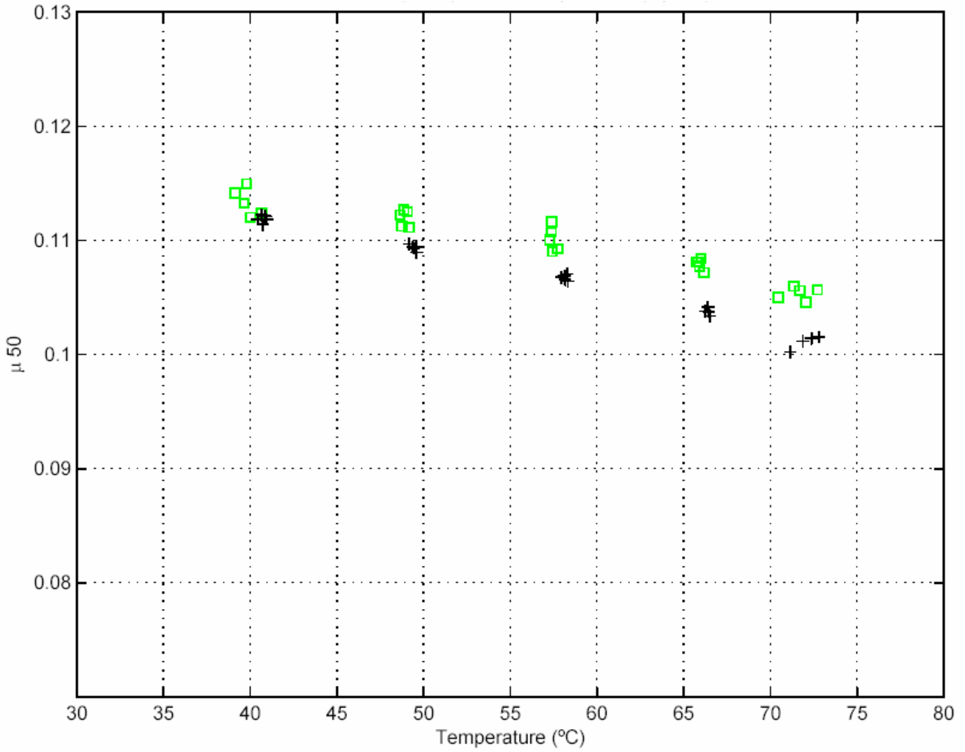


Figure 29 Comparison of coefficient of friction between additive pack fluid (squares) and fluid 3B (crosses)

Observing figure 29 it is possible to notice that the additive pack fluid has a higher coefficient of friction at low sliding speeds while both fluids behave similarly at high sliding speeds. But, as was said before, the commercial package has a greater negative slope at low speeds.

9. Conclusions and further work.

A new lubricant suitable for use in limited slip wet clutches is formulated.

The lubricant shows good performance compared to commercial fluids available today on the market.

The lubricant will be cheaper to manufacture because is not necessary to buy any expensive additive package.

This project ends at this point but the development of the formulation has just begun. Much more testing has to be done before this formulation becomes commercial someday.

The next stage will be life-time testing in the lab. This test will be carried out in a special life-time test rig at Haldex

If that is successful, tests in the real Haldex clutch will begin.

Subsequently, the fluid will be used in cars and its performances will be studied.

Finally the fluid may become commercially available and hopefully people will buy it.

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