OFP - Oil-Free Powertrain

Development of Powertrain and Drive Line Components without Liquid Lubrication

Project No: IPS-2001-80006
Contract No: IPS-2001-CT-98006

Work-package 5
Phase Transition Lubrication

Final Report

June 2004

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Abstract

In work-package 5 “Phase Transition Lubrication” a new concept of lubrication was investigated. The lubrication of the mating surfaces should be maintained by a phase transition under the local conditions within the contact area, as it is in ice skating. For the project a theoretical study of the literature and experimental investigations with a twin disc machine were done. Theoretical papers report that melt lubrication can occur in reality, but further experiments are needed. Papers about experiments show that melt lubrication is possible at very high sliding speeds, as for example in guns. For the experimental investigations coatings consisting of a low melting alloy, of different varnishes containing solid lubricants and consisting of wax were used. For the tests one disc was coated the other one uncoated. An additional substance, which should build a coating, when it is mixed into a common oil was investigated, too. With the varnishes also tests with an additional oil lubrication were done. It was found that most of the varnishes were removed from the disc surface even under EHL. However, the friction behaviour could be improved compared to the uncoated discs, even when the coatings were optically removed from the disc surface. A reason could be that some varnish was still in the grooves of the disc. When the coatings were removed from the surface life-time at dry lubrication wasn’t improved compared to uncoated discs. Another main part of the project were tests at dry lubrication with the different coatings. The results showed that friction behaviour and life-time was improved compared to uncoated discs, best performed the PTFE-coating. Thus the coatings could be used under dry lubrication for applications with a limited load and with a limited life-time. However, an insufficient or even no regeneration of the lubricant film took place. Tests with the additional coating building substance showed that roughness could be decreased with a coating building run at boundary lubrication conditions. Furthermore traces of silicium, which is a part of the coating, could be found on the disc surface, but no coating was detected in a metallographic section. Life-time under dry lubrication was improved, possibly due to the lower roughness compared to uncoated discs. However, friction behaviour wasn’t improved.

Content

NOMENCLATURE

Symbol	Parameter	Unit
E'	reduced elasticity module	N/mm^2
$E_{1,2}$	elasticity module of disc 1,2	N/mm^2
F_N	normal load	N
F_R	friction force	N
F_t	tangential load	N
G	elasticity parameter	-
h_{min}	minimum calculated film thickness	µm
M	torque	Nm
p	pressure	N/mm^2
p_H	Hertzian stress	N/mm^2
R	equivalent radius of curvature	mm
Ra	average value of roughness	µm
$r_{1,2}$	radius of disc 1,2	mm
S	slip	%
ΔT	temperature difference	°C
U	horizontal velocity	m/s
U	velocity parameter	-
V	vertical velocity	m/s
v	sliding speed	m/s
v_Σ	sum velocity	m/s
$v_{1,2}$	circumferential velocity of disc 1,2	m/s
W	load parameter	-

α	viscosity-pressure-coefficient	m^2/N
η_M	dynamic viscosity at bulk temperature	mPas
ϑ_{oil}	oil temperature	°C
λ	relative film thickness	-
μ	coefficient of friction	-
$\nu_{1,2}$	poisson ratio of disc 1,2	-
ν_{40}	kinematic viscosity at 40°C	mm^2/s
ν_{100}	kinematic viscosity at 100°C	mm^2/s
ρ_{15}	density at 15°C	kg/m^3
ω	angular velocity	rad/s

3 TEST APPARATUS

3.1 Test bench

For the experimental part of the work-package tests with a twin disc machine were done. The advantages of using a twin disc machine compared to a back-to-back gear test bench are the lower costs. Therefore this method is very good for experiments regarding the potential of this new lubrication concept. Furthermore the kinematic situation in gears, bearings and cam and tappet systems can be simulated with a twin disc machine. **Figure 12** shows a drawing of the twin disc machine.

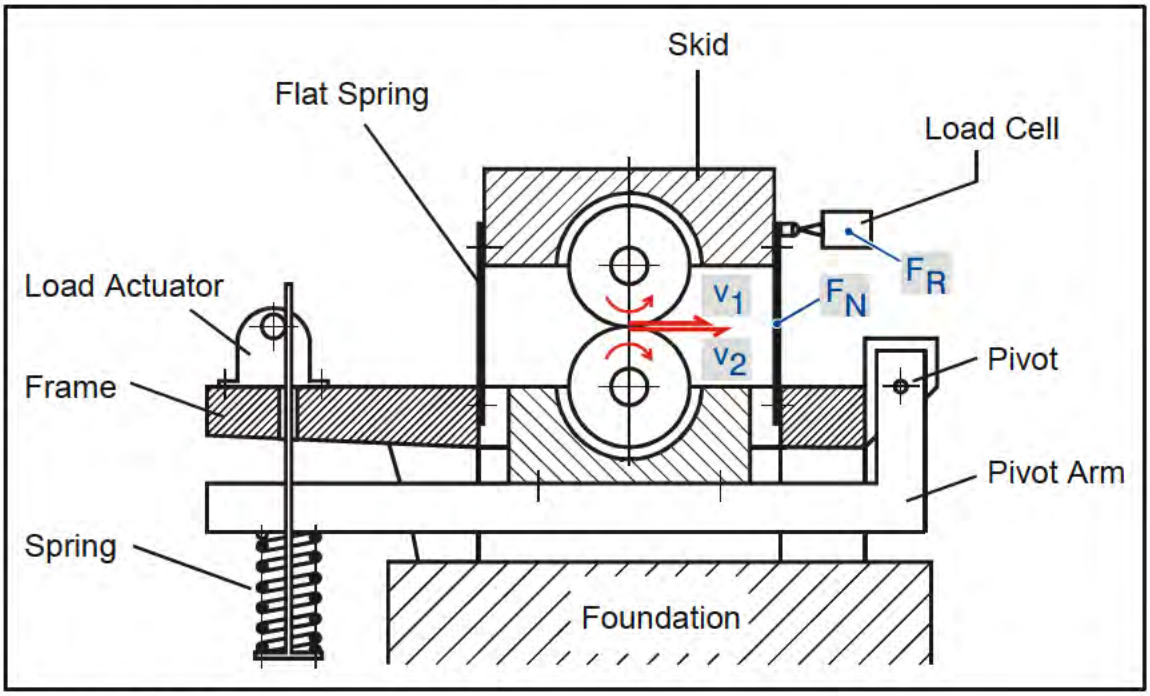


Figure 12: Twin disc machine

Each disc is driven by its own 3-phase-asynchronous motor, for the continuous variation of the speed friction gears are mounted between the motor and the disc's shafts. The speed can be varied from 0 to 3000 rev/min for each disc, therefore the maximum sum velocity for a slip of 50% is 16 m/s. The upper disc is mounted in a skid, which is connected to the frame with flat springs. For the measurement of the normal force strain gauges are mounted on the flat springs. Due to the flat springs a horizontal translation of the skid would be possible, but is restricted by the load cell for the measurement of the friction force. Due to measuring the friction force instead of a friction torque any further losses, as for example losses in bearings, are not included in the friction force. The lower disc is mounted on the frame, which is linked to the pivot arm by a pivot. With this arrangement the normal load can be set with a spring and a load actuator. The maximum normal load, which is possible, is about 4700 N, which corresponds to a Hertzian stress of 1300 N/mm^2 at cylindrical discs with a diameter of 80 mm and a width of 5 mm. All the set parameters, as for example normal load or sum velocity, are regulated by a PC. With normal force and friction force the coefficient of friction can easily be calculated for each operating point, as shown in **Equation 1**. Vojacek [56] did detailed analyses on the accuracy of the measurements and came to the conclusion that an accuracy of the coefficient of friction μ = ± 0.0025 for all possible test conditions is possible.

$$\mu = \frac{F_R}{F_N} \qquad \textbf{Equation 1}$$

For a correct contact zone of the two discs the lower disc can be moved in the horizontal position and also in the angular position. Due to the Hertzian theory a rectangular contact zone is formed at the contact between two cylinders. For checking the correct contact zone an alumimium foil, which is placed between the two discs, is used. When the not rotating discs are pressed together the contact zone is pressed into the foil and thus can be checked. Most of the tests are done with oil lubrication, therefore the test rig is equipped with an oil injection lubrication system. The oil is injected directly into the contact zone of the two discs, the oil volume flow can be set. The oil temperature is regulated with an accuracy of ± 3°C by an oil heating unit.

3.2 Test discs

For the tests cylindrical discs with a diameter of 80 mm and a width of 5 mm were used. **Figure 13** shows a drawing of the discs. The discs, made of the case carburising steel 16MnCr5, were manufactured in the institute's own workshop. The discs were case hardened with a surface hardness between 59 HRC and 63 HRC, the case hardening depth was between 0.8 mm and 1 mm for a limit of hardness of 550 HV1. The bulk strength was between 1000 N/mm^2 and 1300 N/mm^2. After heat treatment the discs were ground in axial direction with their grinding texture perpendicular to the direction of the rolling and sliding speed respectively. Due to that grinding texture a better comparability with gears is given. The measured roughness of the ground discs was Ra = 0.2 µm ± 0.1 µm, which is also comparable to the roughness of gears. **Figure 14** shows an exemplary profile of a

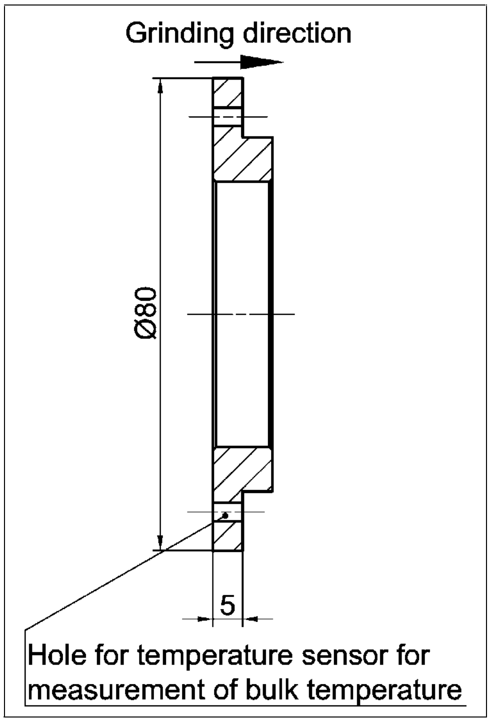


Figure 13: Test disc

roughness measurement.

The bulk temperature of the upper disc is measured 5 mm below the surface continuously during the test with a thermocouple PT100.

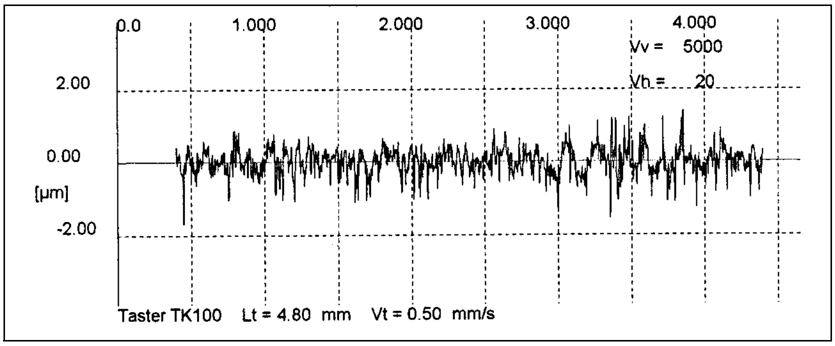


Figure 14: Roughness profile of a ground disc

3.3 Coatings and coating procedures

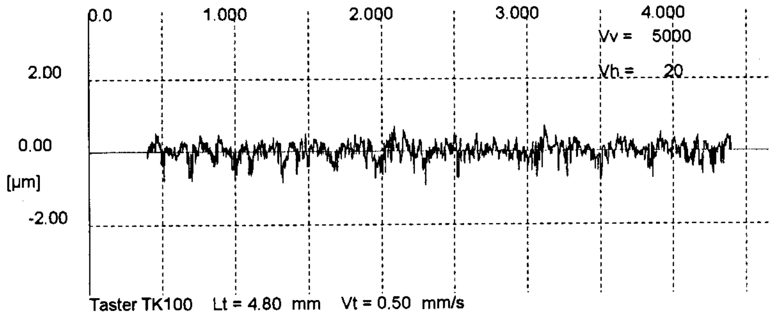
Based on the results of the investigation of the literature three different kinds of coatings were defined, namely coatings consisting of low melting metals, coatings consisting of resinous substances and coatings consisting of wax. The coatings consisting of resinous substances are varnishes containing solid lubricants, as graphite, MoS_2 or PTFE. These kind of varnishes are already used in a lot of applications, where dry lubrication occurs, nowadays [45]. All the coatings and coating materials were brought into the project by industry partners.

Besides the coatings an additional substance containing magnesium-silicium was investigated in the work-package. This substance was mixed into a common oil and should build a coating on the disc surface during operation. The substance was brought into the project by an industry partner.

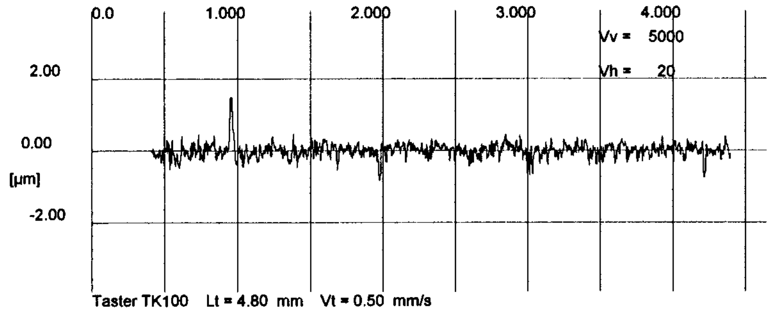
3.3.1 Coatings consisting of low melting metals (MCP124, MCP70)

For the coatings with low melting metals the eutectic alloys MCP124 and MCP70 were brought in by the industry partner MCP, Lübeck, Germany. The alloys consist of lead and bismuth. Bismuth is a metal with a low coefficient of friction and it has anomalous properties like water. This means that the melting temperature decreases, if pressure increases. The alloys have a melting point of 70°C (MCP70) and 124°C (MCP124) respectively and due to their eutectic composition a very fast phase transition. Therefore the alloys are used as melting fuses in existing applications. **Table 1** gives an overview about the properties of the alloys.

for 10 minutes. The roughness of the coating is comparable with the roughness of ground discs, see also **Figure 20**.



uncoated ground disc, Ra = 0.18 µm



coated disc, Ra = 0.19 µm

coated surface

Figure 20: Roughness profiles and surface of disc coated with wax

3.3.6 Coating building substance added to an oil (RVS® Technology)

As already mentioned above the additional coating building substance RVS® Technology was investigated in the work-package. The substance was brought into the project by the industry partner Rewitec, Wetzlar, Germany. The substance consists of natural minerals, mainly magnesium-silicium. According to explanations of Rewitec [43], a chemical reaction, due to the higher temperature within the contact, should take place, when two metallic partners are pressed and sliding on each other. The magnesium atoms should be replaced with iron atoms and a new surface consisting of iron-silicium should be built. Thus the metallic contact is replaced with a metal-ceramic contact. The advantages of that coating are a very low coefficient of friction even under dry lubrication, the smoothening of the surface due to the coating and a high wear resistance due to a higher hardness of the coating compared with a steel surface. Therefore the coated surfaces have excellent emergency operation characteristics. The thickness of the coating lies between some µm and about 1.1 mm. The higher thickness has to be considered, when parts with a specific tolerance, as for example gears, should be coated. However, the coating process ends automatically when all free iron atoms are replaced with iron-silicium atoms. The coating's thermal elongation coefficient is identical with the coefficient of steel, and therefore no problems with coating detachment occur.

Experimental investigations with engines showed an improvement of the cylinder surface and emergency operation properties [23]. Tests with worm gears also showed an improvement of emergency operation properties, when the RVS® Technology substance was added to the oil [13]. Further reports show results of friction and wear tests ([14], [48]).

4 EXPERIMENTAL INVESTIGATIONS WITH AN ADDITIONAL OIL LUBRICATION

Within the work-package both test variants were done, tests with an additional oil lubrication and tests without lubrication. Tests with an additional oil-lubrication were done with the varnishes containing graphite, MoS_2 and PTFE, because this kind of varnishes is often used with an additional oil lubrication today. For the coating building substance RVS® Technology an oil lubrication, at least for the building of the coating, is necessary.

Appendix I gives an overview of the numbers of revolutions per minute of the discs for the different used test parameters.

4.1 Lubricants

For the tests with the different varnishes the FVA reference oil FVA 2 + 4% Anglamol 99 (A99) was used [22]. FVA 2 is a mineral-oil of the viscosity grade ISO VG 32, A99 is a common extreme-pressure (EP) additive on a sulphur-phosphorus basis. Detailed data are shown in **Table 5**.

For the investigations with the substance RVS® Technology the FVA reference oil FVA 3 was used [22]. FVA 3 is a mineral-oil of the viscosity grade ISO VG 100, detailed data are shown in **Table 5**.

	Symbol	FVA 2 + 4% A99	FVA 3
Kinematic viscosity [mm^2/s]			
at 40°C	ν_{40}	29,8	95
at 100°C	ν_{100}	5,2	10,7
Density (at 15°C) [kg/m^3]	ρ_{15}	871	872

Table 5: Properties of used lubricants

4.2 Film thickness

An important parameter for the evaluation of the lubrication conditions is the relative film thickness λ. Niemann [36] defined λ as the quotient of the minimum film thickness divided by the half of the sum of the average roughness of the two mating partners (**Equation 2**).

$$\lambda = \frac{h_{min}}{\sum Ra / 2}$$ **Equation 2**

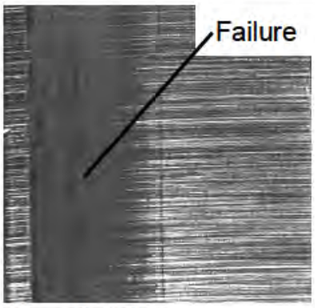
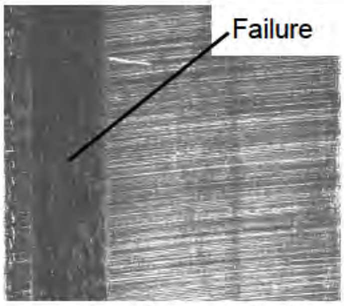
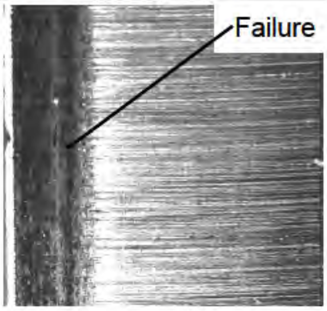
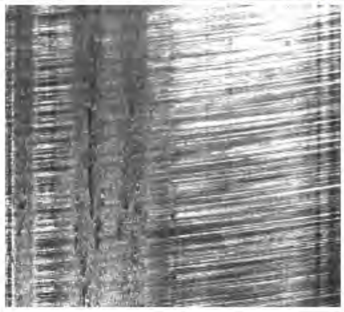
 Uncoated disc	 Disc originally coated with graphite-varnish
 Disc originally coated with MoS_2-varnish	 Disc originally coated with PTFE-varnish

Figure 25: Disc surfaces after test under dry lubrication

The conclusion of these tests is, that originally coated discs can't improve life-time at dry lubrication in a decisive way, if the coatings are optically removed from the surface. Even if there is still some varnish in the grooves, as it seemed to be at the tests with oil lubrication, it is not enough to separate the mating partners at dry lubrication.

4.4 Tests with the RVS® Technology substance

As already mentioned above the RVS® Technology substance should build an iron-silicium coating on a steel surface, which has excellent emergency running properties. For the building of the metal-ceramic coating, the concentrated substance has to be mixed into a common oil and then a coating building run has to be done. After the coating building run investigations of the disc surface and friction measurements in comparison to uncoated discs were done. Due to the fact that the grinding grooves should be filled with the coating the roughness should decrease. Furthermore the micro-hardness of the disc surface should increase and the coefficient of friction decrease. Due to the expected metal-ceramic coating, silicium should be detected in an energy dispersive X-ray analysis. For the coating building run and the friction measurements the reference oil FVA 3 was used. Already run-in discs with a roughness Ra = 0.2 µm were used, thus the roughness profile had the form of a plateau, **Figure 26** shows the roughness profile of a run-in disc.

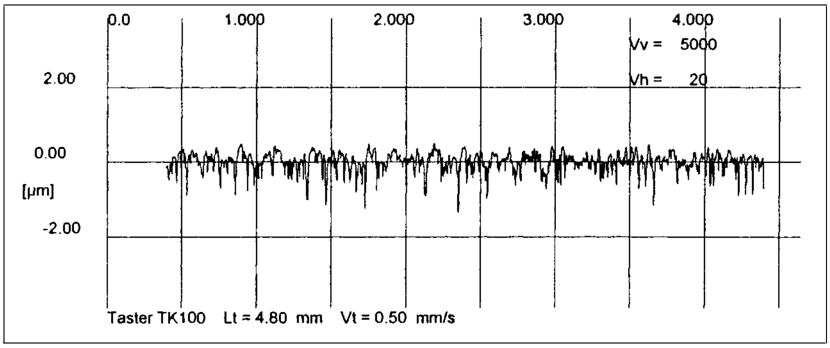


Figure 26: Roughness profile of a run-in disc

The first try of a coating building run took 8 hours at different parameters of load, slip and sum velocity. The normal load increased from F_N = 250 N to F_N = 800 N during the test, which corresponds to a Hertzian stress of p_H = 300 N/mm^2 up to p_H = 540 N/mm^2. Sum velocity increased from 1 m/s up to 16 m/s, slip varied from 10% to 30%. Oil temperature was at 90°C. A detailed list of the different parameters is shown in **Appendix II**. The lubrication conditions during the coating building run can be characterised as follows. During the first 30 minutes boundary lubrication occurred with a relative film thickness λ below 0.7, in the following two hours λ was between 0.7 and 2 and therefore mixed lubrication existed. The remaining 5.5 hours were performed at a relative film thickness λ above 2 and thus the main part of the coating building run was done at EHL lubrication conditions. To avoid settling of the magnesium-silicium particles, the oil was periodically mixed within the oil reservoir.

After the coating building run friction measurements compared to uncoated run-in discs with the same roughness were done. The measurements were done at a normal load of F_N = 1000 N and a Hertzian stress of p_H = 600 N/mm^2 respectively. Sum velocity was varied from 16 m/s to 1 m/s, slip from 1% up to 50%. From the results, shown in **Figure 27**, it can be seen that the coefficient of friction of the discs, run with the RVS® Technology substance, is a little bit higher compared to the uncoated ones in the boundary lubrication regime (λ < 0.7). In the EHL lubrication regime (λ > 2) the two kinds of discs are comparable. Furthermore the roughness after the coating building run with Ra = 0,2 µm is still the same as the roughness before, see **Figure 28**. This already is a hint that no coating was built during this test run. An energy dispersive X-ray analysis also confirmed that no silicium and therefore no coating was on the disc surface.

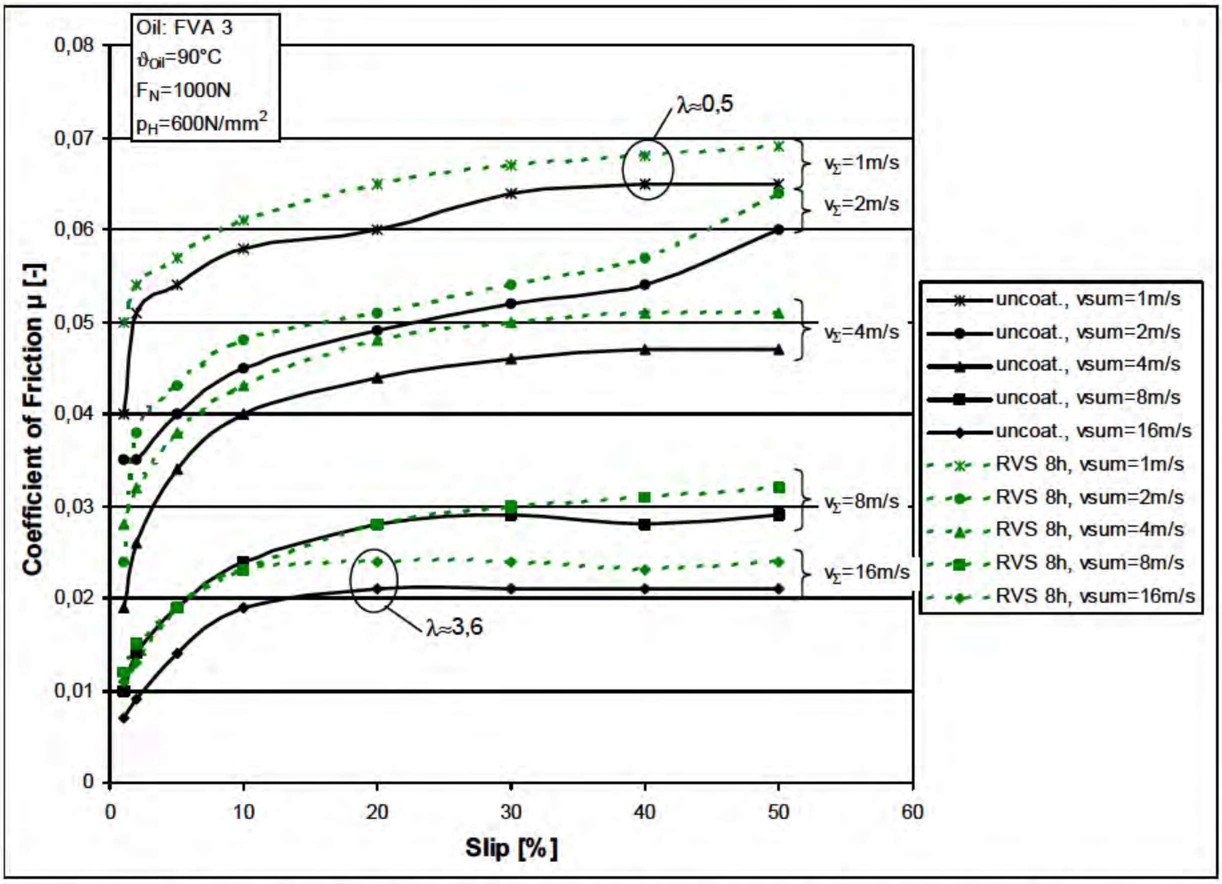


Figure 27: Friction measurements after first coating building run of 8 hours compared to uncoated ones

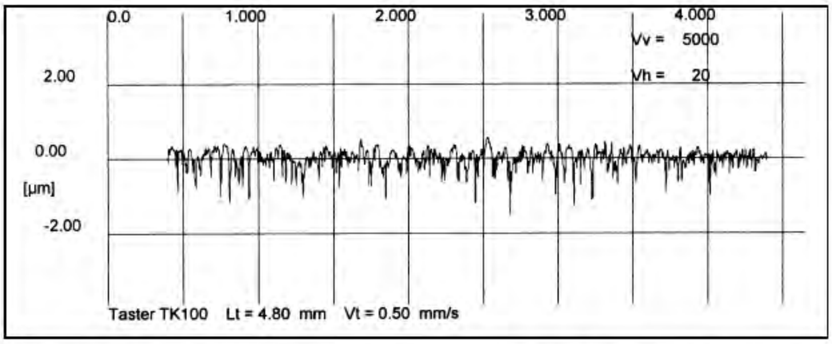


Figure 28: Roughness profile after a coating building run of 8 hours

Based on the results of the first coating building run a second coating building run with 40 hours was done. The same discs were used, the oil temperature again was at 90°C. The normal load was increased to F_N = 1450 N, which is a Hertzian stress of p_H = 720 N/mm^2. Sum velocity was 3 m/s and slip 45%. The calculated relative film thickness λ was about 0.65 and therefore this coating building run was performed at the transition from boundary lubrication to mixed lubrication. Additional RVS® Technology substance was added to the oil at the beginning of the test run, after 10 hours, 20 hours and 30 hours. Again the oil was periodically mixed within the oil reservoir to avoid settling of the magnesium-silicium particles.

After the coating building run friction measurements compared with the uncoated discs were done again. From the results, shown in **Figure 29**, it can be seen that the coefficient of friction of the discs, run with the RVS® Technology substance, is still higher compared to the uncoated ones in the boundary lubrication regime ($\lambda < 0.7$).

The average roughness with a value of Ra = 0.2 µm is still unchanged compared to the roughness before the second coating building run, see also **Figure 30**. In an energy dispersive X-ray analysis traces of magnesium and silicium could be detected on the disc surface. According to explanations of Rewitec, this means that traces of the substance were on the surface, but there was still magnesium there. Thus the replacement of the magnesium particles with iron particles was not finished. Furthermore the hardness of the discs was measured and was about 900 HV1. The hardness of an uncoated disc, heat treated in the same lot, was a little bit lower at 870 HV1, but still comparable.

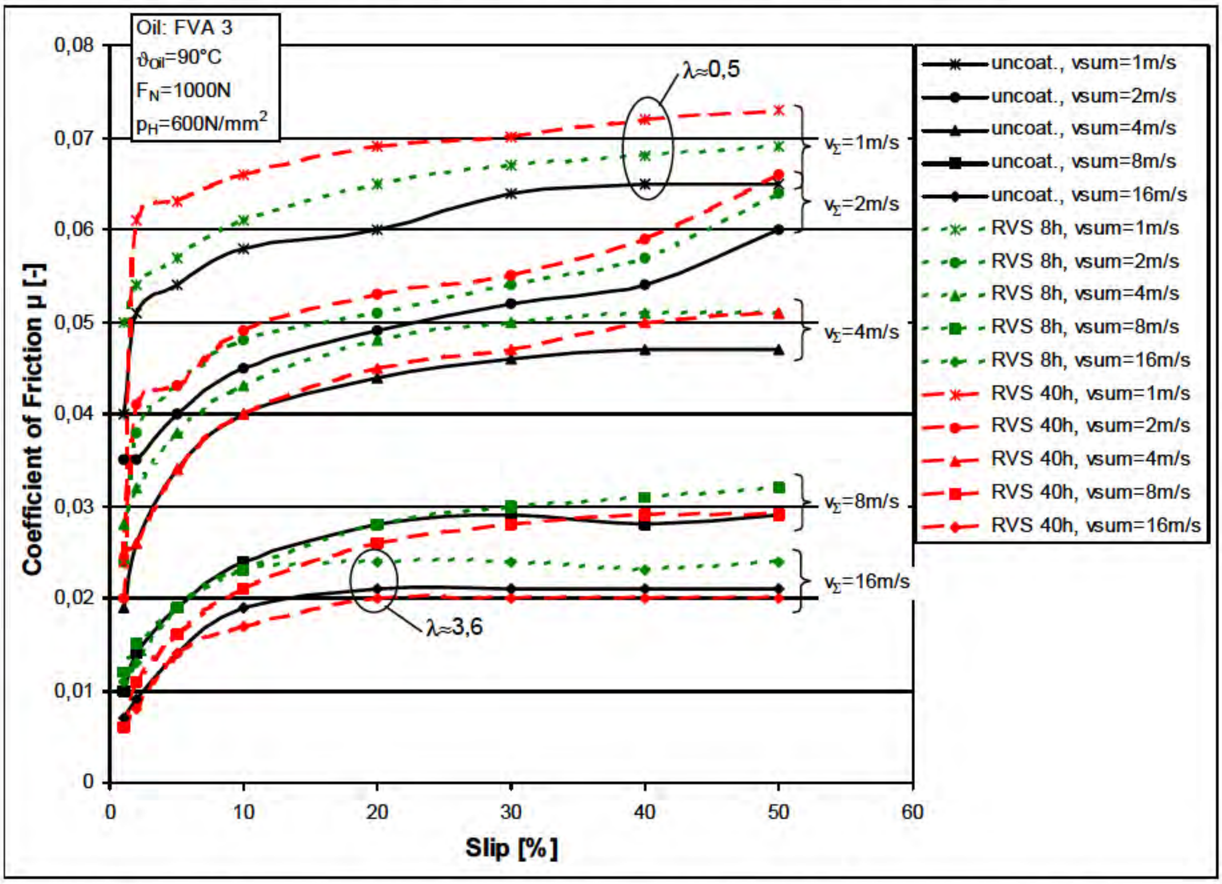


Figure 29: Friction measurements after second coating building run of 40 hours compared to uncoated ones

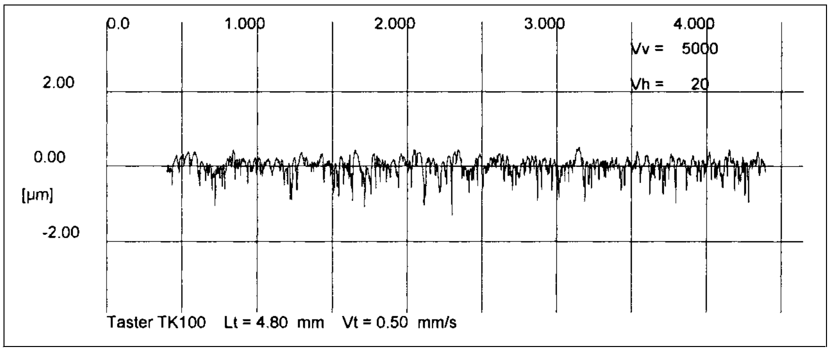


Figure 30: Roughness profile after a coating building run of 40 hours

Based on the results of the first and second coating building run a third run with 47 hours was done. The aim of the third coating building run was a further running in the transition from boundary to mixed lubrication and even worse lubricating conditions. The oil temperature was 80°C, normal load was varied between F_N = 800 N and F_N = 2060 N, which corresponds to a Hertzian stress of p_H = 540 N/mm^2 and p_H = 860 N/mm^2. Sum velocity was varied between 1 m/s and 3 m/s, slip was varied between 20% and 45%. Thus the calculated relative film thickness λ was between 0.7 and 0.9 for about 30 hours and between 0.45 and 0.65 for about 17 hours. The detailed parameters used in the coating building run are shown in **Appendix III**. Additional RVS® Technology substance was added to the oil at the beginning of the test run, after 9 hours and 18 hours. Again the oil was periodically mixed within the oil reservoir to avoid settling of the magnesium-silicium particles.

After the coating building run friction measurements compared with the uncoated discs were done again. From the results, shown in **Figure 31**, it can be seen that the coefficient of friction of the discs, run with the RVS® Technology substance, is still higher compared to the uncoated ones and even increased compared to the coating building run before.

An explanation for the increased friction coefficients could be found in the changed surface structure after this third coating building run. The average roughness decreased to Ra = 0.05 µm, shown in **Figure 32**.

Although the roughness is lower, grooves occurred in circumferential direction. The original grinding grooves perpendicular to circumferential speed aren't visible any more. The surface looked like a lapped surface, the hard magnesium-silicium particles moving through the disc contact could act as abrasives. **Figure 33** shows a scanning electron microscopy picture from the disc surface. These grooves in circumferential direction could cause a higher friction coefficient, because the lubricant could easily be pressed out of the contact. With grooves perpendicular to circumferential speed, the lubricant is brought into the contact very well and can't be pressed out of the contact so easily. This was already investigated by Doleschel [19] and Auer [1]. They confirmed that the coefficient of friction is higher for discs ground in circumferential direction compared to discs ground perpendicular to circumferential speed. Due to the grooves in circumferential direction an additional measurement of the roughness perpendicular to the circumferential direction was done. The roughness, shown in **Figure 34**, is a little bit higher compared to the roughness in circumferential direction (**Figure 32**). However, this roughness with Ra = 0,08 µm decreased, too.

In an energy dispersive X-ray analysis traces of silicium could be detected on the disc surface. Hardness didn't increase compared to the hardness after the second coating building run.

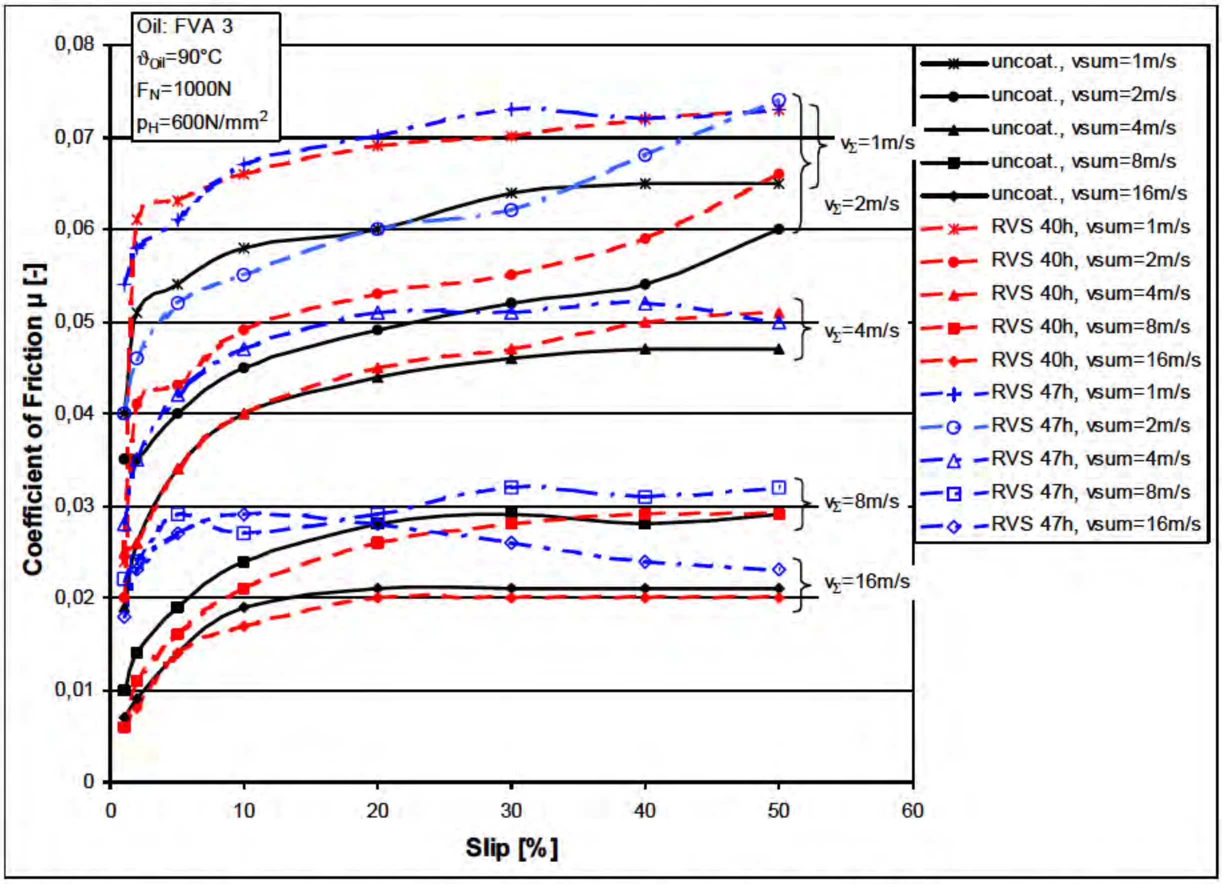


Figure 31: Friction measurements after third coating building run of 47 hours compared to uncoated ones

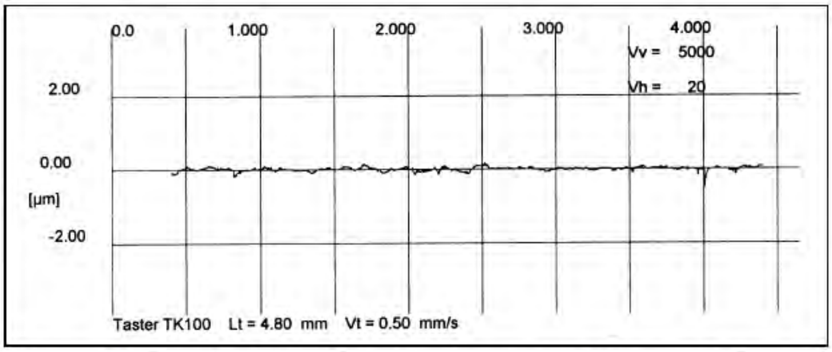


Figure 32: Roughness profile after a coating building run of 47 hours

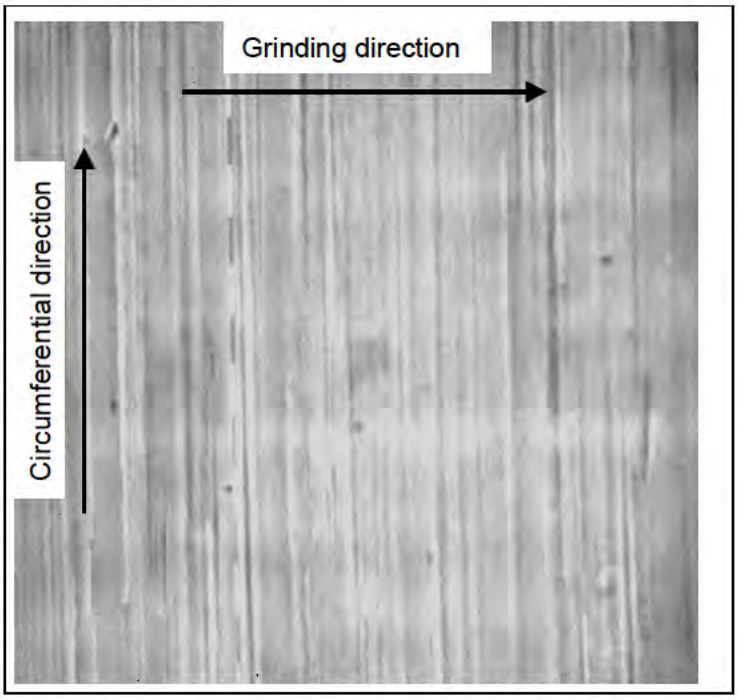


Figure 33: Scanning electron microscopy picture of surface after the coating building run of 47 hours (magnified 960 times)

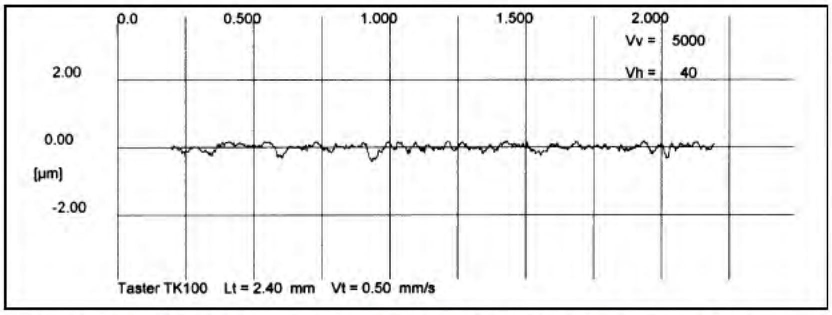


Figure 34 Roughness profile after a coating building run of 47 hours (perpendicular to circumferential direction)

An additional test, simulating an emergency situation for 1 hour by shutting off the oil pump, was done. As already mentioned for the tests with uncoated discs, an oil drop remained throughout the whole test period within the contact zone and therefore dry lubrication didn't occur. Thus the friction coefficient was nearly constant all over the time, **Figure 35** shows the results of this test. Friction measurements after this emergency test were comparable to the ones done before the emergency test.

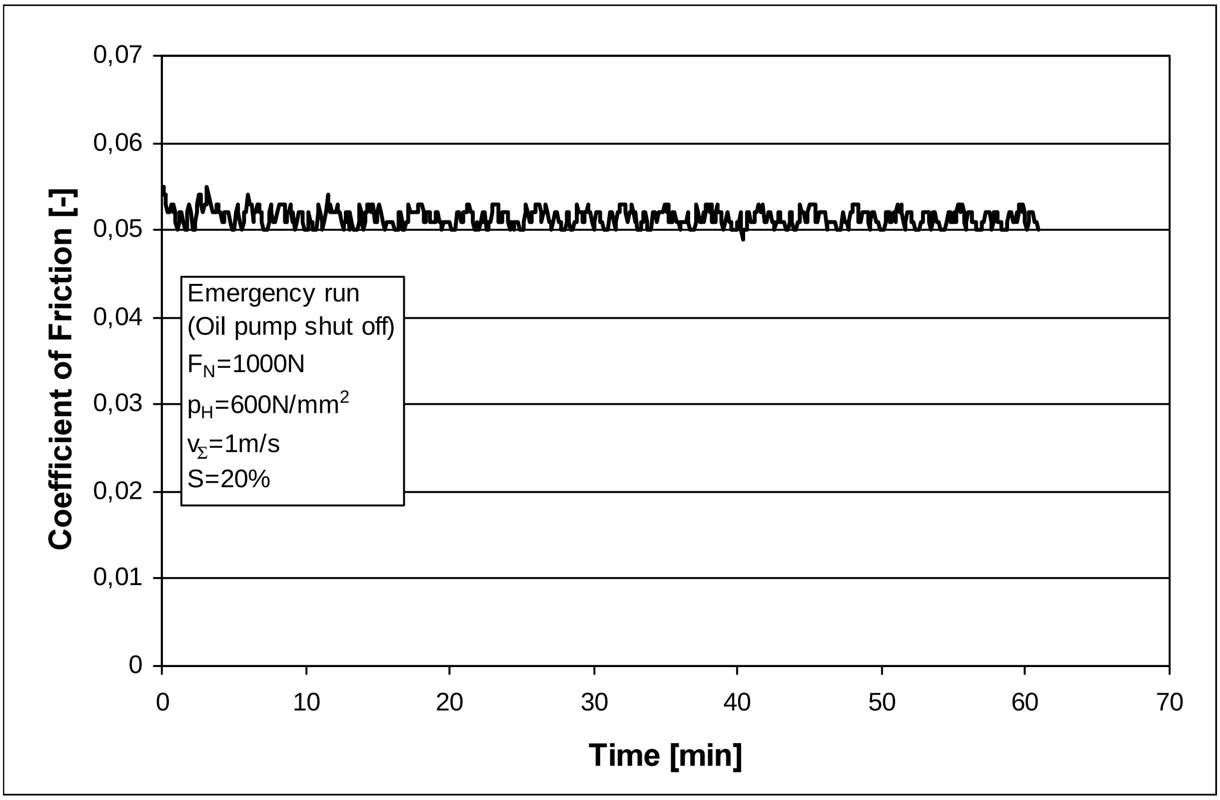


Figure 35: Simulation of an emergency situation for 1 hour

Therefore a further test at dry lubrication was done. This test should show if there is an improvement at dry lubrication compared to uncoated discs. The discs were cleaned with a solvent in an ultrasonic bath. For the test the normal load was set to F_N = 250 N, which is a Hertzian stress of p_H = 300 N/mm^2. Sum velocity was 4 m/s, slip was 20%. The results are shown in **Figure 36**, **Figure 37** shows the failed disc surfaces. The uncoated discs failed within the first 7 minutes, the discs run with the RVS® Technology substance failed after about 15 minutes. Thus the lifetime of these discs was double as high as the lifetime of the uncoated discs. Besides a possible building of a coating with excellent emergency running properties, the lower roughness compared to uncoated discs could be a further reason for the increased lifetime.

After finishing all tests the discs were destroyed and a metallographic section was prepared. **Figure 38** shows the micrograph with a magnification of 1000 times. The analysis of the micrograph showed that no coating could be detected on the disc surface.

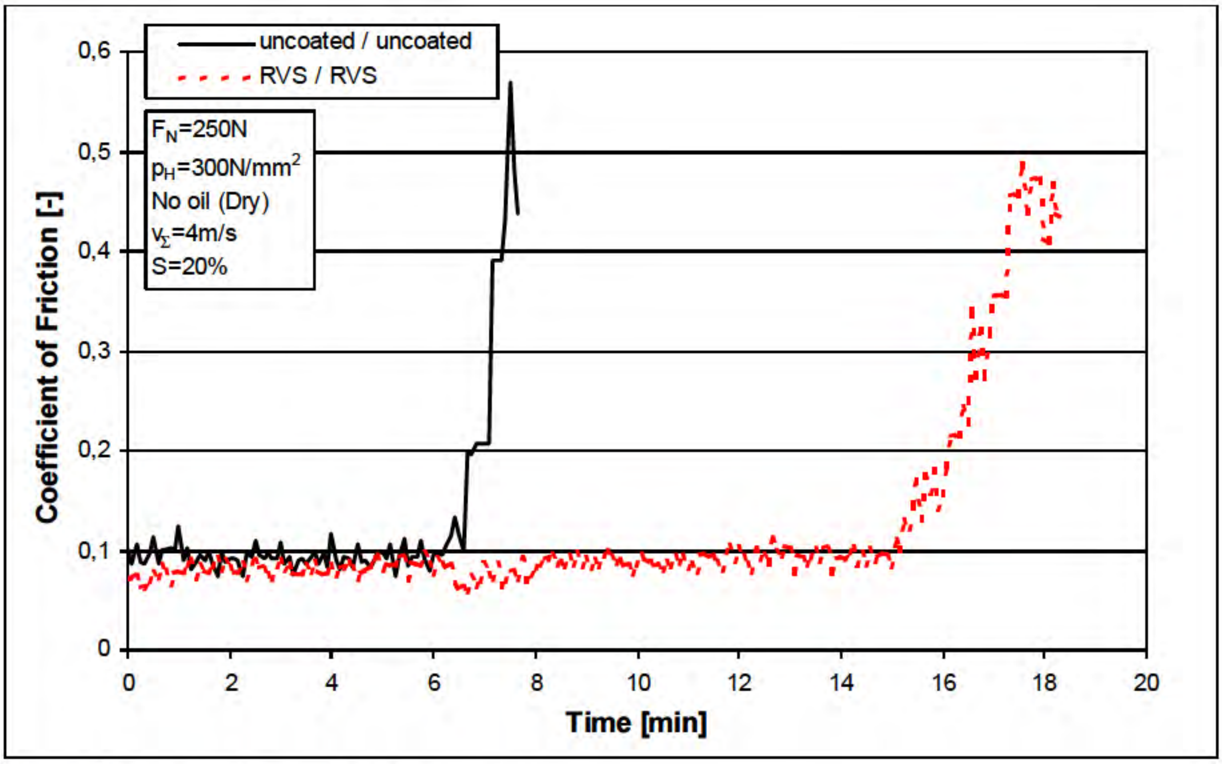


Figure 36: Friction behaviour at dry lubrication

Disc run with RVS® Technology substance | Uncoated disc

Figure 37: Disc surfaces after test under dry lubrication

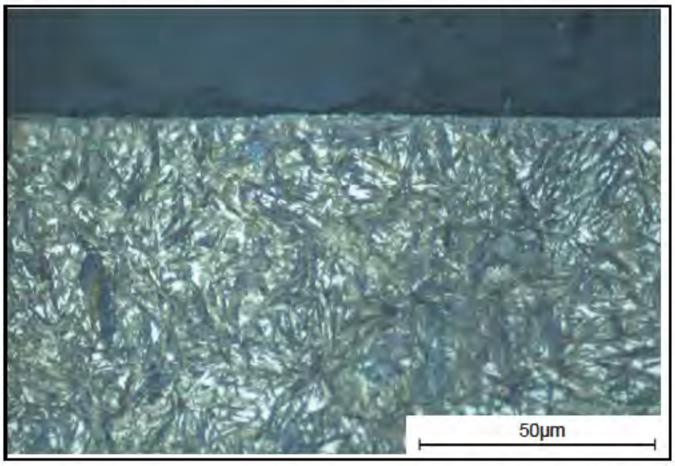


Figure 38: Micrograph of disc surface (magnified 1000 times)

The conclusion from all these tests with the RVS® Technology substance is, that at a coating building run at the transition of boundary to mixed lubrication regime and at boundary lubrication regime has a positive impact on the lifetime under dry lubrication. The disc roughness decreased, possibly due to a kind of a lapping process of the hard silicium particles. Traces of silicium could be detected after this coating building run. However, it was not possible to detect a coating in a metallographic section of the disc surface and to improve the friction behaviour with the RVS® Technology substance.

6 SUMMARY AND FURTHER PROSPECTS

In work-package 5 “Phase transition lubrication” a new concept of lubrication with regard to its potential application in oil-free transmissions was investigated. The lubrication of the mating surfaces should be maintained by a phase transition under the local conditions within the contact area, as it is in ice skating. Under the local conditions of temperature and pressure the coated material should melt and provide in its liquid phase a protecting tribological film between the surfaces as well as low friction. Right after the contact the lubricating material should become solid again and stay on the surface.

Within the project there were two main tasks. At first an investigation of the literature, the definition of suitable materials and the analysis of possible coating procedures had to be done. In the second phase tests with discs were done.
The investigated literature can be divided again in theoretical papers and literature about experiments. The theoretical papers deal with the calculation of the melting rate, coefficient of friction and the film thickness partly taking the unsteady beginning of a melting process additionally into consideration. The analysed melting phenomena are melting due to heat conduction, viscous dissipation and pressure melting for materials having a decreasing melting temperature with increasing pressure. Most of the papers define analytical equations, but there are also some comparisons with numerical solutions and with experimental results. The main conclusion of these theoretical papers is, that melt lubrication can occur in reality, as for example in a manufacturing process or in interior ballistics. Nevertheless future experiments are needed to evaluate the theoretical investigations. Most of the experimental papers deal with sliding tests with different materials at various loads and speeds. Especially at high loads and very high speeds, for example in guns, melt lubrication was observed. But there are also reports about experiments with ball bearings and sliding bearings. Further papers investigate possible coating procedures and necessary parameters, that dry lubrication could be possible.

Based on the results of the investigation of the literature three different kinds of coatings were defined, namely a coating consisting of the low melting metal MCP124, coatings consisting of resinous substances and coatings consisting of wax. The coatings consisting of resinous substances are varnishes containing solid lubricants, as graphite, MoS_2 or PTFE. Besides the coatings an additional substance, named RVS® Technology substance, containing magnesium-silicium was investigated in the work-package. This substance was mixed into a common oil and should build a coating on the disc surface during operation.

Due to the fact that the varnishes are often used with an additional oil lubrication tests with oil lubrication with the different varnishes were done, too. For the tests a coated disc was paired with an uncoated one. The result was, that most of the varnishes were removed from the disc surface, even when lubrication was in the elastohydrodynamic lubrication regime (EHL). Additional friction measurements with the used discs were done in comparison to uncoated discs. Although the coatings were already removed from the disc surface, the friction coefficient of the originally coated discs was lower compared to the uncoated ones in the mixed and boundary lubrication regime, especially with the disc originally coated with graphite-varnish. An explanation for this could be, that there was still some varnish in the grooves of the disc surface. A further test with the already used discs should show if these discs could improve life-time in an emergency situation, what means that oil supply fails, when the discs where used with an additional oil lubrication before. Therefore additional tests at dry lubrication with the used discs where done. However, all tested discs, the uncoated ones and the originally coated ones, failed after a similar test time. The conclusion is, that originally coated discs can't improve life-time at dry lubrication in a decisive way, if the coatings were already optically removed from the surface before. Even if there is still some varnish in the grooves, as it seemed to be at the tests with oil lubrication, it is not enough to separate the mating partners at dry lubrication.

A main part of the experimental investigations were the tests at dry lubrication with the graphite-, MoS_2- and PTFE-varnish, with the wax and the low melting alloy MCP124 and with uncoated discs for comparison. For each test variant again one disc was uncoated the other one coated with the relevant coating. Before the test was started the discs were heated to approximately 70°C, to reach the melting temperature within the contact earlier. At a Hertzian stress of of p_H = 300 N/mm^2 and a sum velocity of 1 m/s the uncoated discs failed, as expected, within some minutes. The disc coated with wax also failed after a test period of about 15 minutes. Normally the wax is used for lower pressures of p_H = 10 N/mm^2. The varnishes containing graphite, MoS_2 and PTFE were partly removed from the disc surface, parts of the low melting alloy were transferred from the coated disc to the uncoated one. At an increased sum velocity of 4 m/s the disc with the MoS_2-varnish failed. In the next test stage, in which the Hertzian stress was increased to p_H = 600 N/mm^2, the disc with the graphite-varnish and the low melting alloy MCP124 failed at a sum velocity of 1 m/s after about 15 minutes. Parts of the PTFE-varnish were still on the disc surface after this test stage. However, the disc with the PTFE-coating also failed at an increased sum velocity of 4 m/s. In sum the disc with the PTFE-varnish ran about 1 hour at different conditions of load, sum velocity and slip until it failed and therefore performed best compared to the other coatings. Another conclusion is, that all coatings improved the friction behaviour and life-time compared to the uncoated discs. However, due to the limited life-time an insufficient or even no regeneration of the lubricant film took place.

Further investigations with the additional coating building substance RVS® Technology were done. To build a coating on the metallic surface a coating building run has to be done. A first coating building run with a duration of 8 hours in the EHL-regime was tried, but an analysis after this test run showed, that no coating was built. Thus a second coating building run with a duration of 40 hours at a relative film thickness of about $\lambda \approx 0.65$ was done. Thus lubrication was at the transition from mixed to boundary lubrication. With an energy dispersive X-ray analysis after the test run traces of magnesium and silicium could be detected on the disc surface. But the roughness still was comparable with the roughness before the test. So a third coating building run for 47 hours at even worse lubrication conditions was done. After the test traces of silicium could be detected on the surface, the roughness also decreased from Ra = 0.2 µm before the test to Ra = 0.05 µm after the test. The original grinding texture perpendicular to the circumferential speed wasn't visible any more, but new grooves in circumferential direction occurred. The hardness didn't increase compared to the hardness before the test.

After the coating building runs friction measurements compared to uncoated discs were done. However, friction behaviour didn't improve, especially for the discs with the grooves in circumferential direction the friction coefficient increased. A reason for that could be, that the lubricant is pressed out of the contact of the two discs very easily, when circumferential grooves exist. Finally tests at dry lubrication compared to uncoated discs were done. Life-time under dry lubrication with the discs treated with the RVS® Technology substance was about double as high as life-time of the uncoated discs. A reason for that possibly the lower roughness compared to the uncoated discs could be, because no coating could be detected in a metallographic section of the disc surface. The micrograph was prepared after all tests were finished.

The conclusion from all these tests with the RVS® Technology substance is, that at a coating building run at boundary lubrication has a positive impact on the life-time under dry lubrication. The disc roughness decreased and traces of silicium could be detected after this coating building run. However, it was not possible to detect a coating in a metallographic section of the disc surface and to improve the friction behaviour with the RVS® Technology substance.

As a further prospect the investigated coatings can be used at dry lubrication for applications, where limited loads occur and only a limited life-time is necessary. Thus in possible applications a regeneration of the coatings must not be a necessity. When the varnishes are used with an additional oil lubrication, friction behaviour can be improved compared to uncoated discs. In future investigations the combination of two coated discs should be investigated. This maybe could bring further improvements.

Regarding the RVS® Technology substance it is still not clear if the resulting grooves in circumferential direction are caused by wear. Thus the substance should be investigated in a back-to-back gear test bench to analyse a possible change of the gear profile during operation.

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APPENDIX I: Overview of numbers of revolutions per minute for used test parameters

Sum velocity v_Σ [m/s]	Slip S [%]	Upper disc n_1 [rev/min]	Lower disc n_2 [rev/min]
1	1	119	120
1	2	118	121
1	5	116	122
1	10	113	126
1	20	106	133
1	30	98	140
1	40	90	149
1	50	80	159
2	1	238	240
2	2	236	241
2	5	233	245
2	10	226	251
2	20	212	265
2	30	197	281
2	40	179	298
2	50	159	318
4	1	475	480
4	2	473	482
4	5	465	490
4	10	452	503
4	20	424	531
4	30	393	562
4	40	358	597
4	50	318	637
8	1	950	960
8	2	945	965
8	5	930	979
8	10	905	1005
8	20	849	1061
8	30	786	1123
8	40	716	1194
8	50	637	1273

Sum velocity v_Σ [m/s]	**Slip S [%]**	**Upper disc n_1 [rev/min]**	**Lower disc n_2 [rev/min]**
16	1	1900	1919
16	2	1891	1929
16	5	1861	1959
16	10	1809	2010
16	20	1698	2122
16	30	1573	2247
16	40	1432	2387
16	50	1273	2546

APPENDIX II: Overview of used parameters for the first coating building run with the RVS® Technology substance

Accumulated time [hh:mm]	Test stage time [hh:mm]	Normal load F_N [N]	Hertzian stress p_H [N/mm^2]	Sum velocity v_Σ [m/s]	Slip S [%]	Upper disc n_1 [rev/min]	Lower disc n_2 [rev/min]
00:10	00:10	250	300	1	10	113	126
00:20	00:10	300	328	1	10	113	126
00:30	00:10	350	355	1	10	113	126
00:40	00:10	350	355	2	10	226	251
00:45	00:05	400	379	2	10	226	251
00:50	00:05	400	379	3	10	339	377
01:00	00:10	450	402	3	10	339	377
01:10	00:10	500	424	4	10	452	503
01:15	00:05	550	445	4	10	452	503
01:20	00:05	550	445	5	10	565	628
01:30	00:10	600	465	5	10	565	628
01:40	00:10	650	484	6	10	679	754
01:45	00:05	700	502	6	10	679	754
01:50	00:05	700	502	7	10	792	880
02:00	00:10	750	519	7	10	792	880
02:05	00:05	800	536	8	10	905	1005
02:20	00:15	800	536	8	20	849	1061
02:35	00:15	800	536	10	20	1061	1326
02:50	00:15	800	536	12	20	1273	1592
03:05	00:15	800	536	14	20	1485	1857
06:05	03:00	800	536	16	20	1698	2122
07:25	01:20	800	536	16	40	1432	2387
08:05	00:40	800	536	16	30	1573	2247

APPENDIX III: Overview of used parameters for the third coating building run with the RVS® Technology substance

Accumulated time [h]	Test stage time [h]	Normal load F_N [N]	Hertzian stress p_H [N/mm^2]	Sum velocity v_Σ [m/s]	Slip S [%]	Upper disc n_1 [rev/min]	Lower disc n_2 [rev/min]
3	3	1450	722	3	45	254	462
6	3	1200	657	2	40	179	298
9	3	800	536	1	20	106	133
12	3	1450	722	3	45	254	462
15	3	1200	657	2	40	179	298
18	3	800	536	1	20	106	133
21	3	1450	722	3	45	254	462
24	3	1450	722	2	40	179	298
27	3	1450	722	1	20	106	133
30	3	1670	775	3	45	254	462
33	3	1670	775	2	40	179	298
36	3	1670	775	1	20	106	133
39	3	2055	860	3	45	254	462
42	3	2055	860	2	40	179	298
47	5	2055	860	1	20	106	133