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RESEARCH

Modelling and Simulation Assisted Tribometrology

Stick-Slip phenomena in wet friction disc systems used in drive trains of modern vehicles can cause vibration or noise which considerably decrease comfort of drives and passengers. For the investigation and characterization of these phenomena, a disc-on-disc tribometer is used at the Austrian Center of Competence for Tribology. A method is presented which is based on a combination of additional sensor technology on the tribometer and computer simulation and allows for determination of dynamic as well as static coefficient of friction during dynamic stick-slip experiments. Examples and interpretations illustrate the presentation of the method.
For advanced and sound understanding of wear processes, especially with respect to piston rings, it is necessary to measure the corresponding wear height or wear volume accurately. Applying radio active isotopes is a very powerful tool to investigate wear behaviour of tribosystems, which are difficult to access, and the only reasonable tool for investigations at real nanometer scale. The nVCT® method (nanoscale wear Volume Coherence Technology) aims at the nanometer sensitiveness and simultaneously assures easy and safe use. To achieve this ambitious goal, fundamental knowledge about the irradiation process and the concentration of isotopes in the very thin surface layer of interest have to be obtained. The application of this method advantageously refers to modelling of system behaviour as to the lubricant circuit and modelling of the contact conditions. The wear processes can be analysed and modelled in terms of running-in behaviour and "progressive" wear characteristics. The methods are illustrated based on the characterization of lubricity of ATF fluids.
The paper focuses on the requirements of selected fields of tribometrology and shows specific solutions of evaluation of test conditions and test results.

Keywords: tribometrology, simulation, dynamic experiments, friction coefficient determination, nano wear measurement

1. INTRODUCTION

1.1 Tribometrology Tasks

Since wear causes material and machinery failure, the characterisation of tribological behaviour of material combinations and components in tribological systems is a very important topic in industry and science. A special focus on test results can be seen in car and engine production industry mostly for life time assessment which is to some extent based on the information derived from tribological data. In order to save costs and time these systems are often investigated using model tribometers that conventionally deliver friction and wear figures. The significance of results can be improved by modelling concepts and simulation.

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1.2 Nanoscale wear measurements

For advanced and sound understanding of wear processes, especially with respect to piston rings, it is necessary to measure the corresponding wear height or wear volume accurately. Conventionally, this is done by weighing or profilometry techniques. Conventionally, this is done by weighing or profilometry techniques. But these methods need very long experiment durations or significantly higher loads for tribological testing than observed in real systems to obtain measurable resolution of the wear height or wear volume. Additionally, the specimens need to be disassembled for measuring. Applying radio active isotopes is a very powerful tool to investigate wear behaviour of tribosystems, which are difficult to access, and the only reasonable tool for investigations at real nanometer scale.

A new technique (nVCT) is conceived for conventional applications in model tribometers like pre-tests of lubricants, materials, or investigations of impacts on model systems. The details of that technique and the evaluation of the results are based on modeling concepts for different aims.

2. DYNAMIC CHARACTERISATION OF FRICTION COEFFICIENT

2.1 Specific background and requirements

Tribosystems capable of oscillations tend – under certain conditions – to self-induced friction controlled vibrations. Problems resulting from those effects can be found in modern drive trains using friction elements. In vehicles equipped with such components sometimes vibrations andfriction noises can be observed that are generated by stickslip effects in friction discs contacts. Such "moaning" significantly reduces the comfort of the passengers and counts as a considerable restriction of quality.

In order to understand the processes behind frictional noises due to a periodical change between stiction and sliding in the tribocontact it is necessary to investigate the friction behaviour on tribometers that preferably represent the conditions of the original system as far as possible. For that reason at the Austrian Center of Competence for Tribology a disc-disc tribometer and original parts from the production are used [1].

Tribometers which enable detection of friction oscillations need to have a certain elasticity which in turninfluences the generation and/or the intensity of friction noises yet depending on the damping properties of the mechanical components involved [2], [3].

Detailed dynamic Analysis and modelling of drive trains or similar units need exact knowledge of dynamic parameters and especially of the characteristics of the friction elements. It is for instance known that the threshold of friction for the transition between sticking and sliding depends amongst others on the preceding duration of stiction [4]. Friction behaviour during sliding shows some dependency from thermal conditions how the system got to sliding ("memory effect"), as well hysteresis can be observed, i.e. different courses of the coefficient of friction versus sliding velocity as a function of acceleration or deceleration, respectively. [5], [6].

If measurement of friction torque is based on the elastic deformation which is a typical situation in most tribometers it is unavoidable to get a failure in the friction signal at highly dynamic test conditions, like stick-slip, due to inertia effects, especially if those effects are in the same order of magnitude as those generated by frictional forces.

2.2 Experimental setup – stick-slip tribometer

At the Austrian Center of Competence for Tribology a friction disc/disc tribometer is used in order to investigate friction elements for drive trains, clutches and brakes etc. as realistic as possible. This rig (described elsewhere [7], Fig. 1 and Fig. 2) is equipped with a torsion element that on the one hand provides through deformation the measurement values for friction moments and on the other hand shows similar dynamic behaviour in terms of frictional oscillations asthey are observed in original drive systems. This torsion element is thus balanced to a frequency of about 75 Hz.

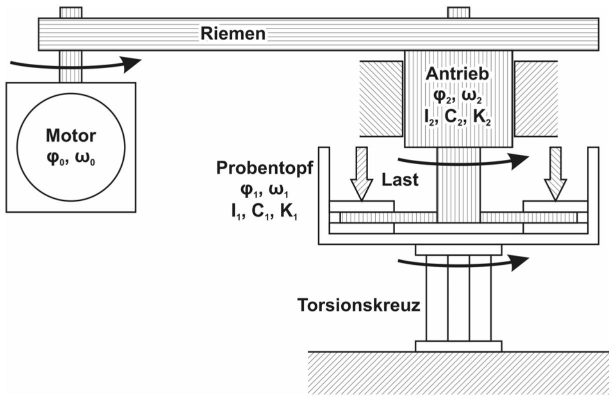

Fig. 1: Schematic of the AC²T friction disc tribometer

For the specific investigations the rig has been adapted. Major improvements concerned the load unit providing loads of 5000 N by a set of saucer springs and an additional accelerometer.

The belt drive enables – in this special setup – a rotating speed of up to 100 min-1. A particular component of the test rig is the torsion element which enables a rotational deflexion of the test chamber with the discs inside according the acting torque moment. The deflexion is proportional the friction moment, yet only for stationary conditions.

In order to overcome these restrictions an additional sensor for the angular acceleration has been implemented which provides information concerning dynamic processes. The mean rotational speed is measured by a tachometer generator.

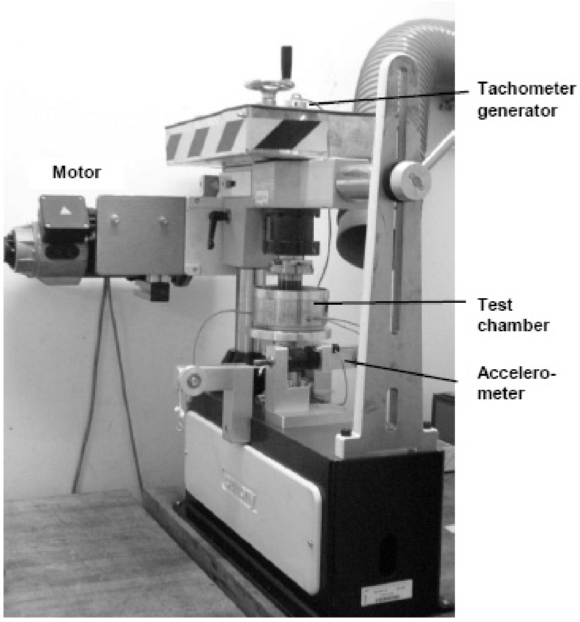

Fig. 2: AC²T friction disc tribometer

As test samples each a set of friction discs was use with “driven discs” teethed on the inner side and “fixed discs” teethed on the outer side. The number of the tested discs is variable; the maximal quantity depends on the disc thicknesses. The samples are immersed in the lubricant defined by the original application. The examples described in the following paragraphs are based on tests with different ATFs (Automatic Transmission Fluids).

2.3 Stick-slip modelling

At AC²T a simulation method has been developed which enables correction of failures of the friction moment sensor due to inertia forces and at the same time delivers information on the dependence of the friction coefficient from the sliding velocity. This method is based on modelling of the dynamic behavior of the mechanical system i.e. the rig.

The mechanical system is modelled as a dynamic system with 2 degrees of freedom considering, firstly, the torsion of the test chamber and secondly the torsion of the driveshaft.

The equation of motions can be defined as

$$I_1\dot{\omega}_1 + K_1\omega_1 + C_1\varphi_1 = M_R(\Delta\omega,\ldots) \qquad (1)$$
$$\dot{\varphi}_1 = \omega_1$$

$$I_2\dot{\omega}_2 + K_2(\omega_2 - \omega_0) + C_2(\varphi_2 - \varphi_0) = -M_R(\Delta\omega,\ldots) \qquad (2)$$
$$\dot{\varphi}_2 = \omega_2$$

with

φ_1, φ_2	angular coordinate
ω_1, ω_2	angular velocity
$\Delta\omega = \omega_1 - \omega_2$	differential velocity
φ_0	nominal angular coordinate
ω_0	nominal angular velocity of the drive
I_1, I_2	mass moments of inertia
K_1, K_2	constants of viscous damping
C_1, C_2	torsional stiffnesses

During sliding the friction moment can be calculated from

$$M_R(\Delta\omega,\ldots) = F_{Ntot}\cdot R\cdot \mathrm{sgn}(\Delta\omega)\mu_{dyn}(\Delta\omega,\ldots) \qquad (3)$$

where it designates

sgn(Δω)	sign of the differential angular velocity
$\mu_{dyn}(\Delta\omega,...)$	speed dependent friction coefficient
F_{Ntot}	total acting normal force (according the actual number of friction pairs)
R	effective friction radius

When sticking occurs additionally Equ. (4) has to be considered:

$$\Delta\omega = 0 \quad \text{respectively} \quad \omega_1 = \omega_2 = \omega \qquad (4)$$

Sliding takes place when the stiction moment *MR* is exceeded

$$\max(|M_R|) = F_{Ntot}\cdot R\cdot \mu_{stat} \qquad (5)$$

Combining Equ. (1), (2), and (4) the actual stiction moment can be described

$$M_R = \frac{I_2(K_1\omega + C_1\varphi_1) - I_1(K_2(\omega-\omega_0) + C_2(\varphi_2-\varphi_0))}{I_1 + I_2} \qquad (6)$$

The relations described above have been implemented into computer simulation using the SIMULIK tool, and detailed studies have been performed in order to elucidate the dynamic behaviour of the system.

2.4 Dynamic behaviour of the tribosystem

The knowledge of the dynamic parameters of the Tribosystem is essential for a realistic modelling. Especially the parameters I_1, K_1, and C_1 govern the dynamic behaviour. In order to determine these parameters the test chamber system (without the other components of the drive) is excited to oscillations. The concerned parameters can be calculated from the observed data – acceleration and torsional moment on the test chamber – during the decay of the oscillations using Equ. (7)

$$I_1 \ddot{\varphi}_1 + K_1 \dot{\varphi}_1 + C_1 \varphi_1 = 0 \tag{7}$$

The system far less reacts on changes of the parameters I_2, K_2, and C_2. which were determined from design parameters (I_2), changing the belt tension (K_2) or comparison of measured and calculated variations of rotating speed (C_2), respectively. In order to give an impression of the ranges of parameters the concerned data are given in Tab. 1.

Tab. 1: Dynamic parameters of the tribometer

Para-meter	Value	Para-meter	Value
I_1	0.0109 kgm²	I_2	0.0315 kgm²
K_1	0.04034 kgm²/s	K_2	4 kgm²/s
C_1	2338.6 Nm/rad	C_2	5975 Nm/rad

2.5 Combination of simulation and experiments

This combination enables the estimation of the friction behaviour as a function of sliding speed. The advantage of this method is that one gets the "spectrum" of friction coefficient – starting from standstill – from routine dynamic tests.

Of course, it is necessary to define a reference model for the friction behaviour, which for the present work has been chosen according Equ. (8), describing the first part of a typical stribeck's curve (i.e. that part which gives the dependency of the friction coefficient on sliding speed for standstill and near standstill in the mixed friction regime, Fig. 3).

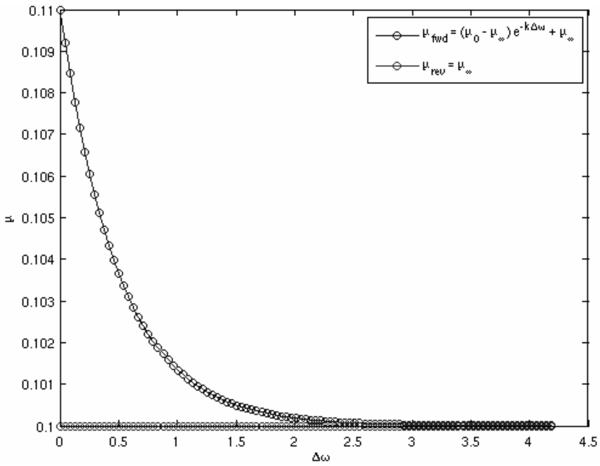

Fig. 3: Modelling of the speed dependency of the friction coefficient (μ versus Δω)

$$\mu(\Delta\omega) = (\mu_0 - \mu_\infty)\exp(-k\,\Delta\omega) + \mu_\infty \tag{8}$$

where it designates

μ_0 static friction coefficient (stiction)
μ_∞ asymptotic value of cof (minimum friction)
k system specific constant (preassigned k = 2)

In case of that the maximum relative speed was already reached (i.e. during the deceleration phase) the friction coefficient was kept constant with $\mu = \mu_\infty$. By means of advanced "curve fitting" – based on minimising the mean quadratic failure – one gets simultaneously both the value for stiction (static friction coefficient) and the course of the dynamic friction versus sliding speed.

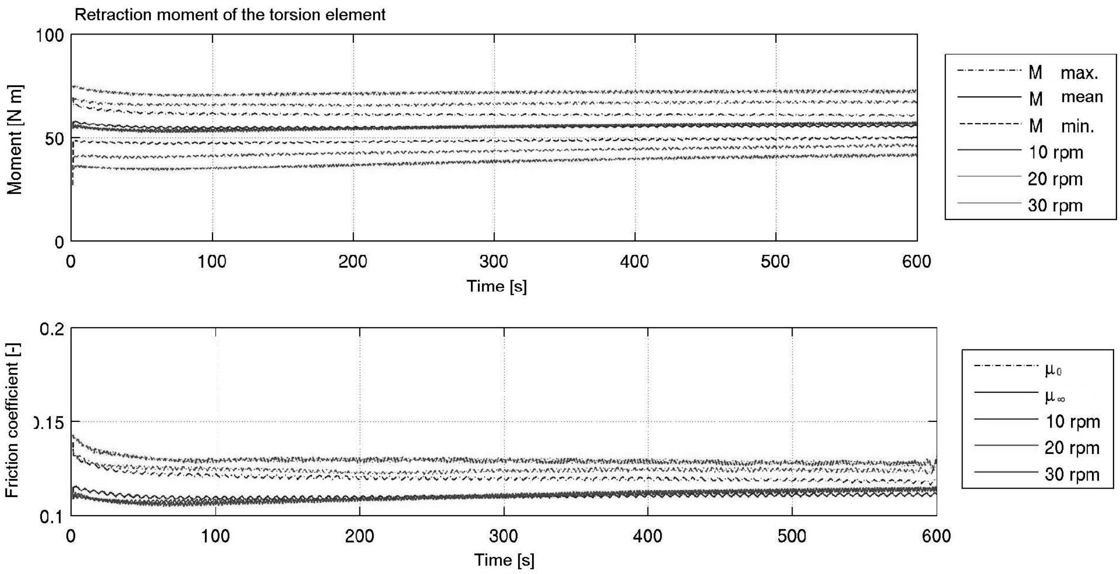

Fig. 4: Speed dependency of the friction coefficient for oil "A"

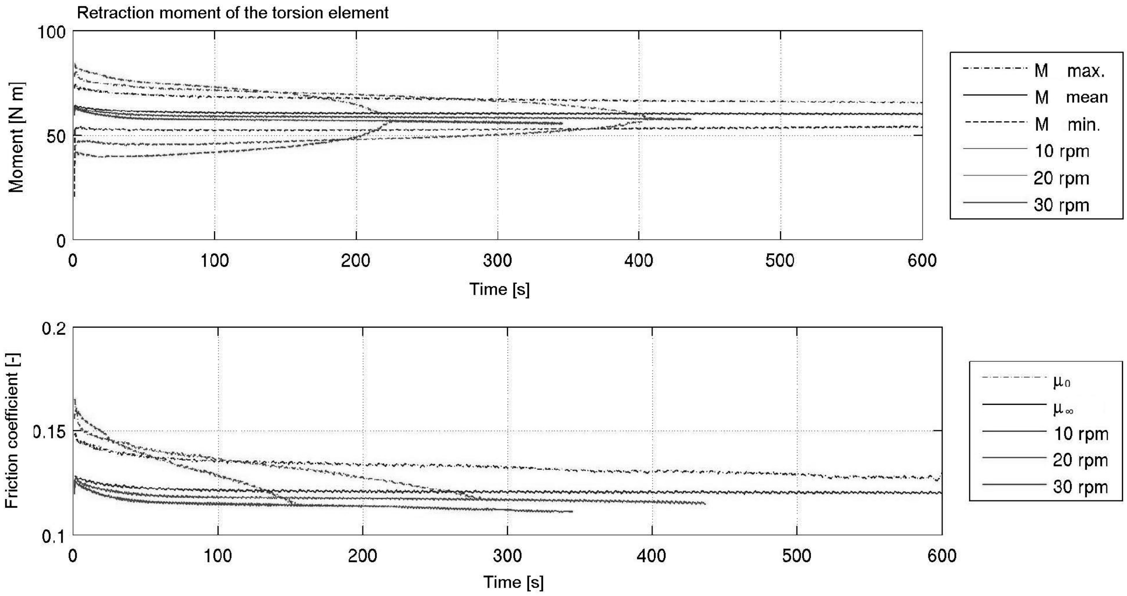

Fig. 5: Speed dependency of the friction coefficient for oil "B"

The optimisation routine has been implemented using the "optimization toolbox" which is provided by MATLAB ®. In combination with SIMULINK ® routine focussing on the evaluation of the measured data one gets the "spectrum" of friction coefficient – starting from standstill – from routine dynamic tests, at first through an off-line process. For that reason the acquired data are each combined in blocks of 1 s and serially processed.

It is possible to differentiate the behaviour of variations of the tribosystem, e.g. when varying the type of lubricant which is shown in the following graphs (Fig. 4 and Fig. 5).

ATF lubricants ("A" and "B") have been tested with 3 different (nominal) rotational speeds. The upper diagrams each show the maximum, minimum, and mean values of the moment on the torsion element, whereas the diagrams below depict the characteristic friction values μ_0 and μ_∞ according the modelled course (Equ. (8)).

It attracts attention that with ATF "A" stick-slip occurs during the whole test duration, whereas with oil "B" the stick-slip oscillations decay during the test duration, especially at higher rotating speeds. Thus it is not necessary to make specially break free tests. It is shown that this method also helps clarifying the type of motion (stick-slip or slip-slip oscillations). The interpretation of Fig. 5 – showing the values of μ_0 and μ_∞earlier converging than the envelopes of minimum and maximum values of the retraction moment of the torsion element – clarifies that the system in that region performs slip-slip oscillations (instead of stick-slipping). This fact is shown more into detail in Fig. 6. Sticking only lasts for a few milliseconds but can reliably be detected. The possibility for on-line evaluation is aimed at which includes the determination based on appropriate variation of friction characteristics.

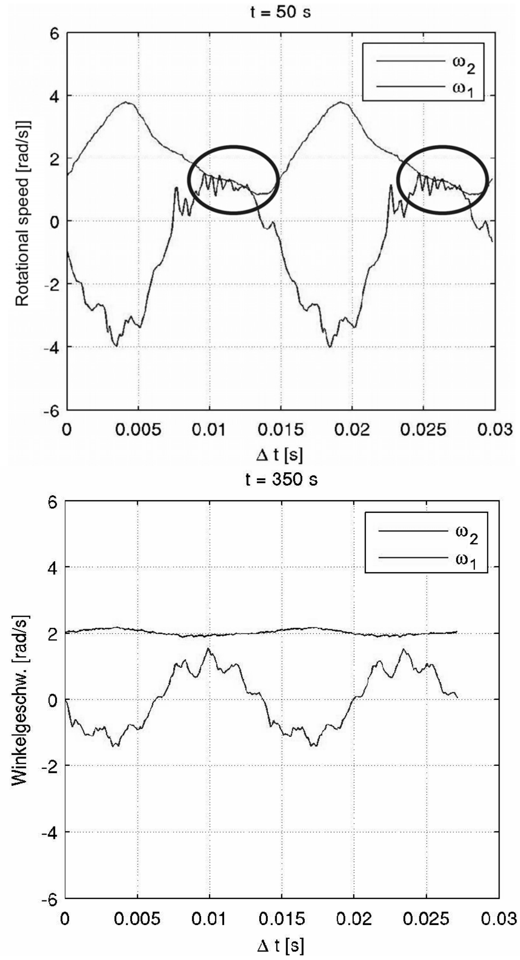

Fig. 6: Details from data measured with ATF "B"; upper diagram: stick-slip regime (phases indicated with ellipses), lower diagram: slip-slip oscillations

3. CONTACT MECHANICS FOR NANO WEAR MEASUREMENT

For the application on a model Tribometer (in this case i.e. a SRV® Tribometer) pieces of piston rings and cylinder liners have to be used due to the limited space. To avoid wear process at the edge of the cylinder liner, the radius of the piston ring has to be slightly smaller compared to that of the cylinder liner. This can be achieved by moderate bending of the piston ring similar to the applied pre-stress of a piston ring in a car engine. The alignment results in a defined area of contact of the two specimens.

The contact area of the piston ring and cylinder liner is very important for the correlation of the wear results to realistic systems and for calculation of the mean wear height of the tribological zone at the piston ring. Assuming the simulation of the ignition pressure of an engine, the force applied at the tribometer must be calculated through the contact area of the model system. In this paper a highly – in the nm/h range – sensitive wear measuring technique, called nVCT® [8], is presented which is capable of online determining the wear behaviour. For the tests, piston rings are used as specimens and sections of cylinder liners as counter acting bodies.

The results of modelling the contact area point out that there is no increase of tribological contact zone and respectively decrease of contact pressure due to the small quantity of wear volume and accordingly wear height. It is assured that the small wear heights of tests have no significance in terms of changes of the contact geometry and consequently the contact pressure.

3.1 Requirements for highly sensitive wear measurements

During the coming years the development of modern engines, alternative drive trains, reduction of fuel consumption, and substitution of conventional mineral oil products due to economic and ecologic reasons will lead to sophisticated tasks in industry and particularly in car industry [9]. On the basis of the upcoming changes of boundary conditions, there is a strong need for principle and fundamental knowledge of tribology. Especially wear behaviour is a crucial factor and has an outstanding position as it is directly linked to life time of components.

For advanced and sound understanding of wear processes, especially with respect to piston rings, it is necessary to measure the corresponding wear height or wear volume accurately. This is conventionally done by weighing or profilometry techniques analysing the specimens before and after the experiment [10]. These methods typically need very long test durations to obtain measurable resolution of the wear height or wear volume. In order to avoid that significantly higher loads for tribological testing in “short term tests” are chosen than observed in systems of real applications. Frequently the specimens need to be disassembled for measuring leading to new running-in.

An alternative method has been practised for several years using radio-nuclides for highly accurate wear measurement (e.g. [11], [12]) for which the concerned samples are tagged with isotopes and the loss of activity is either detected as differences measured at the specimen or the activity of the wear particles in the lubricant is observed and converted into wear volume. The main disadvantage of the methods up till now is that high activity of the samples is necessary to obtain high resolution – accompanied by safety procedures and complicated sample handling. Obviously for very low level of activity the resolution of wear amount is very poor. Consequently, wear measurement with radioactive isotopes was mainly used for investigation of engine prototypes, corresponding engine bench tests, or in special laboratories for highly sophisticated problems (corrosion studies or hip joints) [12].

3.2 Concept of nVCT

The acceptance of wear measurement with radio active tracers is directly connected to overall amount of radioactivity applied. Hence, the main objective of the recently at AC²T developed nVCT® (nanoscale wear Volume Coherence Technology) aims at the nanometer sensitiveness and simultaneously assures easy and safe use. The specimens used for nVCT are prepared by means of “partial thin layer activation” (PTLA). So a very small surface layer of few micro meters of a part of the mating surface of the sample is doped with a very small quantity of radioactive isotopes, thus the samples are below the free limit given by law [13]. The level of activity is set in between the activity of a human body itself and the normal environment. So the specimens (or any other components) of nVCT are regarded as NOT radio active samples and NOT dangerous to deal with.

The nVCT is conceived for conventional applications in model tribometers like pre-tests of lubricants, materials, or investigations of impacts on model systems. To achieve this ambitious goal, fundamental knowledge about the irradiation process and the concentration of isotopes in the very thin surface layer of interest had to be obtained. Great care has been taken to confirm that the irradiation process has no effect on the tribological performance of the specimen.

During the tribological test run wear particles of the specimen are transported to a radiation detector by an ambient medium, in most cases the lubricant or fuel to be investigated. The activity in the ambient medium is therefore the indicator for the quantity of wear of the specimen.

But this simple looking concept is dependent on the complex mathematical correlation of activity *IDET* in the lubricant and concentration Δ*I(h)* of isotopes in the specimen to calculate the volume of wear particles *VI* containing radioactive isotopes (Equ. (8)). The knowledge of this coherence is the basic necessity for this measuring technique.

$$V_I = \frac{I_{DET} \cdot k_{DET}}{\rho_I(h)} \tag{8}$$

where it designates

V_I wear volume

I_{DET} count rate (amount of isotopes) at detector

$\rho_I(h)$ concentration of isotopes (depth profile) in specimen, respectively in wear particles

k_{DET} coefficient of detector: (depending on geometric arrangement and energy efficiency)

Wear volume and concentration of isotopes in the wear zone of the specimen result in the activity in the oil. The concentration depends on the depth profile of isotopes in the specimen and consequently on a lot of parameters of the irradiation process, especially concerning thin layer activation of a few micro meters. Precise knowledge about this non linear concentration profile of isotopes perpendicular to the surface (depth profile Δ*I(h)*) is the key for the use of very low activity specimens for wear measurement in nanometer scale, thus the isotopes in these layers have to be produced and measured precisely.

The depth profile for nVCT is obtained by measuring activity during carefully removing thin layers of reference pins (publication in process). These steps – about 0.1 μm (far less than conventional techniques using stack foils with foils of several micrometers thickness!) – have to be carried out several times to receive a complete depth profile of a few micrometers and a deviation of the depth profile lower than the target resolution of the wear measuring technique.

The pins have to be solid bodies and of the same alloy and same microscopic structure as the specimens for the wear measurement. The removal process may not be done neither by means of grinding or milling, because it is not possible to avoid mixing up of isotopes of different layers, nor by most other methods (like conventional acid etching) due to the necessity to most accurately measure the height of the removed surface layers.

The real profile of isotopes that is produced by means of PTLA in a small surface layer of only a few micrometers is affected by some unpredictable shifts due to the special irradiation process but also by material properties of the realistic specimens like micro structure and roughness of the surface.

3.3 Modified SRV® test procedure

The SRV-tribometer (Fig. 7) is used for investigations of tribological behaviour of lubricants and fuels, contact materials and coatings, impact of load or boundary conditions like temperature, friction movement, and inclination. The relative movement of specimen and counter acting body can be described as reciprocating movement with adjustable stroke and frequency [14].

The fluid circuit supplies the contact zone of the samples in the test cell with a lubricant (Fig. 8). The wear particles are transported by the ambient medium (volume of about 60 ml to 70 ml) from the contact zone into the radiation detector.

The quantity of lubricant is equivalent to the corresponding lubricant volume provided to a slice of piston ring of similar dimensions in an original car engine. As well no filter system is used. By activity measurements of the tubes and all other parts of the circuit after the test run it has been proved that all wear particles are suspended in the oil and that there are no deposits or debris containing wear particles.

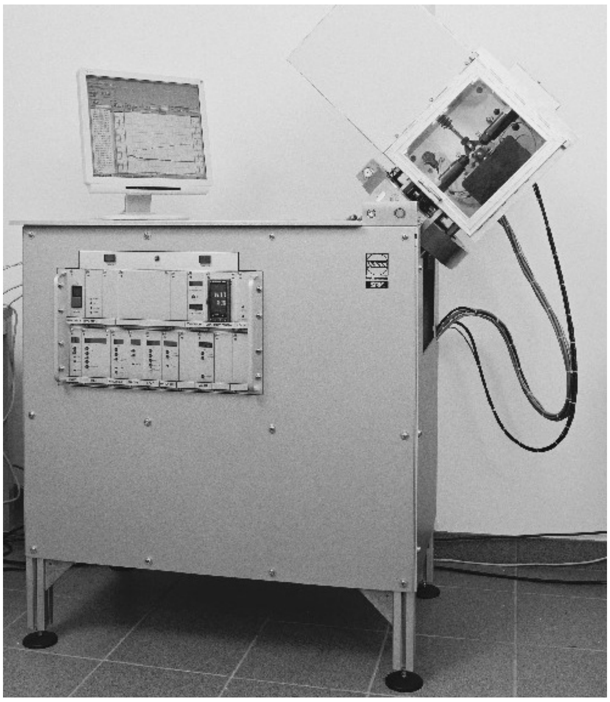

Fig. 7: SRV®4-Tribometer / inclined test cell

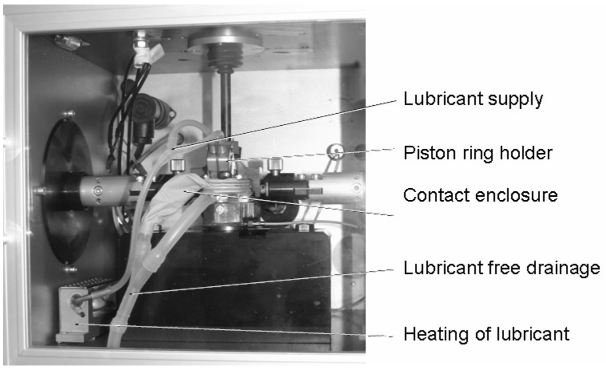

Fig. 8: Test cell with oil circuit adaptation

For the tests exemplarily presented in this paper top piston rings have been used as specimens and sections of cylinder liners as counter acting body. This setup opens up the possibility to investigate real components concerning the geometry or material properties in a tribometer test applying realistic conditions. SAE 0W30 motor oil has been used as lubricant.

3.4 Modelling of contact area

For the application on a model tribometer pieces of piston rings and cylinder liners have to be used due to the limited space. To avoid wear process at the edge of the cylinder liner, the radius of the piston ring has to be slightly smaller compared to that of the cylinder liner.

This can be achieved by moderate bending of the piston ring similar to the applied pre-stress of a piston ring in a car engine. The alignment results in a defined area of contact of the two specimens.

The contact area of the piston ring and cylinder liner in the model tribometer is a very important part for the correlation of the wear results to realistic systems. Assuming the simulation of the ignition pressure of an engine, the force adjusted at the model tribometer must be calculated through the contact area of the model system. The finite element modelling of the contact area takes into account the material properties and the radii of the specimens in the model system.

An accurate determination of the contact area is fundamental for the correct calculation of the real wear volume, especially in a model tribosystem, and can also be used to calculate the mean wear height of the tribological zone at the piston ring.

$$V_W = V_I \cdot k_A = h_W \cdot A_I \cdot k_A \tag{9}$$

with

V_W wear volume

V_I volume of wear particles containing radio active isotopes

k_A ratio of area of tribological contact to area of specimen tagged with isotopes

h_I mean wear height

A_I area of specimen doped with isotopes

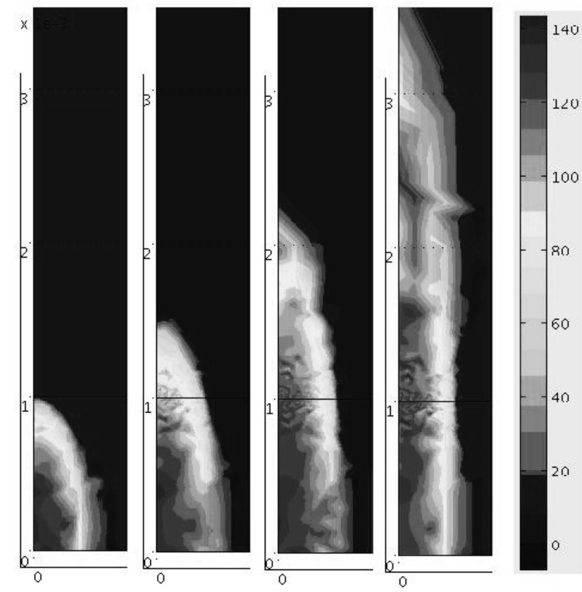

Fig. 9: Pressure distribution for quarter of contact zone of piston ring and cylinder liner model system with respect to applied load (from left to right: 50 N / 100 N / 150 N / 200 N)

The results of modelling the contact area (Fig. 9) also point out that there is no increase of tribological contact zone and respectively decrease of contact pressure due to the small quantity of wear volume and accordingly wear height. It is assured that the small wear heights of tests under the mentioned conditions do not change the contact geometry and consequently the contact pressure.

3.5 Examples for wear analysis

Via online wear measurement it is possible to characterise changes of wear behaviour during the measurement and with a time resolution of several seconds given by the dwell time. Therefore, differences in running-in wear and progressive wear can be investigated.

Fig. 10 and Fig. 11 show exemplarily results of online nVCT wear measurement presented as wear volume over test time. Each data point is obtained by directly converting the count rate of the detector via the above given Equ. (8) and considering Equ. (9) during a certain period of time (i.e. the dwell time of the detector).

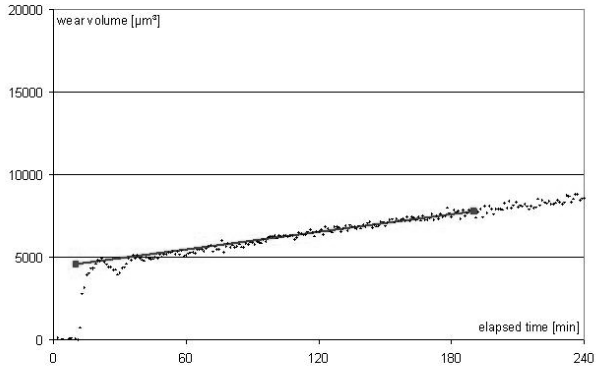

Fig. 10: Online wear measurement (wear volume over test time) and assessed running-in and progressive wear – short term running-in

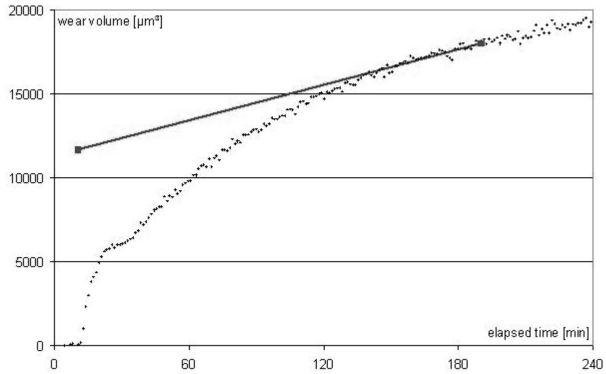

Fig. 11: Online wear measurement (wear volume over test time) and assessed running-in and progressive wear – long term running-in

The course of wear may be described by two major parameters governing the wear process. For interpretation of the nVCT results a mathematical simplification can be used: "progressive" wear as product of linear wear rate and test time. This assumption leads to the consequence that the linear wear rate can be determined as the asymptotic/convergent wear rate at the end of the test run.

For a clear definition and comparability of tests with unequal test time the linear wear rate was taken as the increase of wear volume between 120 and 180 minutes test time for the results shown here.

The "running-in" wear volume consequently is received by subtracting the progressive wear volume from the total wear volume after 180 minutes test run. This procedure respects different kinds of running-in performances like a short time (Fig. 10) or long term (Fig. 11) running-in.

In the nVCT results it can be noticed that the course of wear measurement is affected by some oscillation at the beginning of the wear test which can be explained by the time of circulation of particles in the circuit and a system's response. This behaviour can be modelled in order to separate the results relevant for calculating the wear parameters.

The systematic of describing running-in and progressive wear is a first approach to characterise the nVCT results of the model system piston ring and cylinder liner in the regime of a model tribometer. These results have to be understood on nanometer scale and correlated to realistic wear mechanisms before scientific correlations to already published running-in models [9] may be investigated.

For the presentation of the nVCT results we use the wear coefficient [10]

$$k_W \frac{[\mu m^3]}{[N \cdot m]} = \frac{V_W}{L \cdot d_S} \qquad (10)$$

with

k_W coefficient of area of tribological contact to area of specimen tagged with isotopes

V_W wear volume [µm³]

d_S sliding distance (stroke [m] ×frequency [Hz] ×duration [s])

L load [N]

The wear coefficient is used for describing running-in wear and progressive wear in the same way. This is based on the assumption that wear processes contributing to running-in and progressive wear are present all the time during the test run. This somehow corresponds to the above mentioned running-in wear models as they foresee an exponential decrease of wear rate over time. Hence, running-in wear becomes smaller due to constant conditions but is always contributing to the overall wear amount.

The wear coefficient therefore corresponds to the linear (first order) approximation and is valid for comparing wear results of the same test duration. For understanding the physics of wear behaviour and for coherences of model tests to real systems it seems to be indispensable to use non-linear models.

3.6 Evaluation of wear behaviour

The results of nVCT wear measurement clearly show a divergent (exponential) increase of the wear coefficient due to load and temperature of the piston ring in the interval of 50 N and 200 N. This constraint is necessary as increasing load will also increase the energy exchange and consequently can change wear behavior in a higher load regime. Therefore, the increasing tendency may not be extrapolated for higher load regimes without proof.

In Fig. 12 wear coefficients with respect to temperature, stroke, and frequency are shown. As pointed out above the sliding distance is proportional to the product of stroke and frequency of the relative movement. Although the sliding distance is the same (except for the tests with 25 Hz and 1.5 mm) significant effects due to change of parameters can be seen.

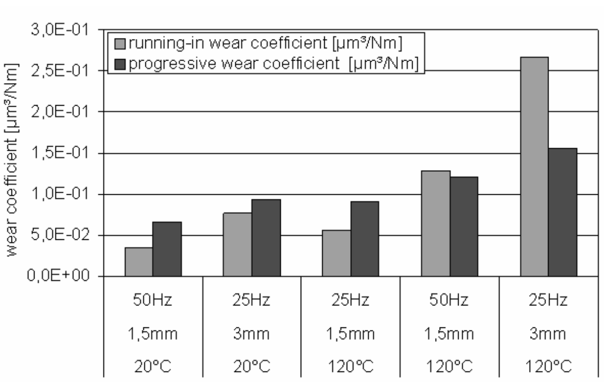

Fig. 12: Progressive wear coefficient – impact of load and temperature (stroke 1.5 mm; frequency 50Hz)

At higher temperature the wear coefficient increases. At a certain temperature the effect of higher stroke, respectively lower frequency, also corresponds to higher wear coefficient. This tendency can be noticed for progressive as well as for running-in wear coefficient. The increase of running-in wear at higher temperature is much more distinctive than compared to that of the progressive wear due to higher stroke.

To investigate running-in behaviour the measuring system should be capable to distinguish effects smaller than the roughness of the specimen surface for runningin in most cases is referred to flattening asperities and establishing a tribological boundary layer.

These investigations lead to understanding of fundamental wear behaviour in a system and consequently open up the possibility to draw coherences of model systems to applications in original engines. Therefore, the improvement of tribosystems due to new materials, system geometries, and lubricant composition can be evaluated saving costs and time.

4. CONCLUSION

Stick-slip effects in drive systems sometimes cause noise effect and vibrations. In order to find influencing parameters model test can be performed. The dynamic behaviour of the friction coefficient is essential for the performance. Usually Stribeck curves give information about the relevant characteristics. It is also possible to derive the “spectrum” of friction coefficient (versus relative speed) from test runs at constant (nominal) speed yet exhibiting dynamic effects (i.e. oscillations). Such test can be performed using tribometers with certain elasticity, e.g. the disc-disc-tribometer at AC²T.

The dynamic conditions of the Tribometer can be simulated. The dynamic evaluation of the data provided by the friction measurement device and the additionally implemented accelerometer enable the calculation of the friction dependency from the relative motion. The already available simulation model shows good correlation with the measurement data provided by the torsion element and the accelerometer. Though some improvements can be implemented this method offers a “robust” determination (not sensitive to signal noise) of stiction and friction coefficient. It is shown that this method also helps clarifying the type of motion (stickslip or slip-slip oscillations).

Wear measurement with radio active isotopes is a very powerful tool to investigate wear behaviour online and in nanometer range. But it depends on extensive knowledge about the techniques concerned especially on determining the depth profile of isotopes in the specimens. The advanced application of radio active isotopes for high sensitive measurements in a model tribometer and with less activity than the free limit (= no precautions) enables measuring wear processes on the correct order of magnitude like needed to investigate real components and systems.

The evaluation method preferably uses accompanying calculations as e.g. on the flow behaviour of the circuit and the contact conditions of the mating surfaces. Moreover, data processing enables the characterization of the wear processes in terms of running-in effects and progressive wear. The tests exemplarily shown in this paper differentiate in short-time tests under realistic loading conditions the influences due to load, temperature, and sliding distance on running-in and progressive wear, yet with similar tendencies. Of course, the relation of running-in and progressive wear is dependent on the holistic effect of loading conditions.

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