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Application oriented tribological test concepts

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1. Introduction

The tribotesting categories as shown in Figure 1 have different scopes with associated "pros" and "cons" and results obtained in one category cannot be simply transferred to another. When going up from categories V&VI to II&I, the impact of design overrules in general the influence of the metallurgy or materials choice.

The "cheap" test methods in categories 5&6 aim pre-screening and assessment of basic properties as well as use mainly for the test specimen SAE E52100 (100Cr6, SUJ2) ball bearings steel and carbon steels. The main test geometries are ball-on-flat/ (disk) or block-on-ring apart 4-ball geometry. The tribological test equipments of today have strongly evolved in terms of data processing and variability of test conditions. This enabled "dynamic" testing, where during a test the "critical" solicitations were repeatedly and freely passed.

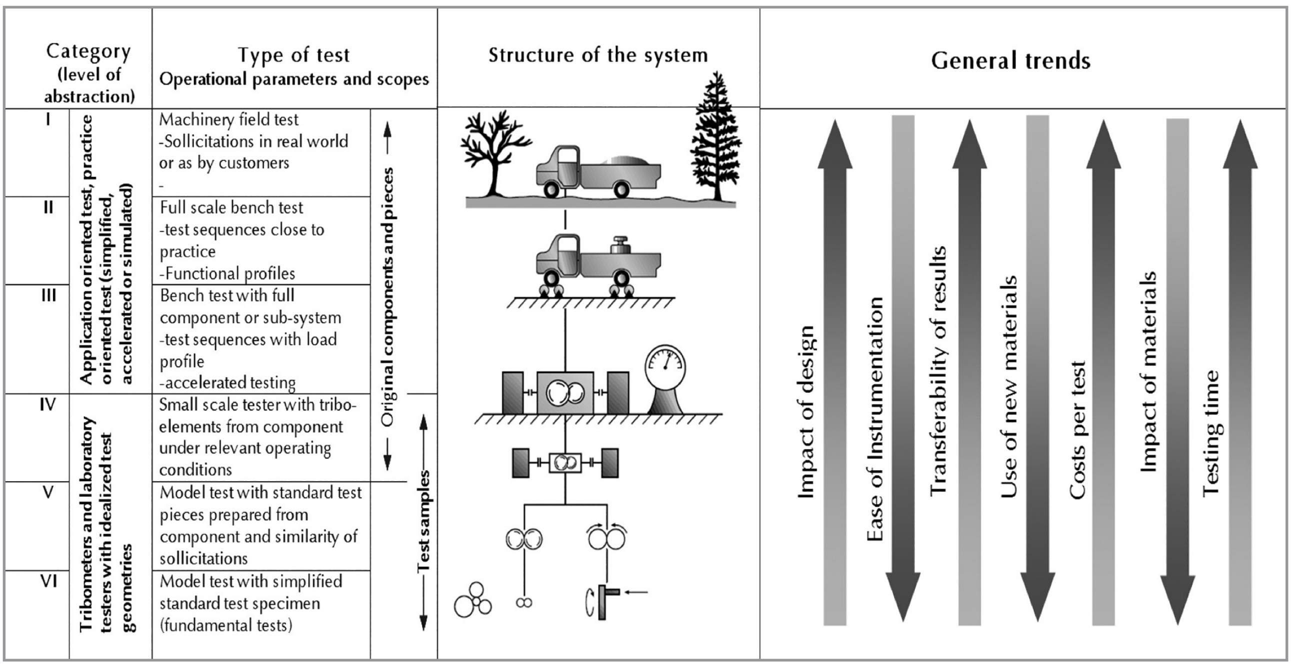

Figure 1: *Categories of tribotesting.*

2. Application oriented test modes

The two key factors for developing meaningful and transferable tribological test modes are:

a. Test pieces/specimens derived from real parts and abstract pieces derived from applications which are as close to the real parts as can be replicated when using new materials and coatings. [1]. Such specimens should contain all metallurgical characteristics of components produced under industrial conditions. At least the metallurgical and topographical similarities between real parts and tribo-specimen should increase the transferability.
b. Test conditions matching the operating conditions of the application based on a tribological system analysis.

Precision statements for test methods are critical to ensure consistency between supplier and customer and to maintain good business relations. This will help to determine the results from two operators on the same samples and whether the results can be considered 'the same' or 'different' given the test method.

In figure 1, V and V1 show the test data transferable to the questions asked in any application, and to distinguish from the outset any development likely between 'meaningful' and 'meaningless' solutions. Here the development is also accelerated.

2.1 Chassis joints

The ASTM D7420 is based on the company standard TRW 62 051 301 (June 2002) of TRW Fahrwerkssysteme (Chassis Systems), D-50543 Düsseldorf, Germany. This test method covers a procedure for determining the friction and wear behaviour of grease-lubricated plastic socket suspension joints, ensuring the integrity of suspension joint greases and quality inspection for those greases under high-frequency linear-oscillation motion using the SRV® test machine (see Figure 2).

Polymeric test disk (Ø= $18.2^{+0.2}$-mm diameter) have three flat pins in a diameter of Ø= 3.0 mm. Injection moulded plastic specimen represent characteristic items of the inner plastic socket surface (POM (Polyoxymethylen-Copolymer), TPU (Thermo plastic polyurethane), Poly-amide PA11). For the lower test disk, aside the standard SRV® test disk in SAE E52100 (100Cr6H, SUJ2), 41CrS4 (DIN 1.7039; ~SAE 5140H) steel including nitro-carburisation should be used. In this test, the coefficient of friction should not exceed ≤0.05.

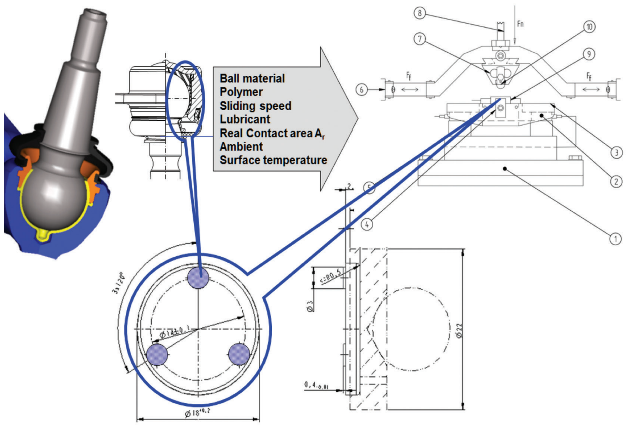

Figure 2: *Abstraction of the tribosystem "plastic socket suspension joints" to tribometer (FN= 2,000 N constant, T= 50°C, f= 50 Hz, △x= 1.5 mm).*

2.2 Synchronizer

The CEC L-66-99 and ASTM D5579 represent two widely used test methods to evaluate manual transmission fluids (MTF). Even brass or other synchroniser materials, like molybdenum coatings, sinter as well as paper and carbon fiber tapes, can be used. A multitude of test geometries and specimens were assessed but found to be an unsuitable match with bench test results. SINOPEC has developed a new screening method published as ASTM D8227 and GB/T 38074-2019 in order to discriminate the frictional behavior of MTF-oils (see Figure 3). The aim is to facilitate and shorten the time taken for MTF's screening and development. The cross check with bench tests indicated a good transferability of results and the round robin tests a very good precision. The next steps in development involve the frictional mapping at different oil temperatures and contact pressures as well as the simultaneous determination of wear volumes in the same test.

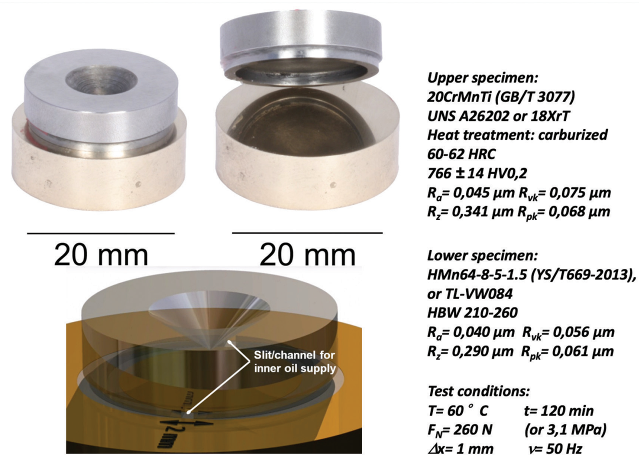

Figure 3: *Test pieces for simulating the frictional behaviour of synchroniser with working conditions.*

2.3 Piston ring/Cylinder liner

The piston groups accounts for ~50% of the internal engine friction and here, scuffing is a major concern. Over the last decades, the costs to complete all the engine tests escalated as the number of test matrices grew, as each:

a. new set of specifications is more technically complex than the previous,
b. the frequency of friction is increasing,
c. the number of candidate oils increases (base oils, additives, up-take of fuel, cylinder liner and piston ring materials)
d. “shelf life” of specs became shorter.

Industry seeks to use test systems that enable a qualitative or even semi-quantitative correlation between lower-cost model tests and more expensive and time-consuming component or product testing. There is a strong demand today for test procedures that can rapidly screen potential lubricants and materials before system-level life engine tests are performed.

The use of such specimen-based engine testing has advantages, especially for OEMs, including:

a. Covering the full existing metallurgy for liners (grey cast iron, AlSi alloys, thermally sprayed coating, etc.), but also for the piston rings
b. Being highly transferable to specific engine operations in terms of friction, wear and scuffing
c. Reducing the necessary full engine test matrix by pre-screening, but also disadvantages for base oil and additive producers and formulators
d. Reduced number of specimens
e. Increasing the test matrix outside of engines
f. Such tests are specific to OEMs
g. Load carrying capacity

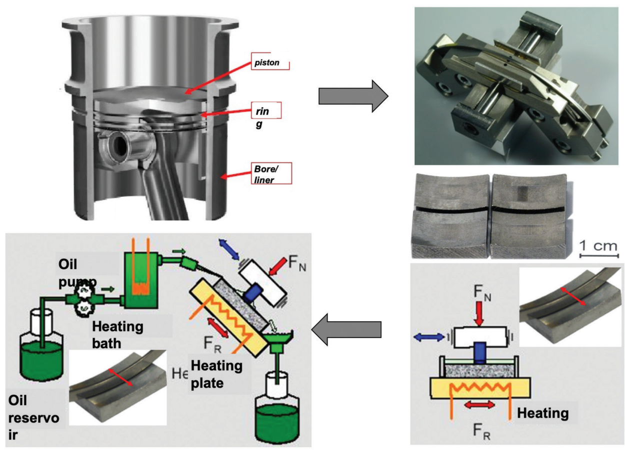

Figure 4: *Abstraction of the tribosystem “piston ring/cylinder liner” to tribometer (Test for load carrying capacity: FN= constants loads >50 N up to 2.000 N, T= 130-270°C, f= 20 Hz, △x= 3 mm).*

2.3.1 Load carrying capacity

The MBN 10474[a] (MBN=Mercedes Benz Standard) prescribes sample specimens machined from engines and tribologically tested in the SRV® test equipment (see Figure 4). MBN 10474 is part of the engine oil specs. The full test matrix for screening of the load carrying capacity and the scuffing limits for one cylinder liner alloy for one oil requires 28 SRV tests [2]. This reciprocating model test aims to reproduce real load situation of the contact condition between the piston-ring and cylinder liner at fired top dead center (FTDC) of internal combustion engines.

[a] *Mercedes Benz Procedural Instruction MBN 10474: Execution of Scuffing Limit Tests with Oscillating-Friction-Wear Tribometer, Version 2016-04.*

Figure 5 displays the results from the test matrix. At high cylinder liner temperatures and low oil supply rates the load carrying capacity (LCC) values obtained are lower than the loads corresponding to cylinder pressures. Therefore, scuffing limits were exceeded and can be evaluated for different combinations of the tribological system piston ring, cylinder liner, and engine oil to sort out the most robust variants [2].

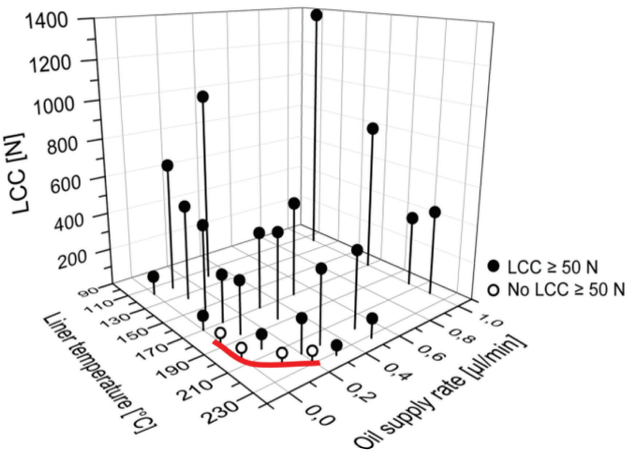

Figure 5: *LCC dependency on liner temperature and oil supply rate [2].*

2.3.2 STRIBECK-type curves

The evaluation of the friction power P_R resulting from all lubrication regimes in a Stribeck-type curve over the velocity range up to 10 m/s. The friction power P_R, illustrated in Figure 6) is the product of friction force and velocity. Thus, the frictional power P_R is a function of the normal force, tangential force, velocity and temperature over all lubrication regimes. The hydrodynamic lubrication regime dominates the frictional power P_R.

The frictional work W_R (see lower left in Figure 6) is the integral under the curve of the frictional power PR (here from 0 to 10 m/s), which covers the total response under all lubrication regimes in order to allow an accurate comparison of different fluid chemistries and formulations. It is visible from the Figure 6 (centre left), that the hydrodynamic friction has a large contribution to the frictional power losses and becomes dominant. This means that test methods operating only in the regime of mixed/boundary lubrication can´t differentiate formulations in terms of their contribution to friction reduction in an engine or e.g. in terms of fuel economy. Increasing the oil temperature reduces the frictional work W_R.

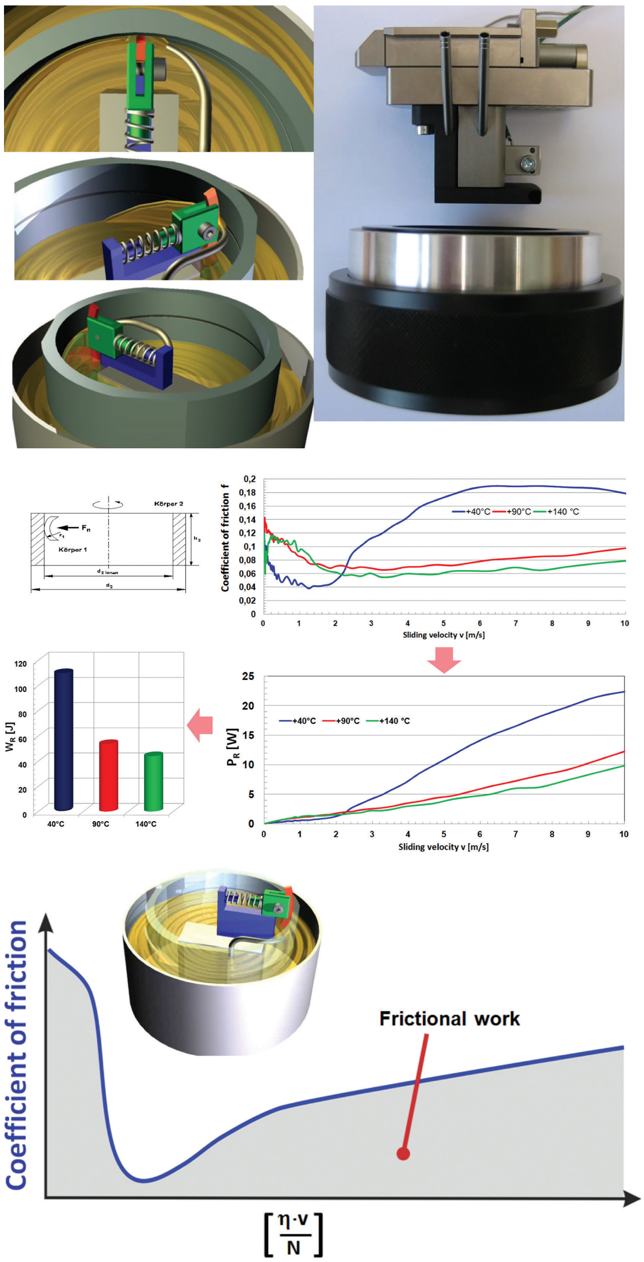

Figure 6: *Schematic representation of the effect of temperature and sliding speed on (top) coefficient of friction (lower left) friction power P_R (lower right) friction work W_R [3].*

W_R is the friction represented by the summary of the values of given oil temperature in response to the lubrication regimes, showing a comparison of different fluid chemistries and formulations.

2.4 Tribological profile of hydraulic oils

The vane pump, which is a key component in hydraulic systems and many other tribosystems, especially in high-pressure hydraulics, also merits tribological attention. The target is to evaluate simultaneously friction, wear and extreme pressure properties of hydraulic oils by using pre-existing SRV®-based ASTM test methods. The tribological profile tested at +80°C comprises:

1. Extreme pressure D7421-16/ISO19291 ($\triangle$x= 2 mm, step load)
   Set limit: >900 N (P_{0max} ~ 3017 MPa)
2. Anti-wear properties and coefficients of friction D6425-16/DIN 51834-2:2017/ISO19291. (F_N= 300 N (P_{0max} >FZG 14)) with calculated wear rates k_v of ball and disk using D7755 or DIN 51834, part 3. Proposed set limits for wear rates are:
   a. kv kv ball < 3.5 10-9 mm³/N·m
   b. kv disk < 2 10-9 mm³/N·m
3. Light optical microscopic (LOM) photos of the wear tracks (flat disk) and graphs of evolutions of coefficients of friction for validation to unmask adhesive mechanisms.

This test methodology was validated in two international round robin tests with twelve test oils and are filed as research reports at ASTM headquarters. For determining the amount or volume of wear on 2 tribo-elements (specimens) according to ASTM D7755/DIN51834-3, contributing to the loss of mass of the vane and ring in the Vickers pump D7043, it is necessary to assess the tribological profile, which is extended in the SRV®-based concept by extreme pressure properties and a graph of the evolution of the coefficient of friction. Hence, the benchmark and validation of hydraulic oil formulations on a wider range of tribological properties.

By using D7421 hydraulic oils rated as "borderline" with a tendency for adhesive failures can be identified and D6425 correlates to Vickers pump tests in D7043, as shown in an ASTM round robin test in 2015.

Frictional properties under mixed/boundary lubrication are also assessed by the SRV®-based test concept. It should be noted that hydraulic circuits with wet clutches require an elevated frictional level, and are not related to base oil type.

3. Tribological profile of thin films

The adhesion of thin film coatings is widely determined by means of a scratch test according to ASTM C1624 or DIN EN 1071-3. It is a step load test, in which a diamond stylus is moved over a specimen surface with a linearly increasing load until failure occurs at critical loads. A new method of evaluating the anti-adhesion characteristics of DLC films by a reciprocating wear test using a high-frequency, linear-oscillation (SRV®) ball-on-plate test machine under a step loading condition was developed, and processes up to the occurrence of delamination were investigated [4]. By combining the signal of the coefficient of friction with the stroke (see Figure 7), the initiation of delamination can be detected earlier as when it becomes later at higher loads visual. Changes in friction (e.g. increase in friction) are mainly due to initiation of delamination of the coating. Coating failure is indicated by two cases:

a) When the delamination of the DLC film occurred, the friction coefficient increased and the oscillation stroke decreased
b) Beginning fragmentation of the film, without delamination, generates wear debris, which agglomerate or stick in the contact zone and increase friction and reduce the stroke.

The present new and functional test method enables to identify the onset point of an O.K./pass load of beginning delamination and/or wear or fragmentation, even as the test continues to run.

At the onset point of an O.K./pass load, the test can be interrupted to study the metallurgical origins of delamination. Another option to detect tribologically initiated cracks in thin films is acoustic emission [5]. Simultaneously, the coefficient of friction is recorded for different loads. This test can also be run under lubricated conditions or in any liquid media.

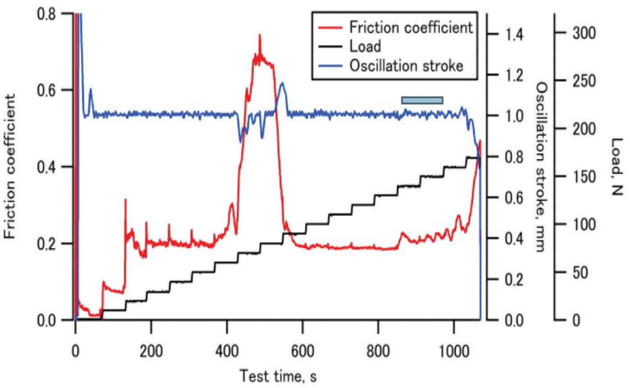

Figure 7: *Parallel evolution of stroke and friction in a load step test (uncoated ball: AISI 440C (X105CrMo17), F_N= load step of 10N every minute, T= 40°C, air, 30-50 rel. humidity, f= 1 Hz, △x= 1 mm) [4].*

The tribological performances of NCD (Nano Crystalline Diamond) is investigated by using the ball-on-plate geometry in the linear-oscillation (SRV®) test machine [6]. The target was to understand the tribological response of NCD-films in the presence of high-performance lubricants and exploring the possibility of using them in future automotive tribo-systems.

In the last decade, the development of thin films reduced the demands to lubricants and even enabled unlubricated systems.

Many coatings with tailored properties are being developed and are available in the market. In addition to all great scientific works done, a short screening wear and friction test of unlubricated systems is needed. For this purpose, 5 different coatings with different qualities were deposited on standard SRV® disk (100Cr6) by 3 companies (see table 1).

Coatings No.	Type of coating	Thickness [µm]	Ra aprox. [µm]	Hartness	Kind of layer
1	ta-C	< 1.0	0.01 - 0.05	5000	Monolayer
2	a-C:H	2.0 - 4.0	0.1	3000	Multilayer Cr based
5	a-C:H:Si	1.5	0.01 - 0.05	2200	Multilayer with Ti as intermediate layer
6	a-C:H	1.5	0.26	2000 - 2500	Intermediate layer Cr / W / Ti
7	a-C:H	2.0	0.25	1000 - 2000	Intermediate layer Si

Table 1: *characteristics of the 6 tested different coatings qualities.*

As upper specimen (counter body) two different materials (100Cr6 and Al_2O_3) as balls of 6 mm diameter were chosen. The chosen environment conditions were as follows:
Temperature: 25 °C, no lubricant, relative humidity: a. 30 % r.h. and b.90 % r.h. as well as the test parameters on SRV® were: test duration: 30 min, F_N= 5 N, frequency: 1 Hz and stroke: 5 mm.

Figure 8 illustrates the evolutions of the coefficients of friction of coating #6. The effect of the counter body material and relative humidity for each DLC-Coating quality was observed for all six DLC coatings.

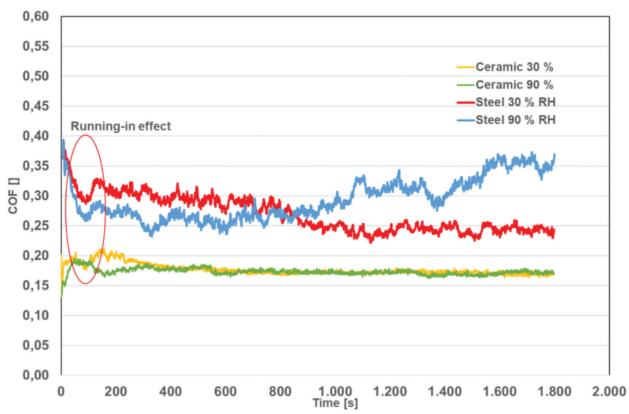

Figure 8: *Coefficients of friction for a-C:H coating #6 for two different ball materials and two different humidities.*

Conclusions

Different tribological test methodologies with SRV® offer an overview of the tribological product's performances under the relevant operating conditions. The functional profile is assessed by mapping the tribological behaviour under different operating conditions and/or by using test specimen prepared from components.

Additionally, the different quantities, like coefficient of friction and acoustic emission, can be combined.

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