Triboactive materials for dry reciprocating sliding motion at ultra-high frequency

Dirk Spaltmann*, Manfred Hartelt, Mathias Woydt

Federal Institute for Materials Research and Testing (BAM), Division VI.2, Tribology and Wear Protection, D-12200 Berlin, Germany

**A R T I C L E I N F O**

<table>
<thead>
<tr>
<th>Article history:</th>
<th>© 2008 Elsevier B.V. All rights reserved.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Received 19 December 2007</td>
<td>—</td>
</tr>
<tr>
<td>Received in revised form 27 May 2008</td>
<td>—</td>
</tr>
<tr>
<td>Accepted 9 June 2008</td>
<td>—</td>
</tr>
<tr>
<td>Available online xxx</td>
<td>—</td>
</tr>
</tbody>
</table>

**Keywords:**
- Frequency
- Tribometer
- Sliding friction
- Wear
- Triboactive materials
- Magnéli-type phases

**A B S T R A C T**

High-power piezo-electric motors with power densities of 1.4 kW/kg display a potential for substituting hydraulic actuators. For this application, two novel tribometers of the same type have been designed using commercially available components for sliding motion at 40 kHz with amplitudes between 2.5 μm and 5 μm. The tribometers are equipped with means to measure amplitude, frequency, power required to keep the samples in motion and load applied. The effective motion between the two contacting bodies is monitored in each of the tribometers. These data are used to evaluate the coefficient of friction. The wear rate was determined after the tests. The set-ups were tested using well-known 100Cr6H (AISI 52100) samples before investigating novel, non-commercial substrates such as AlFeCrTi-alloys and tungsten carbide-based coatings as well as Magnéli-type coatings (Ti₈₋₂Cr₂Oₙ₋₁₋₂ and Ti₆O₄₋₁). This paper presents the principle of the ultra-high frequency tribometers and first tribological quantities of materials and coatings tested up to and above 10¹¹ cycles. Very low wear rates in the range 10⁻⁶ mm³/Nm down to 10⁻¹⁰ mm³/Nm were determined under dry oscillation in air.

**1. Introduction**

In modern aviation, especially for civil aircrafts, intense efforts are made to replace hydraulic actuators with electromagnetic, i.e., fully electric ones, in order to home in on the goal of a maintenance-free air plane. Even the later ones may be replaced by innovative, high-power motors or high force, linear actuators based on piezo-electrics aiming at a reduction in system weight. This allows not only increasing the intervals between maintenance inspections, but also avoids environmentally hazardous fluids with fire risks and regular top-ups.

The piezo-electric effect can only be transferred in a mechanical motion by forming a tribosystem, e.g., a frictional contact. Piezo-ceramic materials convert electric energy via the dilatation between two surfaces into mechanical energy, e.g., a movement. This essential point is common for all mechanical set-ups (actuators and motors) using the piezo-electric principles, such as

a. travelling wave or ultrasonic motors (AEG/Shinsei),
b. piezo-electric actuator drive (PAD) [1],
c. inchworm motor or actuator or
d. torsional actuator motor (NAVAL Research).

One of these concepts currently pursued in the PIBRAC project [2] is the high-power motor as described in US 6,204,590. Here, investigations are on their way to demonstrate the feasibility as a piezo-electric brake actuator in order to replace hydraulic ones. The piezo-electric actuator and motor operate at oscillating frequencies up to 40 kHz and for these specific avionic purposes of a typical shuttle and mid-range carrier are expected to encounter up to 1 × 10¹² cycles during a maintenance-free lifetime. This mission is composed of operations during braking, taxiing and parking. For the PIBRAC motor to have a high efficiency, the current design requires components, forming the contact between the acting piezo-ceramics and the moving parts, to have a constant coefficient of friction of about 0.5. This places high demands on the wear resistance of coatings protecting the respective components in order to use the maximum of the force, which can be generated by the quite low elongation of the piezo-stacks. The tribological parameters can only be obtained by experimental tests and are very dependent on the conditions of the surrounding environment (i.e., temperature, humidity). So far, only very few or even no tribological properties seem to exist in literature for the frequency range required. The same is true for the respective testing devices for frequencies above 2 kHz, as they are far above the oscillating frequencies typical for fretting contacts. Therefore, there is a clear need for an ultra-high frequency tribometer which was set up to map the tribological behaviour of candidate materials and coatings in an application oriented way.
2. Experimental details

2.1. Ultra-high frequency tribometers

One of the first high-frequency tribometers were “fretting testers” operating up to 1.5 kHz. The oscillating sample mounted on a magnetostriuctive rod is actuated by a magnetic coil and loaded by a dead weight. The low displacement amplitude of 1 μm corresponds to the partial slip regime [3]. However, dead weights are of no use, as they can give rise to changes in the Eigen frequency of the system and it might also cause ‘parasitic’ vibrations in unwanted directions. The torque and wear behaviour [4] of Si-doped diamond like carbon and other thin films were evaluated in a travelling wave motor. The “high-cycles” tests of up to 700,000 cycles for microscale piezo-electric actuators of Hess and coworkers [5] performed at 1.5 Hz are far off the frequency range needed for the high-power motor. In another version of an ultra-high frequency tribometer, the high-frequency micro-slip for simulating the kinetic movement of travelling wave motors was generated by setting a pin in a reciprocating motion with 27.71 kHz against a rotational disk (ν = 5.2–6.3 mm/s) [6].

Hard/soft and also hard/hard (steel/alumina; self-mated alumina) tribological characterized by using a set-up, in which macroscopic sliding was superimposed to high-frequency micro-slip. The high-frequency micro-slip was generated by two different booster-sonotrodes (amplitudes of 4.5–8.0 μm at 21 kHz and 12–24 μm at 20.4 kHz). This arrangement was dedicated to the situation of travelling-wave-type motor having a stator and a rotor. The relative micro-motions between the two specimens were analyzed using a laser interferometer (Polytec OFV 502 with controller 3000) in order to confirm gross-slip [7].

The use of a sonotrode as an actuator and a laser interferometer for monitoring the amplitude seemed to be of advantage and are used in the tribometer design described here.

In order to have the tribometer setup quickly for operation, its design was based on commercially available parts with as little modifications as possible. In Fig. 1, the components of the ultra-high frequency tribometer are shown and the numbers in parenthes-

sises refer to this figure. In order to test novel and state-of-the-art materials and combinations thereof under conditions required for applications in piezo-electric motors, the ultra-high frequency tribometer fulfils the following requirements:

(a) It provides a reciprocating motion with amplitude of about 2.5 μm at a frequency of about 40 kHz.
(b) The tribometer design ensures that the test samples are actually moving relative to each other.
(c) It operates continuously for up to 10¹² cycles at a time.
(d) At the start of the test the tribometer grants a defined, initial contact situation comparable to low frequency tests.
(e) The normal force is applied in a defined manner without parasitic vibrations in unwanted directions.
(f) The samples can be tested in a temperature range of between −70 °C and +210 °C.
(g) The tribometer provides means to adjust the relative humidity between about 3% and 98%.
(h) The ultra-high frequency tribometer is based on BAM’s modular design so that it is compatible with existing tribometers and extends the respective features.

All components of the ultra-high frequency tribometer are rigidly mounted on a massive base plate (1), which is suspended in a damping system, preventing vibrations of the building itself and/or subsonic noise from affecting the tribometer. The actual moving part in the tribometer is the sonotrode (2). One end of the sonotrode provides a means for the connection to the converter (3). The other end has the shape of a 10-mm thick section of a sphere with a radius of 21 mm. The counter sample (4) is the flat side of a disc. This in turn leads to a contact geometry for which Hertzian equations can be used to calculate the initial average pressure at the start of the test. The sonotrode is generally manufactured of a certain aluminium alloy (AlMgZnCu1.5) with optimized conditions for acoustic wave propagation. This material and its dimensions ensure that it can be operated in resonance at a frequency of about 40 kHz. This frequency leads to accelerations of up to 315,000 m/s² which require a monolithic piece for the sonotrode, being actuator and tribo-sample at the same time. The Sonotrodes were made

Fig. 1. Components of the ultra-high frequency tribometer: (1) base plate with vibration damping system, (2) sonotrode, (3) converter, (4) counter body/disc, (5) pipe to supply air-cooling, (6) mount for converter (4), (7) spring suspension system, (8) distance sensor, (9) liquid nitrogen reservoir, (10) implemented heating facility, (11) reservoir to influence humidity and (12) laser vibrometer.

Please cite this article in press as: D. Spaltmann, et al., Triboactive materials for dry reciprocating sliding motion at ultra-high frequency, Wear (2008), doi:10.1016/j.wear.2008.06.004
of different alloys, such as AlMgZnCu1.5, TiAl6V4, AISI 52100 and AlFeXY-alloys, or coated. The spherical, coated sonotrodes were polished to reduce the roughness of the respective surfaces to $R_1 < 0.3\, \mu m$ and $R_2 < 0.3\, \mu m$ and re-tuned to have again an Eigen frequency close to 40 kHz.

In order to have the converter, whose main component is a piezo-stack, driving the sonotrode in a permanent manner for an frequency close to 40 kHz.

Velocity $0.25$

Properties of the single-point laser vibrometer

Table 1

<table>
<thead>
<tr>
<th>Maximum velocity</th>
<th>405 mm/s or 810 mm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency range</td>
<td>0 Hz to 2 MHz</td>
</tr>
<tr>
<td>Maximum displacement error</td>
<td>$\pm 1%$ of RMS reading for 1–100 nm</td>
</tr>
<tr>
<td></td>
<td>$\pm 0.2%$ of RMS reading for displace. &gt;100 nm</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.25 $\mu m/s$ @ 20 kHz, 2.5 $\mu m/s$ @ 200 kHz, 25 $\mu m/s$ @ 2.000 kHz</td>
</tr>
</tbody>
</table>

2.2. Measurement of wear and friction

The samples to be tested are standard polished to have roughness values of $R_2 < 0.3\, \mu m$ and $R_1 < 0.3\, \mu m$. The wear scars created during the tribo test are recorded and analyzed at the end of the experiment. A Hommel surface profilometer is used to evaluate the respective wear rate via a 3D-measurement of the wear scar. In order to determine the coefficient of friction (COF or $\mu$), the sonotrode is at first operated without load close to the sample surface (without forming a contact). It is essential to operate the actuator for at least 1 h to reach stable working conditions. The power $P_0$ necessary to vibrate the sonotrode under such conditions is monitored. After bringing the sonotrode into contact with the sample surface and applying a load, the increased power $P_{Load}$ is monitored as well. During a single sliding cycle, the sonotrode travels four times the amplitude $A_i$ measured by the monitoring system. Such a cycle lasts the period $T_i$, which is the reciprocal of the frequency $f_i$ of the vibration of the sonotrode. The index $i$ is to be replaced by ‘0’ for sonotrode operating conditions before applying the load and by ‘Load’ after its application. Using basic relations one obtains the following simple equation to estimate the acting forces:

$$F_i = \frac{P_i}{4 \times A_i \times f_i} \quad (i: 0, \text{Load})$$  

The sonotrode is operated above, but closed to resonance conditions. In contrast to Ref. [9] the powers $P_i$ were therefore converted first into the respective forces $F_i$ using the parameters measured for the unloaded and loaded condition, respectively.

The difference in forces needed to keep the sonotrode vibrating before and after contact is attributed to the acting friction force. Thus, the coefficient of friction $\mu$ can be calculated as follows:

$$\mu = \frac{F_{Load} - F_0}{F_N}$$

Here $F_N$ is the load applied by and evaluated via the system described earlier. The frequency $f$ and the power (100% power equalling 200 W) are supplied by the controller of the actuator.

2.3. Testing standard materials at ultra-high frequencies

Presently, there does not seem to exist a unanimously accepted standard to calibrate force measurement systems at ultra-high frequencies such as 40 kHz. Therefore, well-defined tribological systems were tested with proven tribometers. The resulting COF were compared with data obtained by the UFT to assess its performance and whether or not it generates results in the expected range. For the comparison tests the proven tribometer were run at parameters which came ‘closest’ to the conditions in the UFT, i.e., at a frequency of 50 Hz and a stroke of 200 $\mu m$. In comparing these data, three issues are of importance. The first issue here is the frequency. In the author’s institution, tribological tests with well known and proven tribometers are carried out at frequencies between 1 Hz and, meanwhile, 100 Hz pushing the limit towards 500 Hz. Within this range, no significant effect of the frequency on the COF could be observed. Extrapolating this finding over two orders of magnitude is a working hypothesis to start with. The second issue is the one related to the evaluation of the friction force. The method applied in the UFT assumes a rectangular force–distance curve. Whether or not a rectangular force–displacement curve can be achieved with the small strokes for the UFT is also a matter of tribometer stiffness with respect to the load applied. In Ref. [10] it was shown that a rectangular force displacement curve can be observed even at such small strokes of 2 $\mu m$ with a load of 0.2 N and 50 Hz. Although loads between 3 and 10 N were applied in the UFT, its sonotrode arrangement is
much stiffer than the conventional tribometer arrangement. Thus, a similar rectangular force displacement curve can be expected, suggesting full sliding. The third issue is that at a stroke of 200 μm under the conditions given the contact area according to Hertzian equations is nearly completely out of contact, while at a stroke of 5 μm it is not. This can lead to differing conditions for the conventional tribometer compared to the UFT. For the comparison tests the sonotrode material was limited to aluminium. The counter

<table>
<thead>
<tr>
<th>Material / Parameters</th>
<th>Optical Microscope Images</th>
<th>Profilometric Images /Line scans</th>
</tr>
</thead>
</table>
| a) 100Cr6 sonotrode against 100Cr6H1 disc  
- Dry  
Cycles: $2.86 \times 10^3$
Stroke: 5.08 μm
Freq.: 39.280 Hz
Load: 3.3 N
$P_{cav}$: 180 MPa
$P_{fat}$: 25 MPa
Top: Sonotrode
Depth: 20 μm
Bottom: Disc
Height: 25 μm
Balls: 500 μm |
| ![Image](image1.png) |
| ![Image](image2.png) |
| b) TM23 coated sonotrode against 100Cr6H1 disc  
- Dry  
Cycles: $1.70 \times 10^3$
Stroke: 5.04 μm
Freq.: 40.438 Hz
Load: 3.5 N
$P_{cav}$: 220 MPa
$P_{fat}$: 17 MPa
Top: Sonotrode
Height: 30 μm
Bottom: Disc
Depth: 16 μm
Balls: 500 μm |
| ![Image](image3.png) |
| ![Image](image4.png) |
| c) TM23 coated sonotrode against TM23/AlFe2XY disc  
- Dry  
Cycles: $1.70 \times 10^3$
Stroke: 5.08 μm
Freq.: 40.399 Hz
Load: 3.6 N
$P_{cav}$: 200 MPa
$P_{fat}$: 24 MPa
Top: Sonotrode
Depth: 1.5 μm
Bottom: Disc
Depth: 6 μm
Balls: 500 μm |
| ![Image](image5.png) |
| ![Image](image6.png) |
| d) TM23 coated sonotrode against TM23/AlFe2XY disc  
- BAM-Trac  
Cycles: $1.70 \times 10^3$
Stroke: 5.16 μm
Freq.: 40.412 Hz
Load: 3.5 N
$P_{cav}$: 200 MPa
$P_{fat}$: 32 MPa
Top: Sonotrode
Depth: 2 μm
Bottom: Disc
Depth: 1 μm
Balls: 500 μm |
| ![Image](image7.png) |
| ![Image](image8.png) |
| e) TiCr2O3 coated sonotrode against TM23/AlFe2XY disc  
- Dry  
Cycles: $1.08 \times 10^3$
Stroke: 5.30 μm
Freq.: 40.580 Hz
Load: 3.0 N
$P_{cav}$: 190 MPa
$P_{fat}$: 3.9 MPa
Top: Sonotrode
Height: 22 μm
Bottom: Disc
Depth: 22 μm
Balls: 500 μm |
| ![Image](image9.png) |
| ![Image](image10.png) |

**Fig. 2.** Optical microscope images and 3D profiles of contact surfaces after tests in the ultra-high frequency tribometer.

Please cite this article in press as: D. Spaltmann, et al., Triboactive materials for dry reciprocating sliding motion at ultra-high frequency, Wear (2008), doi:10.1016/j.wear.2008.06.004
discs were made of aluminium and 100Cr6 steel. Reference tests of aluminium against aluminium were carried out under similar conditions as in the ultra-high frequency tribometer (UFT), but at 50 Hz and a stroke of 200 μm, leading to a COF of about μ = 0.74. In literature values for the COF are reported ranging between μ = 0.5 and 0.8 depending on the actual composition of the aluminium alloy [11]. These values compare to μ = 0.55 as measured with the UFT. For the system aluminium against steel, a COF of μ = 0.5 is reported [12] which is the same value delivered by the UFT. In tests with a sonotrode made of 100Cr6 against a 100Cr6H counter disc COF in the range of μ = 0.29–0.46 were observed. This compares to values of μ = 0.6–0.8 as reported in the literature for such systems [13]. However, as is shown in smaller insets in Fig. 2a, a massive production of wear particles has occurred. While at longer strokes wear particles produced could be moved out of contact, they tend to stay in contact at smaller strokes as achieved with the UFT. In this case, the wear particles could act as bearings causing a reduction in the COF observed with the UFT compared to those measured with a conventional tribometer.

2.4. New material concepts for testing at ultra-high frequencies

Considering the ultra-high frequency tribometer and assuming μ > 0.6, the typical maximum P × v-values, for oscillations also known as power parameter, lie in range of (190 MPa × 1.26 m/s > × > 0.6) × 144 W/mm². This already indicates the demand for adapted tribomaterials which are able to avoid adhesive wear mechanisms. Hot spot temperatures and the heating-up during operating, as the piezo-electric PIBRAC-motor has no active cooling, severe the tribological solicitation. Such figures of frictional heat inputs into mating surfaces under dry friction favour adhesive wear mechanisms and welding. The tribocoactive materials identified in FR 2 702 895 allow a high coefficient of friction with the absence of adhesive wear mechanisms, because the powders of some of them can only be densified by means of hot-pressing or thermal spraying, indicating an unwillingness for adhesion. The generic class of such materials remain to so-called Magnéli-type phases having a planar oxygen defect, such as Ti₃O₂₋₁, with ≤ 3 ≤ n ≤ 9, or Ti₅₋₂Cr₂O₃₋₁, with ≤ 6 ≤ n ≤ 9, as well as substances, such as the cermets (Ti,Mo)(C,N) + xx binder, forming these by tribo-oxidation [14–16], namely γ-Ti₃O₅, Ti₃O₅, Ti₅O₁₇ and Mo₉₇Ti₄O₂₃ as well as double oxides such as NiO₃ and β-NiMo₉O₄.

Unfortunately, state-of-the-art aluminium alloys have no prone adhesion preventing tribological properties under dry friction. This represents a key issue for tribological components of the piezo-electric motor, such as the rotors, which require light-weight materials. Therefore, the sonotrodes were generally coated or made of novel AlFeXY-alloys. Especially the AlFeCrTi-alloy with a Young’s modulus at room temperature of $E_{RT} = 100.4$ GPa is “stiff” and attractive in order to fulfill the light-weight versus performance requirement in aeronautics. The AlFeVSi-alloy with $E_{RT} = 85.7$ GPa is still much stiffer than state-of-the-art aluminium alloys. The novel AlFeXY-alloys contain no ceramic platelets, fibres or particles, but form dendritically embedded inter-metallic phases, such as Al₃Fe, Al₃MoV₁₂Fe₇, Al₃(Fe,Cr), Al₃(Ti,Cr) and/or Al₃Ti [17]. The nominal composition of the casted AlFeXY-alloys was either 88.5Al₈5.5Fe1.3V₁.1Si or Al₈4.4Fe₇.0Cr₆.0Ti₂.5. These novel aluminium alloys form the substrate for the tribocoactive Magnéli-type materials in the tests presented here. These novel materials for an application in piezo-motors and actuators are also discussed in FR 2 819 650 and FR 2 844 933. These substrates were cast and sent to Škoda Vizkum and returned coated with four different tribocoactive coatings, such as (Ti,Mo)(C,N)+23 wt.% NiMo (TM23), Ti₅₋₂Cr₂O₃₋₁ or Ti₅₋₂Cr₂O₃₋₁, which exhibit highest wear resistances associated with (controlled) coefficients of friction above 0.5 under dry friction. All spray powders were agglomerated to spherical granules and pre-sintered. The basic composition of the produced Ti₃O₂₋₁ coatings with 6 ≤ n ≤ 9, consisted of 21–33 mol% Cr₂O₃ as solid solution in TiO₂ or leading to an analyzed composition in the spray coating by means of ESMAs of 26.2 at.% titanium, 9.80 at.% chromium and 64.0 at.% oxygen [14,18]. Analysis with XRD of the Ti₅O₅₋₁ coatings exhibit peaks of Magnéli phases, mainly of Ti₃O₅, aside from rutile and anatase. In the spray powders, however, ca. 66 wt.% Ti₃O₅, ca. 17 wt.% Ti₃O₁₇ and ca. 17 wt.% Ti₅O₅ were detected. The composition and microstructure of (Ti,Mo)(C,N)-cermets is detailed in Ref. [19].

3. Tribological results

3.1. Volumetric wear

The ultra-high frequency tribometer was designed to test the wear resistance of coatings on novel, non-commercial substrates such as casted AlFeCrTi-alloys coated with four different tribocoactive coatings, such as (Ti,Mo)(C,N)+23 wt.% NiMo (TM23), Ti₅₋₂Cr₂O₃₋₁ or Ti₅₋₂Cr₂O₃₋₁, in order to check whether they comply with the tribological specification for the piezo-electric motor. The tribological tests started with well-known 100Cr6H steel for comparison. The results are summarized in Fig. 2 and Table 2. The left part in Fig. 2 lists the operating conditions of the tribometer, such as the duration of the tests in number of cycles, the stroke, the sliding frequency, the load applied and the contact pressures at the beginning and the end of the tests. The contact pressure at the start of the tests is the initial average pressure calculated using Hertzian equations for ball on flat characteristics [11]. At the end of the tests the contact area was evaluated using the optical microscope images listed in Fig. 2. In combination with the load applied the respective contact pressure was calculated. The smaller insets in Fig. 2 show optical microscope images of the surfaces directly after the test, while the larger ones show the surfaces after cleaning with propanol-2. For each combination of material the top images always show the contact zone of the respective sonotrode and the lower ones the surface of the counter discs. Each optical image is accompanied by a three-dimensional profile of the respective contact areas and a central horizontal line scan taken with a Hommel profilometer. The 2D profiles in Fig. 2 are meant to give an impression of the grey-scale of the 3D plots. For the evaluation of the volumetric wear values only the 3D scans were used. Always a larger surface segment was scanned including not only the actual wear scar, but also areas of unaf-

Table 2

<table>
<thead>
<tr>
<th>Sonotrode/coating</th>
<th>Disc/coating</th>
<th>Load (N)</th>
<th>Cycles (10⁶)</th>
<th>Distance (m)</th>
<th>$K_v$ sonotrode (10⁻⁴ mm³(Nm⁻¹))</th>
<th>$K_v$ disc (10⁻⁴ mm³(Nm⁻¹))</th>
<th>$K_v$ total (10⁻⁴ mm³(Nm⁻¹))</th>
</tr>
</thead>
<tbody>
<tr>
<td>100Cr6H/-</td>
<td>100Cr6H/-</td>
<td>3.3</td>
<td>2.86</td>
<td>2.91×10⁵</td>
<td>3.46×10⁻²</td>
<td>1.50×10⁻¹</td>
<td>3.61×10⁻²</td>
</tr>
<tr>
<td>100MgZnCu1.5/TM23</td>
<td>100Cr6H/-</td>
<td>3.5</td>
<td>1.70</td>
<td>1.71×10⁵</td>
<td>4.80×10⁻³</td>
<td>1.67×10⁻¹</td>
<td>1.21×10⁻¹</td>
</tr>
<tr>
<td>100MgZnCu1.5/TM23</td>
<td>AlFeXY/TM23</td>
<td>3.6</td>
<td>1.70</td>
<td>1.73×10⁵</td>
<td>3.02×10⁻³</td>
<td>3.38×10⁻¹</td>
<td>1.70×10⁻¹</td>
</tr>
<tr>
<td>100MgZnCu1.5/TM23</td>
<td>AlFeXY/TM23</td>
<td>3.5</td>
<td>1.70</td>
<td>1.75×10⁵</td>
<td>1.48×10⁻³</td>
<td>4.67×10⁻³</td>
<td>6.13×10⁻³</td>
</tr>
<tr>
<td>100MgZnCu1.5/Ti₃Cr₄O₁₇</td>
<td>AlFeXY/TM23</td>
<td>3.0</td>
<td>1.08×10³</td>
<td>1.14×10⁵</td>
<td>1.28×10⁻⁴</td>
<td>6.19×10⁻⁴</td>
<td>7.47×10⁻⁴</td>
</tr>
</tbody>
</table>

Please cite this article in press as: D. Spaltmann, et al., Tribocoactive materials for dry reciprocating sliding motion at ultra-high frequency, Wear (2008), doi:10.1016/j.wear.2008.06.004
fected surface. The later was used as a reference for the baseline. The volumetric wear was calculated regarding only values below this baseline. $K_v$ total (right column in Table 2) is the sum of the respective values for the sonotrode and the disc. The three-dimensional profile images show that volumetric wear is mainly due to materials transfer. This transfer seems to occur from the less hard material to the harder one. According to the optical images in the insets, wear debris was mainly generated on unprotected/un-coated steel surfaces (see Fig. 2a and b). Further debris was produced in the long duration test (see Fig. 2e) lasting about a thousand times longer than the other tests. As can be seen from the respective images and the volumetric wear values in Table 2, the coating acts as a protective layer reducing the amount of wear produced. In the case of the TM23-coated sonotrode against the 100Cr6H counter disc, the amount of wear of the protected sonotrode is reduced by an order of magnitude compared to the test of unprotected steel sonotrode against steel disc. However, protecting/coating only one partner of the tribo-couple does not seem to be sufficient, as the wear volume on the un-coated steel disc is larger by far, causing an even larger total wear volume than in the case of the steel against steel test. Thus, coating both partners in the test with TM23 (see Fig. 2c) leads to a massive reduction of the volumetric wear volume. This value already being at the sensitivity limit of the profilometer could be further reduced using the BAM-Trac lubricant. While the respective optical microscope images show a difference (Fig. 2c compared to d), it was difficult to find and scan the contact areas with the profilometer. These low wear rates encouraged the long duration test shown in Fig. 2e. Here, a Ti$_2$Cr$_2$O$_7$ coated sonotrode was tested against a TM23 coated disc leading to a total volumetric wear value below $1 \times 10^{-3}$ after more than $1 \times 10^{11}$ cycles (see Table 2). The 3D surface profile (Fig. 2e) was taken after rinsing the samples with propanol. There does seem to be a circular zone which is affected by debris with only little wear. Close to the centre however is a heavily worn area which takes most of the wear volume. This becomes more evident, if single lines of the sonotrode and the disc profile are compared. Fig. 3 shows single line scans of the 3D profile, one each of the Ti$_2$Cr$_2$O$_7$-coated sonotrode and of the TM23 coated disc. Ideal curves with a radius of 21 mm are fitted for comparison. The milder wear seems to be plastic deformation of the disc. For the line scans to exactly fit, the sonotrode would deform elastically. It is interesting to note that material transfer and loss match exactly. Does this happen at the very point of (first) contact? Metallographic cross-section should help to answer this question. They are scheduled towards the end of the project, as these investigations render the discs and sonotrodes useless.

The encouraging results of a Ti$_2$Cr$_2$O$_7$-coated sonotrode and a TM23-coated disc lead to further long-duration tests of various Magnéli-type coatings. The tests were running at about 40 kHz for around 30 days non-stop to reach about $1 \times 10^{11}$ cycles. The respective results are listed in Table 3 including the one for a Ti$_2$Cr$_2$O$_7$-coated sonotrode and a TM23-coated disc of Table 2 for comparison. All Magnéli-type coatings tested here seem to lead to superior low volumetric wear volumes. There are two further noteworthy aspects in Table 3. In the tests, the sonotrode is always the moving part, while the disc is stationary. Exchanging the sonotrode coating (moving part) with the disc coating (stationary) or vice versa does not seem to have a significant effect on the values of the wear volume. This is suggested considering the tests with the Ti$_2$Cr$_2$O$_7$- and Ti$_2$O$_7$/Ti$_3$O$_9$-coated samples (see Table 3).

In the case of the self-mated tests of the Ti$_2$Cr$_2$O$_7$ coating, the load was increased by a factor of three and the temperature in the contact has been increased to 210 °C. Comparing the respective results with those of a test carried out at standard load and temperature with the same coatings shows that such an elevated load and temperature do not seem to have an effect on the volumetric wear values.

### 3.2. Coefficient of friction

Using friction loops of force–distance curves to evaluate the friction coefficient would be very challenging in view of the very high sampling rate of 4 MHz (100 data points for one hysteresis with 40,000 hysterisis’s per second). Therefore, the power per cycle approach has been applied as described in the friction force measurement section. As the friction force values are deduced from the power the converter needs to vibrate the sonotrode, all depends on the accuracy with which these respective measurements are performed. The values marked with ‘b’ in Table 4 are based on a power measurement which has an accuracy of 1%. This corresponds to a change in power by ±1 W. The first tribological tests were carried out using this standard data output of the converter controller. However, at typical frequency and amplitude values this causes an error in the friction force of ±2 N. Assuming a load of 4 N, this causes a change in the COF values of ±0.5. Therefore, measures were implemented to access the full range of the built in D/A-converter. The values in Table 4 labelled with ‘c’ are deduced from tests carried out after this improvement of the power measurement device. The

---

**Table 3**

Volumetric wear values of long duration tests with strokes of about 5 μm and frequencies around 40 kHz under dry conditions

<table>
<thead>
<tr>
<th>Sonotrode/coating</th>
<th>Disc/coating</th>
<th>Load (N)</th>
<th>Cycles ($10^9$)</th>
<th>Distance ($10^6$ m)</th>
<th>$K_v$ sonotrode ($10^{-4}$ mm$^3$/Nm))</th>
<th>$K_v$ disc ($10^{-4}$ mm$^3$/Nm))</th>
<th>$K_v$ total ($10^{-4}$ mm$^3$/Nm))</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlMgZnCu1.5/Ti$_2$Cr$_2$O$_7$</td>
<td>AlFeXY/TM23</td>
<td>2.8</td>
<td>$1.08 \times 10^9$</td>
<td>1.14</td>
<td>$1.28 \times 10^{-4}$</td>
<td>$6.19 \times 10^{-4}$</td>
<td>$7.47 \times 10^{-4}$</td>
</tr>
<tr>
<td>AlMgZnCu1.5/Ti$_2$Cr$_2$O$_7$</td>
<td>AlFeXY/Ti$_2$Cr$_2$O$_7$</td>
<td>3.0</td>
<td>$5.96 \times 10^9$</td>
<td>0.64</td>
<td>$8.69 \times 10^{-5}$</td>
<td>$0.69 \times 10^{-4}$</td>
<td>$1.56 \times 10^{-4}$</td>
</tr>
<tr>
<td>AlMgZnCu1.5/Ti$_2$Cr$_2$O$_7$ (210 °C)</td>
<td>AlFeXY/Ti$_2$Cr$_2$O$_7$</td>
<td>9.4</td>
<td>$7.55 \times 10^9$</td>
<td>0.80</td>
<td>$7.53 \times 10^{-5}$</td>
<td>$9.59 \times 10^{-4}$</td>
<td>$1.70 \times 10^{-4}$</td>
</tr>
<tr>
<td>AlMgZnCu1.5/Ti$_2$Cr$_2$O$_7$</td>
<td>AlFeXY/Ti$_2$O$_3$/Ti$_3$O$_9$</td>
<td>3.1</td>
<td>$1.11 \times 10^9$</td>
<td>1.10</td>
<td>$2.40 \times 10^{-4}$</td>
<td>$1.38 \times 10^{-4}$</td>
<td>$3.78 \times 10^{-4}$</td>
</tr>
<tr>
<td>AlMgZnCu1.5/Ti$_2$O$_7$/Ti$_3$O$_9$</td>
<td>AlFeXY/Ti$_2$Cr$_2$O$_7$</td>
<td>3.4</td>
<td>$1.04 \times 10^9$</td>
<td>1.02</td>
<td>$9.11 \times 10^{-5}$</td>
<td>$1.05 \times 10^{-4}$</td>
<td>$1.96 \times 10^{-4}$</td>
</tr>
<tr>
<td>AlMgZnCu1.5/Ti$_2$Cr$_2$O$_7$</td>
<td>AlFeXY/Ti$_2$O$_3$/Ti$_3$O$_9$</td>
<td>3.0</td>
<td>$0.90 \times 10^9$</td>
<td>0.96</td>
<td>$1.74 \times 10^{-4}$</td>
<td>$0.50 \times 10^{-4}$</td>
<td>$2.24 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
accuracy could thus be improved by a factor of ten leading to systematic errors in the COF values of ±0.05. The values labelled ‘a’ are of tests performed after the latest improvement of the power measurement, which has now an accuracy of 4 mW corresponding to errors in the COF values of ±0.01.

The converter is operated close to and above resonance conditions. As soon as the sonotrode establishes contact, the friction force acts as a change in the damping of the system. The controller would then search for a more optimal point of operation, i.e., it would change the frequency. Close to resonance a change in frequency could affect the power needed to operate the converter. Therefore, power would change the frequency. Close to resonance a change in frequency could lead to errors in the COF values of Ti2Cr2O7. The amount of debris produced is pictured in Fig. 2e) and Fig. 4, respectively. In the case of the self-mated tests of the TM23 coatings and the Ti2Cr2O7 coatings the COF values observed above seem to be exaggerated due to a larger error in the power measurement. However, a COF value above unity can also be an indication of the formation of chemical bonds in the contact area. The relatively low starting value of the COF observed for the tests of the Ti2Cr2O7, respectively low starting value of the COF observed for the tests of the self-mated Ti2Cr2O7 at 210 °C could be a consequence of the high relative humidity of close to 100%. This experiment was the first to test the influence of relative humidity at high temperature in the newly constructed humidity and temperature facility. Unfortunately, the dimensions of its water reservoir were not sufficient to ensure a relative humidity close to 100% at 210 °C for a long duration test (30 days non-stop). Towards the end of the test, relative humidity was therefore close 0% due to the elevated temperature. In the case of the experiment with BAM-Trac lubrication involved, the accuracy of the then available power measurement equipment was not sufficient to obtain reliable friction force values.

### 4. Summary and conclusions

A novel ultra-high frequency tribometer has been designed to test tribo-active coatings such as Magnéli-type phases on novel AlFeCrTi-alloys as substrates. The tribometer has been designed

---

**Table 4**

Corresponding coefficient of friction at the start and end of the tests listed in Tables 3 and 4 with strokes of about 5 µm and frequencies around 40 kHz under dry conditions

<table>
<thead>
<tr>
<th>Sonotrode/coating</th>
<th>Disc/coating</th>
<th>Load (N)</th>
<th>Cycles (10^8)</th>
<th>Distance (m)</th>
<th>Friction force (N) start/end</th>
<th>COF ([1]) start/end</th>
<th>(K_t) total ([10^{-6} \text{mm}^3/(\text{Nm})])</th>
</tr>
</thead>
<tbody>
<tr>
<td>100Cr6H/-</td>
<td>100Cr6H/-</td>
<td>3.3</td>
<td>2.86</td>
<td>2.91 (10^3)</td>
<td>1.69/0.77</td>
<td>0.52/0.22</td>
<td>3.61 (10^{-2})</td>
</tr>
<tr>
<td>AlMgZnCu1.5/TM23</td>
<td>100Cr6H/-</td>
<td>3.5</td>
<td>1.70</td>
<td>1.71 (10^3)</td>
<td>2.65/2.32</td>
<td>0.76/0.66</td>
<td>1.21 (10^{-1})</td>
</tr>
<tr>
<td>AlMgZnCu1.5/TM23</td>
<td>AlFeXY/TM23</td>
<td>3.6</td>
<td>1.70</td>
<td>1.73 (10^3)</td>
<td>3.92/4.74</td>
<td>1.09/1.32</td>
<td>7.00 (10^{-1})</td>
</tr>
<tr>
<td>AlMgZnCu1.5/Ti2Cr2O7</td>
<td>AlFeXY/TM23</td>
<td>2.8</td>
<td>1.08 (10^3)</td>
<td>1.14 (10^3)</td>
<td>1.48/0.24</td>
<td>0.53/0.09</td>
<td>7.47 (10^{-4})</td>
</tr>
<tr>
<td>AlMgZnCu1.5/Ti2Cr2O7</td>
<td>AlFeXY/Ti2Cr2O7</td>
<td>3.0</td>
<td>5.96 (10^2)</td>
<td>6.64 (10^6)</td>
<td>1.42/5.97</td>
<td>0.47/1.99</td>
<td>1.56 (10^{-4})</td>
</tr>
<tr>
<td>AlMgZnCu1.5/Ti2Cr2O7 (210 °C)</td>
<td>AlFeXY/Ti2Cr2O7</td>
<td>9.4</td>
<td>7.55 (10^2)</td>
<td>0.80 (10^6)</td>
<td>0.45/3.71</td>
<td>0.05/0.39</td>
<td>1.70 (10^{-4})</td>
</tr>
<tr>
<td>AlMgZnCu1.5/Ti2Cr2O7</td>
<td>AlFeXY/Ti2Cr2O7</td>
<td>3.1</td>
<td>1.11 (10^3)</td>
<td>1.10 (10^3)</td>
<td>4.18/1.29</td>
<td>1.30/0.41</td>
<td>3.78 (10^{-4})</td>
</tr>
<tr>
<td>AlMgZnCu1.5/Ti2Cr2O7</td>
<td>AlFeXY/Ti2Cr2O7</td>
<td>3.4</td>
<td>1.04 (10^3)</td>
<td>1.02 (10^6)</td>
<td>1.25/0.08</td>
<td>0.17/0.02</td>
<td>1.96 (10^{-4})</td>
</tr>
<tr>
<td>AlMgZnCu1.5/Ti2Cr2O7</td>
<td>AlFeXY/Ti2Cr2O7</td>
<td>3.0</td>
<td>0.90 (10^3)</td>
<td>0.96 (10^6)</td>
<td>1.52/1.01</td>
<td>0.50/0.34</td>
<td>2.24 (10^{-4})</td>
</tr>
</tbody>
</table>

\(a\) Error ±0.01.
\(b\) Error ±0.5.
\(c\) Error ±0.05.
\(d\) Relative humidity close to 100% at the start of the test.

---

**Fig. 4.** TiO2/TiO2-coated sonotrode and the respective Ti2Cr2O7/AlFeXX disc before and after removing of wear debris.
for reciprocating sliding motion at 40 kHz with amplitudes of up to 5 \mu m. Commercially available devices have been included for measuring load, power, frequency and amplitude so that the coefficient of friction can be evaluated. Results of wear rates of coatings after 1.7×10^9 and up to 10^{11} cycles have been presented. The triboactive materials presented here exhibit the desired coefficients of friction around 0.5 and are partly free of adhesive wear mechanisms. The dry wear rates under linear oscillation of some triboactive materials lying in the range of 10^{-8} \text{mm}^3/Nm down to 10^{-10} \text{mm}^3/Nm were lower than those known from diamond thin film coatings. Nevertheless, the newly developed substrate materials and coatings fulfill or exceed the tribological requirements for the piezo-electric PIBRAC motor.

Acknowledgements

The authors are indebted to Sigrid Binkowski and Christine Neu mann, both of BAM, for providing the optical microscope images as well as for performing the 3D surface profile scans. Frantisek Zahalik of Škoda Vyzkum (Czech Republic) is thanked for supplying the coatings. Many thanks are extended to Dieter Schiefl of Martin Walter Ultrasonicall AG and Hans-Joachim Meissner of Rinco Ultrasons GmbH, both of Germany, for fruitful discussions on the converter control and for the simulations of the sonotrode. The financial support of the European Commission under the contract PIBRAC “PIezo BRake ACtuator” (AST4-CT-2005-516111) is gratefully acknowledged.

References


