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# Tribological Behaviour of Solid Lubricants in Hydrogen Environment

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## 1. Introduction

In a future energy supply system based on renewable sources hydrogen technology will play a key role. Because the amount of energy from renewable sources, such as wind or solar power, differs seasonally and regionally, an energy storage method is necessary. Hydrogen, as an environmentally friendly energy carrier, can fill this gap in an ideal way, in particular for mobile applications (Wurster et al., 2009). Already today, in Germany the amount of hydrogen as a byproduct in chemical industry is enough for fuelling about 1 Mio passenger cars<sup>1</sup>. Excess electrical power can be used to produce hydrogen by electrolysis. On demand, this hydrogen can be used for mobile or stationary fuel cells. Beside this new developing technology, hydrogen is used as fuel for rocket engines and in chemical industry since a long time. Table 1 comprises some physical parameters of hydrogen. It can be seen that hydrogen gas has a very low density which makes storage at high pressure or in liquid form (LH<sub>2</sub>) necessary.

Melting temperature		-259.35°C (13.80 K)
Boiling temperature (1.013 bar)		-252.87°C (20.28 K)
Gas densities	at 0°C, p = 1.013 bar	0.08989 kg/m <sup>3</sup>
	at boiling temperature	1.338 kg/m <sup>3</sup>
	density ratio H <sub>2</sub> /air	0.0695 kg/m <sup>3</sup>
Density of the liquid at boiling temperature		0.07098 kg/l
evaporation enthalpy at boiling temperature h <sub>l</sub>		0.915 kJ/mol
Heat conductivity (0°C; 1.013 bar)		0.1739 W/(m K)
Heat capacity of the liquid at boiling temperature		9.69 kJ/(kg K)
Specific heat (0°C; 1.013 bar)	c <sub>p</sub>	28.59 J/(mol K)
	c <sub>v</sub>	20.3 J/(mol K)
Critical temperature T <sub>c</sub>		-240.17°C (32.98 K)
Critical pressure p <sub>c</sub>		12.93 bar

Table 1. Physical parameters of hydrogen (Bulletin M 055, 1991 and Frey & Haefer, 1981)

<sup>1</sup> Supplement "Frankfurter Allgemeine Zeitung", March 22. 2011

With increasing utilisation of hydrogen it will be necessary to optimize components which are in contact with this medium. If these components contain tribosystems directly exposed to hydrogen they are critical in respect of excess wear, because of vanishing protective oxide layers in the presence of a chemically reducing environment. Furthermore, liquid lubricants are often not applicable, because of purity requirements, or very low temperatures in the case of liquid hydrogen. Thus, for numerous components in hydrogen technology, solid lubrication is the only possible method for reducing friction and wear.

Although the tribological behaviour of typical solid lubricants such as graphite, DLC, and MoS<sub>2</sub> has been characterized comprehensively (Landsdown, 1999; Donnet & Erdemir, 2004; Gradt et al., 2001), information about their suitability for hydrogen environment is very limited. Therefore, based on available literature and own measurements, an overview of solid lubricants and other materials for tribosystems in hydrogen environment is given in the following.

## 2. Tribosystems in hydrogen environment

Prominent examples for extremely stressed components in hydrogen environment are turbopumps for cryogenic propellants in rocket engines. They comprise numerous tribosystems, such as shaft seals or self-lubricated bearings, which have to work in hydrogen environment at low temperatures and high pressures. In the tribo-components of a turbopump various solid lubricants such as gold, silver, silver-copper alloy, PTFE, graphite, and MoS<sub>2</sub> or wear resistant coatings as WC, Cr, Cr<sub>2</sub>O<sub>3</sub>, and TiN are applied (Nosaka, 2011).

The LH<sub>2</sub>-turbopump of the LE-7 engine for the Japanese H-2 rocket has a flow rate of 510 l/s, a shaft power of 19,700 kW, and a rotational speed of 42,000 rpm. All steel bearings made from AISI 440C with lubrication by PTFE transfer from the retainer to the raceways showed sufficient performance. These bearings were operated at 50,000 rpm without severe wear (Nosaka, 2011). For better performance and rotational speeds up to 100,000 rpm hybrid ceramic bearings with Si<sub>3</sub>N<sub>4</sub> balls and steel rings are used. Such bearings were developed for the space shuttle (Gipson, 2001), the future VINCI launcher in Europe, and the Japanese LE-7 rocket engine (Nosaka et al., 2010). Hybrid ball bearings with ceramic balls can be operated up to 120,000 rpm in liquid hydrogen.

Hydrogen environment influences the friction behaviour of materials such as transition metals and metals that react chemically with hydrogen by building stable hydrides (Fukuda & Sugimura, 2008). In the case of transition metals, chemisorption is the main mechanism. The influence of hydrogen on the tribological properties of steels cannot be derived directly from these mechanisms, although the main components in steels are transition metals (Fukuda et al., 2011).

A general problem for materials, especially metals, exposed to hydrogen is environmentally induced embrittlement, which is also active in tribologically stressed systems. One example is embrittlement of raceways in ball bearings. The effect of hydrogen on the fatigue behaviour of bearing steel AISI 52100 was studied by Fujita et al. (2010). He investigated samples of steel under cyclic loading. Samples precharged with hydrogen showed a significant shorter lifetime, which could be attributed to the occurrence of an increased number of cracks.

However, hydrogen embrittlement is a general materials problem and not specific to tribosystems. Friction induced changes in the structure of steels that lead to embrittlement phenomena are treated in chapter 4. More specific to tribologically stressed surfaces is the

fact that oxide layers, which protect many metals against wear and corrosion, are not renewed after they are worn away. In the special case of tribosystems running in liquid hydrogen, the environmental temperature is 20 K (-253°C) and far too low for any liquid lubricant. In such cases, solid lubricants can be employed for reducing friction and wear. Also, in applications such as fuel cells or semiconductor fabrication, gaseous hydrogen of high purity is required and high demands on the outgassing of the materials are made, which usually cannot be met by liquid lubricants.

Commercial hydrogen gas contains a certain amount of water and oxygen. The influence of residual water in hydrogen gas on the fretting wear behaviour of bearing steel SUJ2 (similar to AISI 52100) was investigated by Izumi et al. (2011). These tests were performed in hydrogen and nitrogen gas with water content between 2 and 70 ppm. In both gases friction decreases, but wear increases with increasing water content.

### 3. Test devices for friction tests in cryogenic hydrogen environment

In general, test equipment for hydrogen environment has to meet the safety standards for handling this medium. In particular, explosion safe electrical installations, proper venting, gas tight experimental chambers, filling, and venting tubes are necessary. For liquid hydrogen also cryogenic equipment has to be employed. As examples two cryotribometers which are available at BAM<sup>2</sup> are shown in Figures 1 and 2 (Gradt, et al., 2001). Both cryotribometers are appropriate for liquid and gaseous hydrogen. The sample chambers are thermally insulated by vacuum superinsulation and cooled directly by a bath of liquid cryogen or by a heat exchanger.

In the case of CT 2 (Fig. 1) the liquid coolant is filled directly into the sample chamber (bath cryostat). The complete friction sample is immersed into the liquid cryogen and the environmental temperature is equal to the boiling temperature of the coolant (liquid nitrogen, LN<sub>2</sub>: 77.3 K; liquid hydrogen, LH<sub>2</sub>: 20.3 K; liquid helium, LHe: 4.2 K). The advantage of this method is a very effective cooling of the sample by making use of the heat of evaporation of the liquid.

Most of the tests are carried out by using the standard pin-on-disc configuration where a fixed flat pin or ball is continuously sliding against a rotating disc. The rotation is transmitted via a rotary vacuum feedthrough to a shaft with the sample disc at the lower end. In CT2 loading is performed by means of a gas bellow which acts on a frame with the fixed sample (pin) mounted on its lower beam. The mechanical stability of this assembly allows normal forces up to 500 N. The friction force is measured by means of a torque sensor on top of the motor journal or a beam force transducer integrated in the sample holder.

The sample chamber of the tribometer CT 3 is designed for pressures between 10<sup>-3</sup> mbar and 20 bar and cooled by a heat exchanger (continuous flow cryostat). The coolant is pumped through the heat exchanger, evaporates and removes heat from the inner vessel. Thus, it is possible to adjust the temperature between 4.2 K (with LHe cooling) and room temperature independently from the pressure. There is not limitation to an equilibrium state of the boiling coolant as in a bath cryostat. In hydrogen environment, the behaviour of tribosystems in gaseous or liquid environment as well as in the vicinity of the critical point can be investigated, which is of importance for the design of high performance hydrogen pumps.

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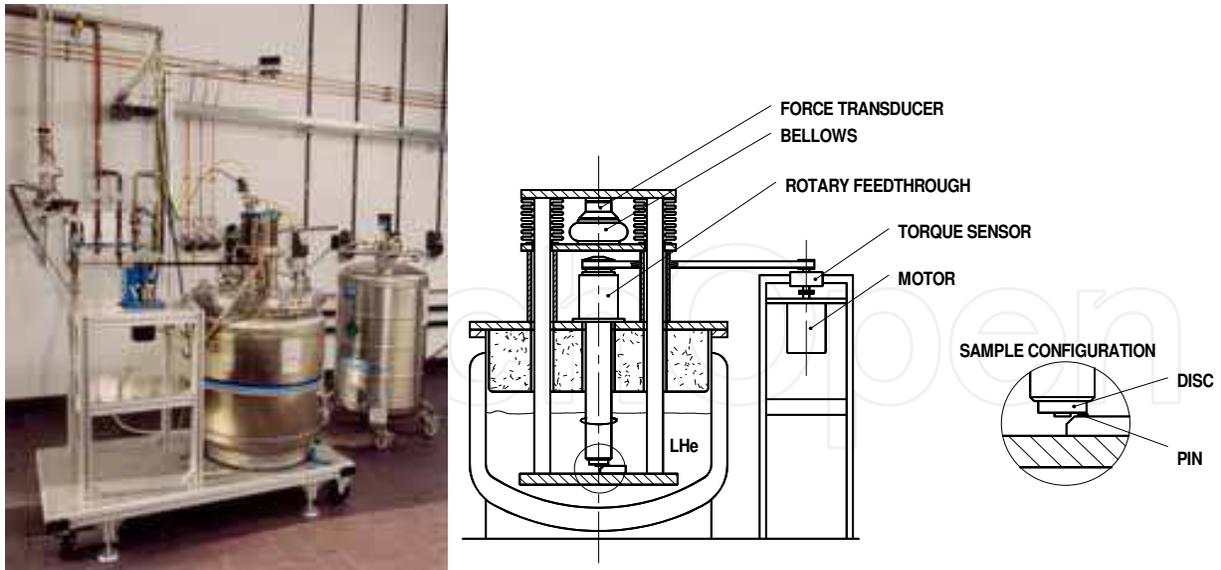


Fig. 1. Cryotribometer CT 2 (bath cryostat)

While in CT 2 the loading unit is located in the room temperature part of the apparatus, in CT 3 loading and force measurement is performed close to the friction couple in the cold part. Therefore, combined loading and measuring units are employed. The sample holder for the counterbody is directly mounted on a two dimensional beam force transducer for measuring normal and friction forces. Loading is accomplished by pressurized He-gas which acts on a piston that moves the beam with the sample holder upwards and presses the counterbody against the lower face of the rotating disk.

To remove any residual gases and condensed liquids, the sample chamber is evacuated to a pressure below  $10^{-3}$  mbar and filled with pure He-gas. The pump-down-refill cycle is repeated three times. During the experiment, the sliding force and the displacement of the pin are measured. After the measurement, the wear scars of both bodies can be examined by profilometry, light, electron, or atomic force microscopy.

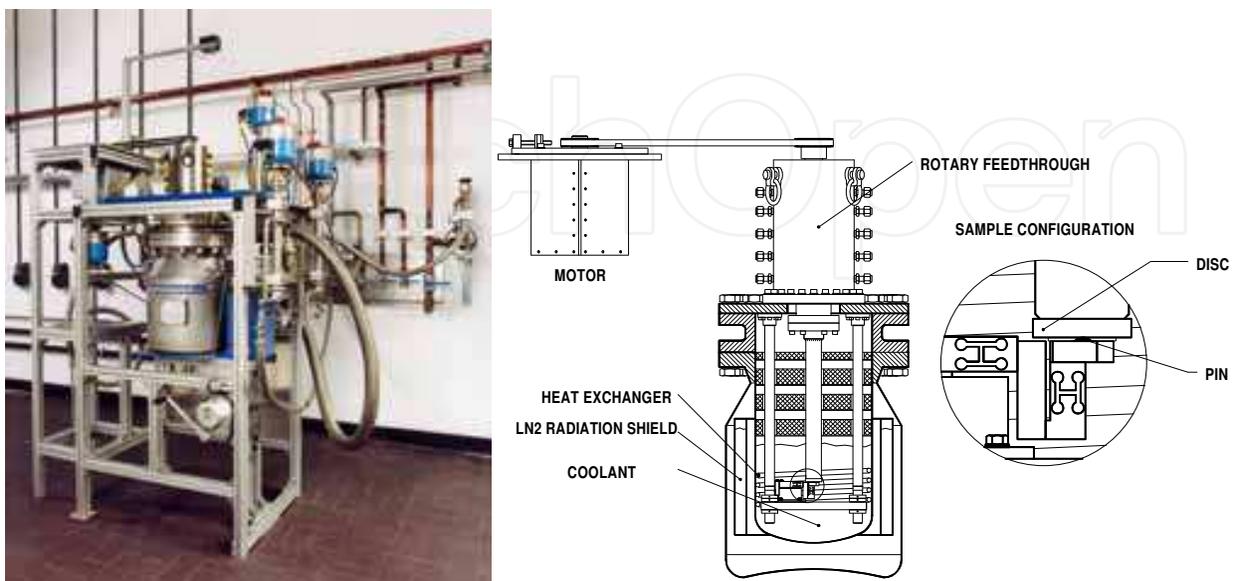


Fig. 2. Cryotribometer CT 3 (flow cryostat)

## 4. Tribological behaviour of metals in hydrogen environment

### 4.1 Soft metals as solid lubricants

Soft Metals such as gold, silver, lead, and indium can serve as solid lubricants. Thin films with good adhesion can be applied by ion-plating with an optimum thickness of about 1  $\mu\text{m}$ . The tribological properties of soft metals are similar in ambient air and vacuum environment with friction coefficients of about 0.1 and remain unchanged during cooling down to cryogenic temperatures. Furthermore, as they have a f.c.c. crystal structure, they are not affected by hydrogen embrittlement (Moulder & Hust, 1983) and therefore, applicable for tribosystems in gaseous and liquid hydrogen. However, in sliding friction in vacuum these materials have higher friction and wear than lamellar solids (Roberts, 1990, Subramonian et al., 2005).

### 4.2 Properties of steels in cryogenic hydrogen environment

A large number of ferrous alloys are employed for tribosystems, including those running in hydrogen environment. As many of these materials suffer from hydrogen embrittlement, they are treated in this chapter, although they are no solid lubricants. In particular, ferritic and martensitic steels with b.c.c. lattice are strongly affected by hydrogen. Austenitic FeCrNi alloys with f.c.c. structure don't show hydrogen embrittlement, and therefore, these alloys are the favoured materials in hydrogen technology. As these steels have good mechanical properties even at cryogenic temperatures they are also appropriate for components in contact with liquid hydrogen. However, in highly stressed tribosystems deformation-induced generation of martensite is possible, and the danger of embrittlement in these regions arises. Furthermore, an uptake of hydrogen can intensify the deterioration of the material. In an austenitic lattice solute hydrogen decreases the stacking fault energy (SFE) (Holzworth & Louthan, 1968). As a consequence, the deformation behaviour changes and the martensite generation is facilitated. In Fig. 3 (Butakova, 1973) the generation of martensite in tensile testing in dependence of the SFE for various FeCrNi-alloys is shown.

Therefore, it is necessary to investigate the tribological behaviour of austenitic steels in hydrogen-containing environments. The friction and wear behaviour in liquid hydrogen of the austenitic steels 1.4301 (AISI 304), 1.4439 (comparable to AISI 316), 1.4876, and 1.4591 (German materials numbers) was studied by Huebner, et al. (2003a). These FeCrNi alloys have different stability of their austenitic structure and are included in Fig. 3.

Steel 1.4301 is a metastable austenite. Its SFE is very low and thus, deformation-induced structure transformation is possible, even at room temperature. Steel 1.4439 is a so-called stable austenitic steel. Transformation is impeded because of its increased SFE. Finally, in materials 1.4876 and 1.4591 with very high contents of Ni, the SFE is rather high, and the generation of martensite should be impossible. As counterbodies  $\text{Al}_2\text{O}_3$  ceramic balls were used to avoid metal transfer to the steels samples. The austenitic steels were tested in inert environments at low temperatures and in  $\text{LH}_2$ . After the friction experiments, the transformation to martensite in the wear scars was detected by changes of the materials magnetic properties (magneto-inductive single-pole probe). This method has been shown to be sensitive enough to describe the transformation at a crack tip (Bowe et al., 1979).

The amount of martensite vs. temperature for 1.4301 is shown in Fig. 4. The amount of martensite strongly depends on the temperature with a maximum at about 30 K. Below this temperature the generation of martensite decreases. For this metastable steel, hydrogen environment was without any influence on the amount of austenite transformed into martensite (symbol  $\times$ ).

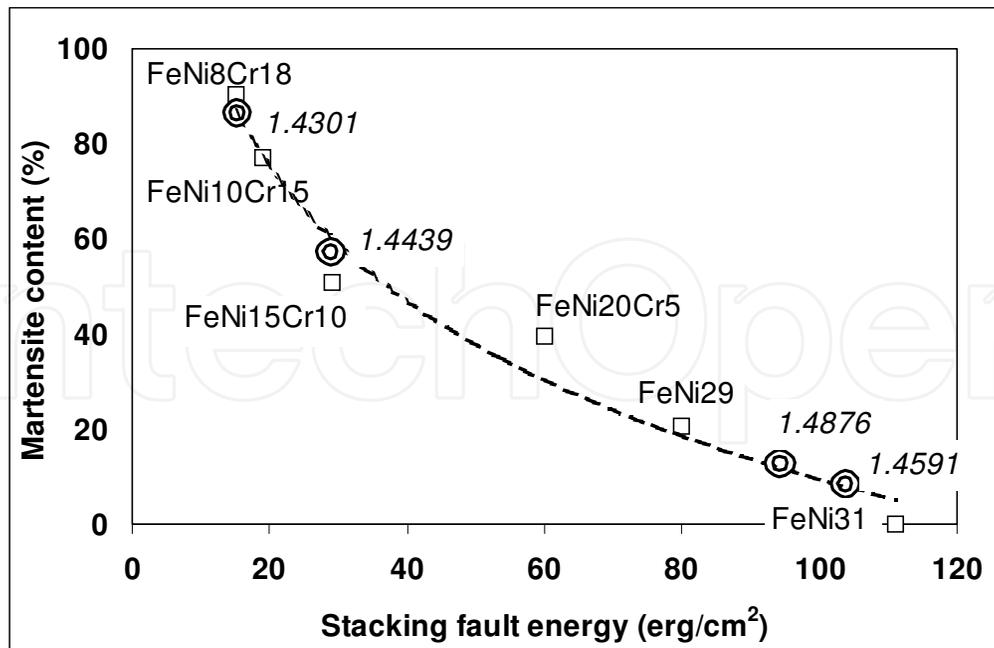


Fig. 3. Influence of the SFE of austenitic FeNiCr alloys on the martensite volume fraction after 80% plastic deformation in tensile testing (according to Butakova, 1973)

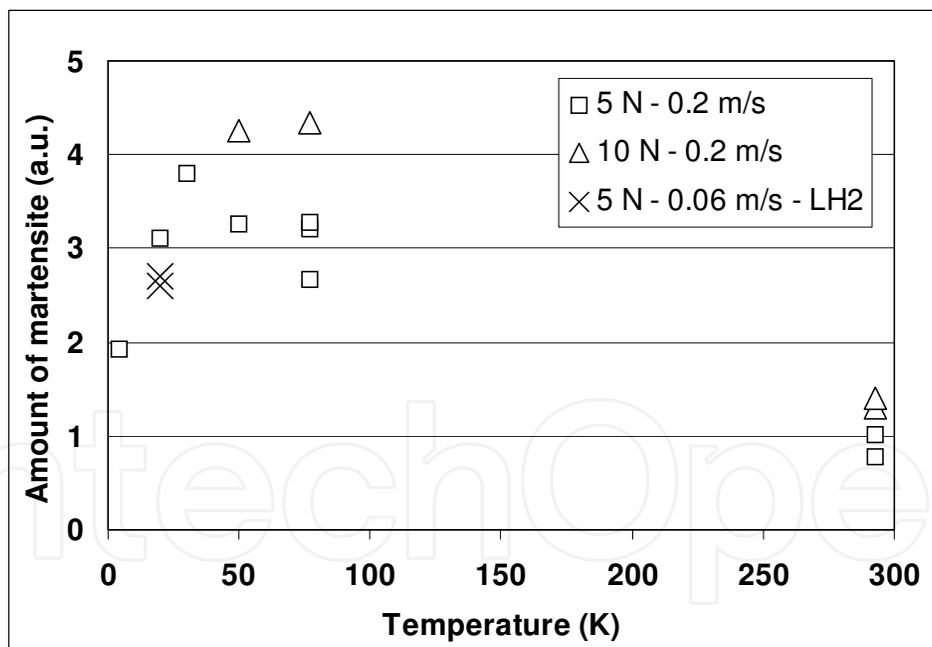


Fig. 4. Steel 1.4301, Temperature-dependence of friction-induced generation of martensite

Contrary to steel 1.4301, the transformation behaviour of the steel 1.4439 showed a distinct influence of the environment (Fig. 5). In LN<sub>2</sub> and at 20 K in gaseous He, only local magnetisation was detected in the wear scars (symbols: □, Δ). It could be shown by scanning electron microscopy that locations with magnetic signals correspond to extremely deformed transfer particles (Hübner, 2001). After a test in liquid hydrogen (symbol: +), magnetic changes were observed in the entire circular wear track.

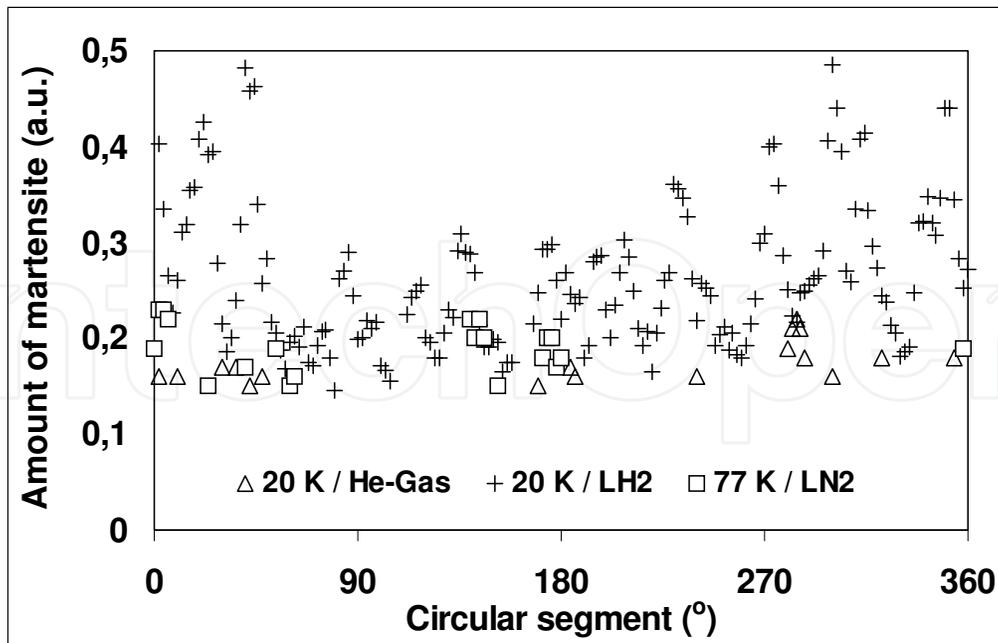


Fig. 5. Steel 1.4439, Influence of hydrogen on the generation of martensite during friction

After the tests in inert environment, extremely deformed wear debris was found all over the wear track. However, these particles did not show any embrittlement. After sliding in hydrogen, the surface showed completely different features. The wear scar exhibits a net of microcracks (Fig. 6). This topography was detected for all austenitic alloys chosen for these experiments, even for the highly alloyed materials 1.4876 and 1.4591. This is clear indication for the occurrence of hydrogen induced embrittlement, even in LH<sub>2</sub>. These findings could be confirmed by measurements of residual stresses in the deformed zone (Hübner et al., 2003b).

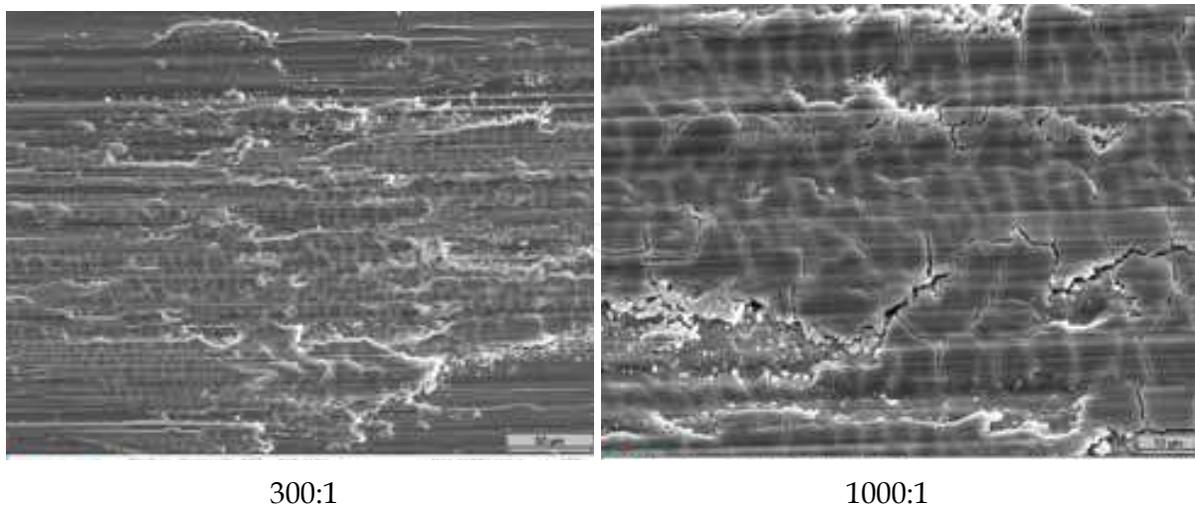


Fig. 6. Steel 1.4591, SEM images of the wear track; net of brittle cracks in the wear scar after frictional stressing in LH<sub>2</sub>

For influencing the deformation behaviour, it is necessary that atomic hydrogen exists in the material. In LH<sub>2</sub> thermally initiated dissociation is not possible. Thus, the dissociation process could only be activated by mechanical energy from sliding.

The influence of hydrogen on the deformation mechanisms is also visible in the shape of the X-ray diffraction line profiles. Fig. 7 shows the  $\gamma_{311}$  reflection of the austenitic steel 1.4876 after sliding in air, LHe, and LH<sub>2</sub>. The reflection profiles of the tests in air and LHe are symmetrical. They exhibit only deformation-induced broadening. However, in LH<sub>2</sub> an asymmetry occurs, which is a clear indication for hydrogen uptake. Hydrogen lowers the stacking fault energy of the austenite lattice, which enhances the building of the epsilon phase (Whiteman & Troiano, 1984, Pontini & Hermida, 1997).

Gavriljuk et al. (1995) described in detail how hydrogen influences the transformation behaviour of unstable as well as stable austenitic steels. In so-called unstable steels, already cold working induces phase transformation. Stable steels may be subject to structure changes after charging with hydrogen, which causes a decrease in SFE. These explanations are in good agreement with the results shown in Figures 4 and 5. A significant influence of hydrogen on the austenite-martensite transformation is observed only in the stable steel (Fig. 5), because the metastable steel 1.4301 (Fig. 4) experiences structure changes already during the low-temperature deformation.

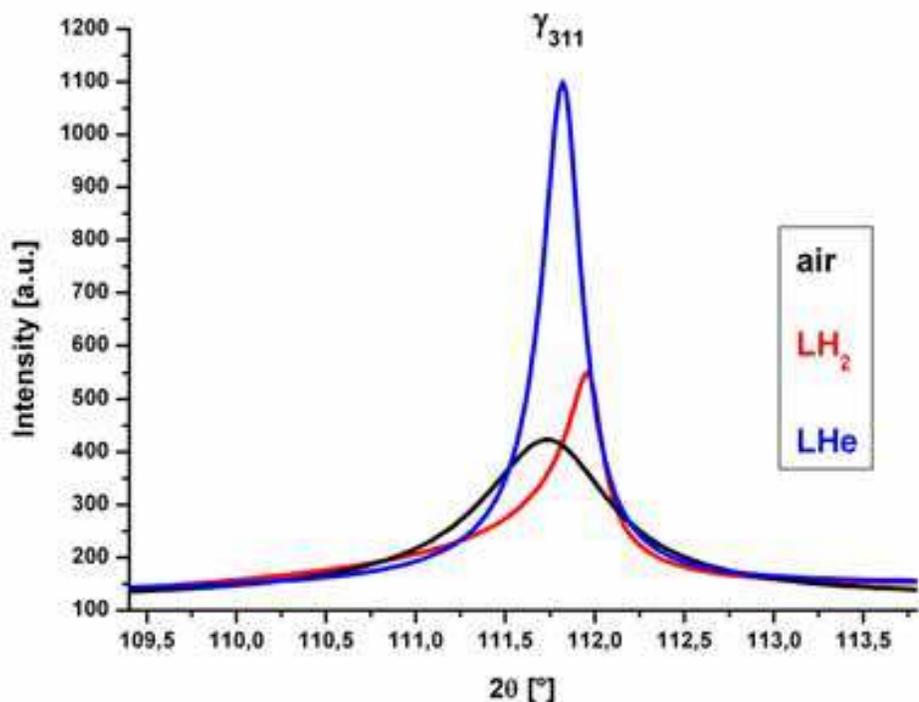


Fig. 7. Steel 1.4876, Asymmetry of the  $\gamma_{311}$  reflection of the after frictional stressing in LH<sub>2</sub>

Beside deformation enhanced creation of martensite, also other mechanisms can lead to increased wear in austenitic stainless steel. Kubota et al. (2011) reported a reduction of the fretting fatigue limit in hydrogen gas for steel AISI 304. He found that small cracks which were stable in air propagated in hydrogen gas. The reason for this effect was an increased local adhesion in hydrogen environment.

#### 4.3 Other metals

The tribological properties of Zr and Nb in hydrogen environment were investigated by Murakami et al. (2010). Coatings of Zr-alloys on high strength steels are considered as a diffusion-barrier for hydrogen. Furthermore, Zr forms hydrides which have the same

structure as  $\text{CaF}_2$ , which can be used as solid lubricant. As  $\text{NbH}_2$  has a lattice structure similar to  $\text{CaF}_2$  it may also have lubricating properties. Pure Zr and Nb were tested as self-mated pairs in pin-on-disc tests with a sliding speed of  $3.49 \times 10^{-2} \text{ ms}^{-1}$  and loads of 25 and 70 N. Both materials showed lower friction coefficients in  $\text{H}_2$  gas atmosphere than in air, He gas, and vacuum. In  $\text{H}_2$ -gas atmosphere the friction coefficients of the Nb specimens were much higher than those of the Zr specimens. X-ray diffraction analysis showed that the wear particles, which were formed by sliding Zr and Nb specimens in the  $\text{H}_2$  gas atmosphere, consisted mainly of the  $\text{ZrH}_2$  phase ( $\epsilon$  phase) and  $\text{NbH}$  phase ( $\beta$  phase), respectively. X-ray diffraction analysis also showed that the wear particles, which were formed by sliding in air, consisted mainly of the  $\alpha\text{Zr}$  and Nb phases, respectively.

## 5. Solid lubricant coatings

An amorphous carbon (DLC-), a  $\text{MoS}_2$ -coating, prepared by physical vapour deposition (PVD), and two types of anti-friction coatings (AFC 1 and AFC 2) were tested in dry and humid  $\text{N}_2$ -,  $\text{H}_2$ -, and  $\text{CH}_4$ -environment at BAM (Gradt & Theiler, 2010). In dry gas, the residual water content was in the ppm-range. In humid environment the relative humidity was close to 100%. The solid lubricant in both AF- coatings was PTFE. The tests were performed in ball-on-flat configuration in reciprocating sliding at room temperature. The test parameters are given in Table 2.

Substrate	100Cr6 (AISI 52100)
Coatings	DLC, $\text{MoS}_2$ , AF-Coatings (lubricant: PTFE)
Counterbody	uncoated ball, $d = 4 \text{ mm}$ . X90CrMoV18 (AISI 440B)
Environment	$\text{N}_2$ -, $\text{H}_2$ -, $\text{CH}_4$ -gas, dry/humid
Gas pressure, bar	3
$F_N$ , N	5; 10
Stroke, $\mu\text{m}$	200
Frequency, Hz	20
Test duration	2 h (144,000 Cycles)

Table 2. Test parameters, solid lubricant coatings

Fig. 8 summarizes the measured friction coefficients in the miscellaneous environments. The carbon coating shows a distinct sensitivity to the humidity. While in dry gases the friction coefficient is about 0.15, it rises to 0.19 to 0.25 in humid environment. Also the wear of this type of DLC-coating rises under high humidity, as can be seen in Figures 9 and 10. Fig. 9 shows an SEM-image of a wear scar after a test in hydrogen of high humidity. The complete coating is worn away, and abrasive wear of the substrate is visible. Fig. 10 shows an image of a wear scar after the same sliding distance in dry hydrogen. It can be seen that the coating is still intact, and the wear track has a very smooth, polished-like surface.

Both AF-coatings showed friction coefficients around 0.15 in dry hydrogen and nitrogen. They have not been tested in these gases with high humidity. Such comparative measurements were done in methane gas. It can be seen that AFC 1 reaches a low friction coefficient of 0.08 in dry and humid  $\text{CH}_4$ . Thus, this coating is sensitive to the particular type

of gas and not to general chemical reactivity or humidity. AFC 2 also changes its frictional behaviour in  $\text{CH}_4$ . However, while methane seems to have a beneficial effect on AFC 1, it causes an increasing friction of AFC 2.

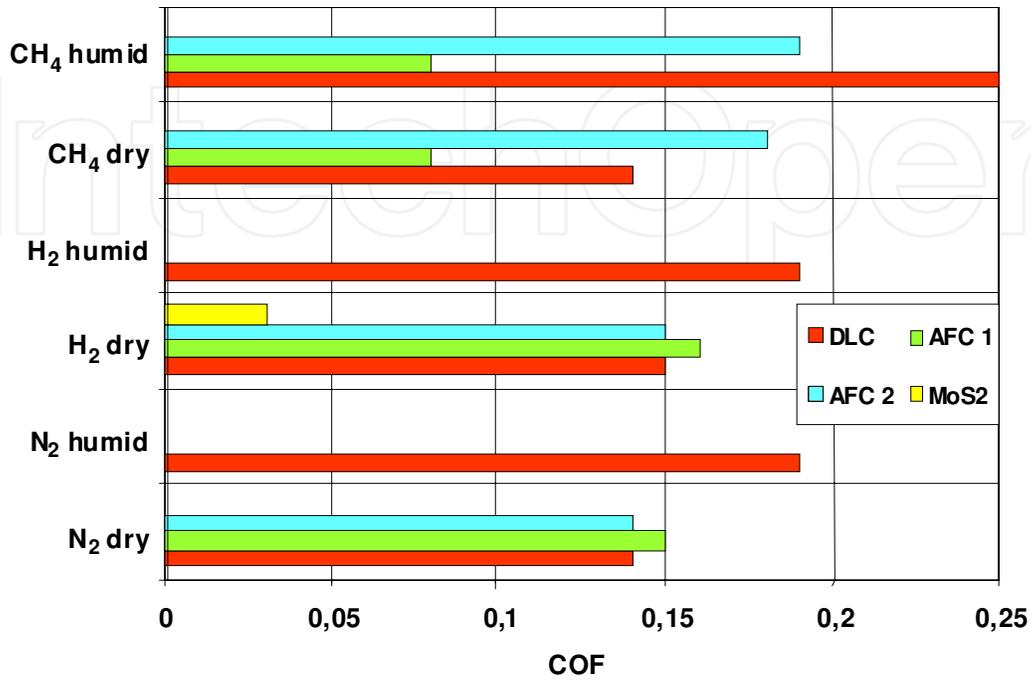


Fig. 8. Friction coefficients of several solid lubricants in inert and reactive gaseous environment

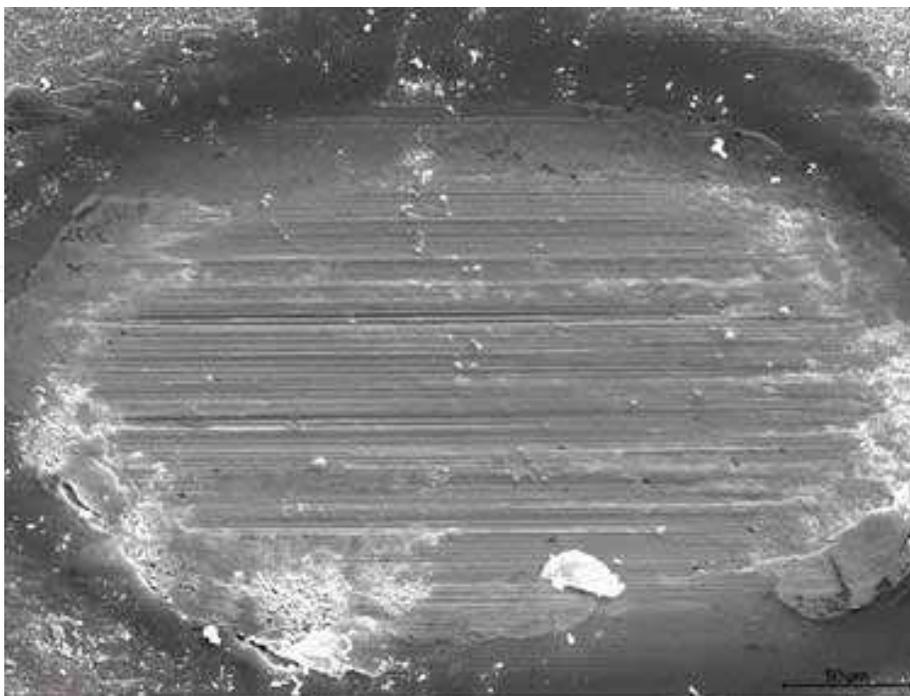


Fig. 9. Coating failure of a DLC-coating after a reciprocating sliding test in humid  $\text{H}_2$ -environment (SEM-image of the wear scar)

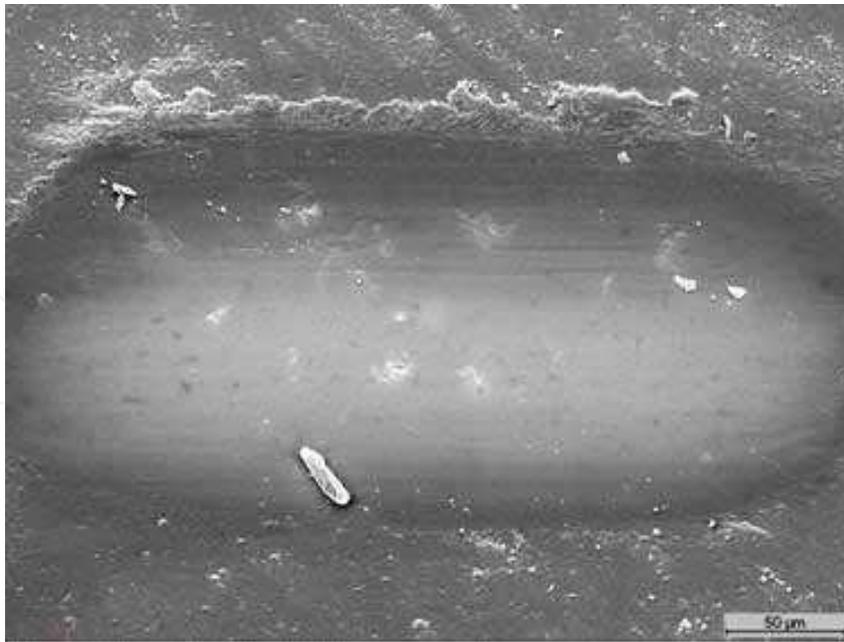


Fig. 10. Smooth wear track of the a DLC-coating after a reciprocating sliding test in dry  $H_2$ -environment (SEM-image of the wear scar)

The lowest coefficient of friction ( $COF = 0.03$ ) was observed for  $MoS_2$ . This coating showed a very smooth sliding behaviour with nearly no running-in. Fig. 11 shows the development of the COF of the three tested  $MoS_2$ -coatings in comparison to DLC. The DLC-coatings showed a higher COF and a pronounced running-in behaviour. However, the lifetime of the  $MoS_2$ -coatings was much shorter than that of DLC and not sufficient in the scope of this test series, where more than 100,000 cycles were necessary. Therefore, no further tests in other environments were carried out. Nevertheless, for dry sliding tribosystems, where a lifetime of 10,000 friction cycles is sufficient,  $MoS_2$ -lubrication seems to be applicable in hydrogen environment.

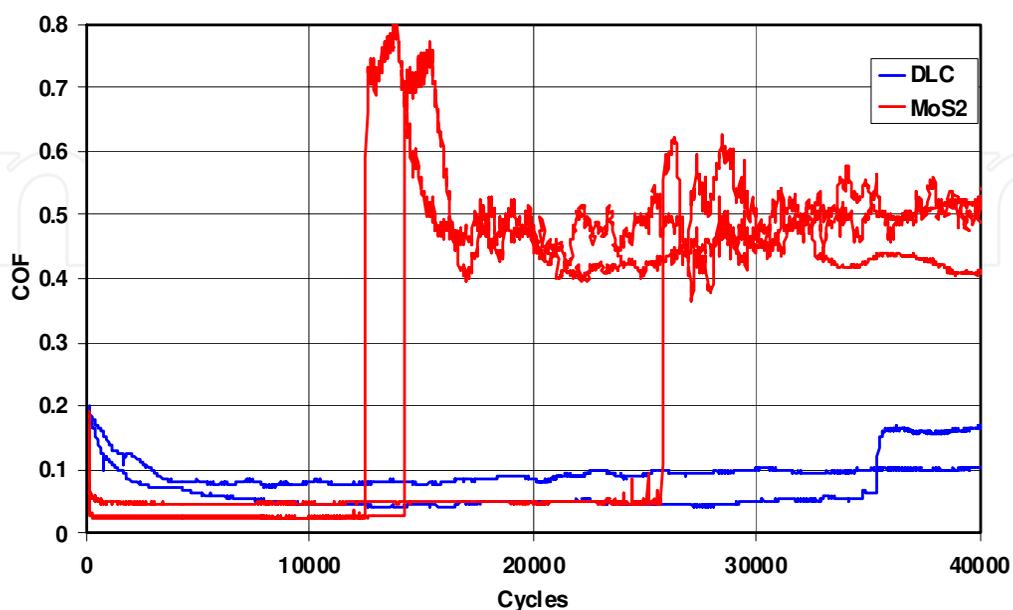


Fig. 11. Oscillating friction of DLC- and  $MoS_2$ -coatings in gaseous hydrogen

## 6. Solid lubricants in polymer composites

Polymers and polymer composites are widely used as dry sliding materials in friction assemblies where external supply of lubricants is impossible, or not recommended. The field of application of self-lubricating materials in tribological systems is considerably extending also to extreme environments (Gardos, 1986). Over the years, composite materials have replaced many traditional metallic materials in sliding components. They offer not only low weight and corrosion resistance, but also excellent tribological properties. In view of hydrogen technology, numerous polymer composites containing PTFE, MoS<sub>2</sub>, and graphite respectively have been tested in hydrogen and inert media such as nitrogen and helium (Theiler & Gradt, 2007). Some of these materials were also tested in liquid hydrogen. Fig. 12 shows the test configuration, and Table 3 summarizes the materials and test parameters. The material compositions are given in the figures of the test results below.

Polymer matrix	PTFE: polytetrafluoroethylene PEEK: polyetheretherketone PI: polyimide PA: Polyamide PEI: polyetherimide EP: epoxy
Fibers	CF: carbon fibers
Fillers	PEEK, PPS bronze TiO <sub>2</sub>
Lubricants	PTFE, MoS <sub>2</sub> , graphite
Normal load, N	16; 50 N
Sliding speed, m/s	0.2
Sliding distance, m	2000

Table 3. Materials and test parameters, polymer composites

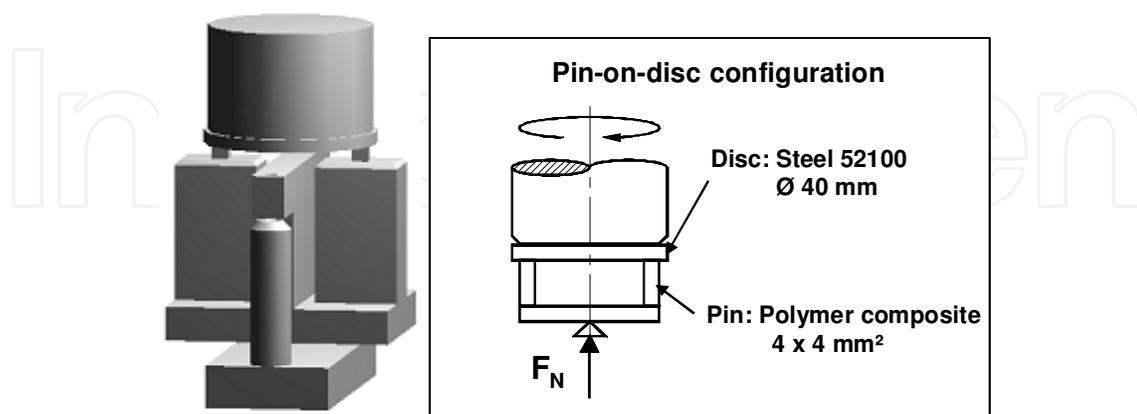


Fig. 12. Sample configuration for tests of polymer composites

Fig. 13 shows the friction coefficient of various polymer composites against steel in air and liquid hydrogen (Theiler & Gradt, 2007). Except the first one, all tested composites have lower friction in LH<sub>2</sub> than in air at room temperature. A decrease of friction at lower

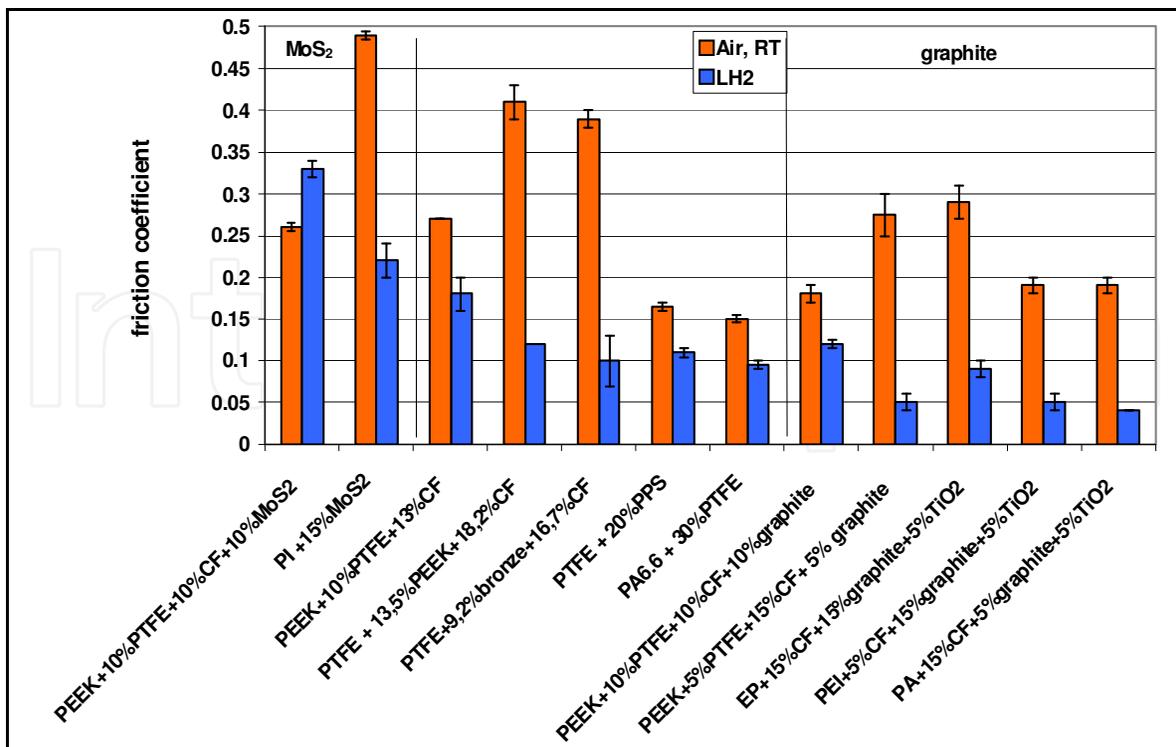


Fig. 13. Sliding friction of polymer composites against steel (Theiler & Gradt, 2007)

temperatures is observed for many polymers and is due to the fact that hardness and Young's modulus of the polymers increase with decreasing temperature. Both lead to lower deformation and a smaller real area of contact. This causes a lower shearing force at the interface and thus a lower friction (Theiler et al., 2004).

Another tendency is that graphite containing composites have the lowest friction coefficients in liquid hydrogen, in one case even lower than 0.05. On the other hand, composites containing MoS<sub>2</sub> don't reach values below 0.2. Thus, for hydrogen applications graphite seems to be a much more efficient component for improving the lubricating properties of polymers.

The friction coefficients of the composites without graphite or MoS<sub>2</sub> are between 0.1 and 0.2 in LH<sub>2</sub> which is sufficient for many applications. All materials of this group contain PTFE, which also acts as a solid lubricant. In some cases, the large difference between ambient air and LH<sub>2</sub> is a possible drawback for practical application.

A comparison of the friction coefficients in liquid hydrogen, hydrogen gas, and ambient air at room temperature for two composites with PTFE- and two with PEEK-matrix is shown in Fig. 14. The materials with PTFE-matrix show a large difference in COF between normal air and hydrogen environment and no significant influence of the temperature. This difference is much smaller for the PEEK materials with additions of PTFE. Additional admixture of graphite leads to a COF of about 0.15, which depends only very little on the environment. Although the other composites exhibit lower friction under certain conditions, this low dependence on the environment makes the graphite containing composite a most suitable material for hydrogen applications.

The wear behaviour of the PTFE- and PEEK-composites follows a similar tendency. As shown in Fig. 15, the wear rate of the two materials without graphite is much smaller in hydrogen environment than in air. The wear of the graphite containing material is not significantly influenced by the environment. Furthermore, a wear rate below 10<sup>-6</sup> makes this material suitable for application in sliding bearings or in cages for roller bearings.

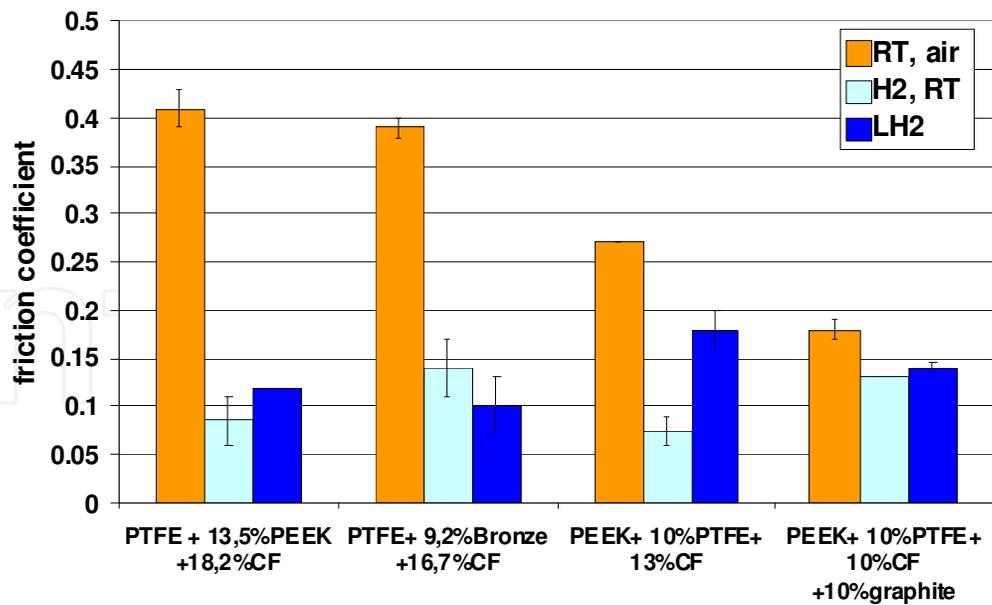


Fig. 14. Friction of polymer composites in air and H<sub>2</sub>

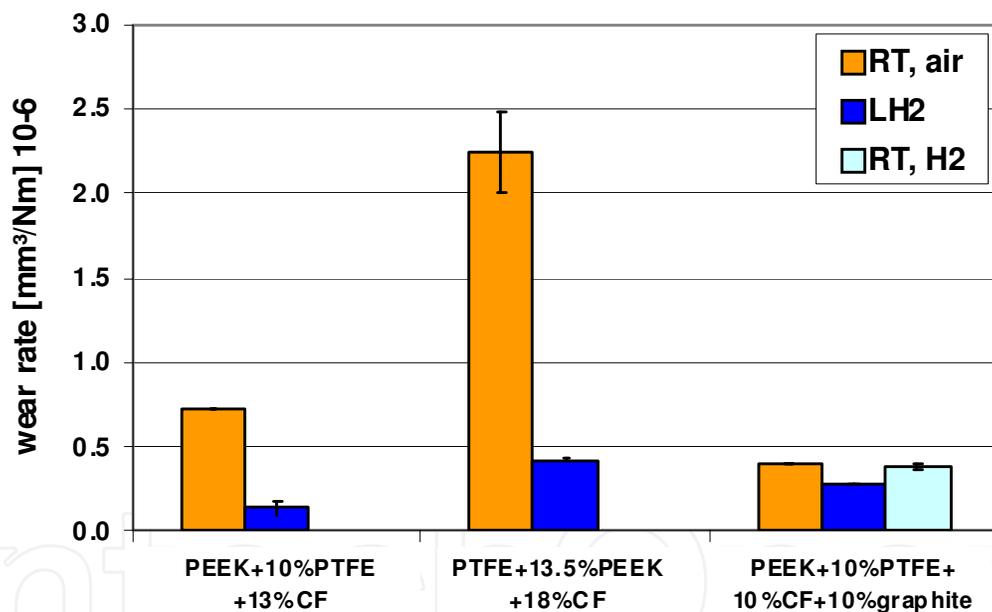


Fig. 15. Wear of polymer composites in air and H<sub>2</sub>

## 7. Conclusion

Tribosystems directly exposed to hydrogen are critical in respect of excess wear, because they may experience hydrogen embrittlement, chemical reactions to hydrides, and vanishing protective oxide layers respectively. Furthermore, liquid lubricants are often not applicable, because of purity requirements, or very low temperatures in the case of liquid hydrogen.

Hydrogen uptake and material deterioration influences wear processes also in austenitic stainless steels. Hydrogen lowers the stacking fault energy of the austenite lattice, which enhances the building of deformation induced martensite that is prone to hydrogen embrittlement.

For numerous components in hydrogen technology solid lubrication is the only possible method for reducing friction and wear. Solid lubricants such as PTFE, graphite, DLC, and MoS<sub>2</sub> applied as coatings, or as components in polymer composites, in general are able to reduce friction and wear in gaseous as well as in liquid hydrogen.

MoS<sub>2</sub>-coatings have low friction, but a very short lifetime in hydrogen environment. The tested carbon coating showed higher friction, but a much longer lifetime in dry environment. In humid environment this type of coating fails rapidly.

PTFE-based anti friction (AF-) coatings exhibit low friction and a negligible sensitivity to humidity. However, the type of gas influences their frictional behaviour, independent of the humidity.

In general, friction coefficients and wear rates of polymer composites decrease with decreasing temperature. Also hydrogen has a beneficial effect on the friction behaviour of polymer composites. The addition of graphite leads to a favourable tribological behaviour which is not significantly influenced by the environmental medium. This makes graphite-containing PEEK-composites most suitable materials for hydrogen applications.

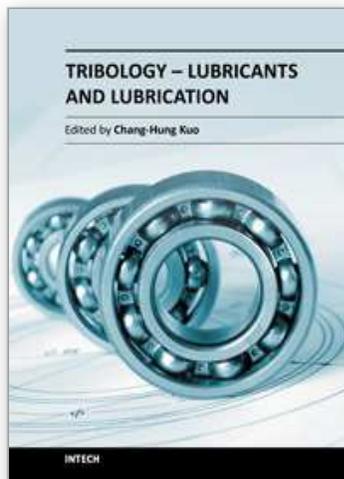
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In the past decades, significant advances in tribology have been made as engineers strive to develop more reliable and high performance products. The advancements are mainly driven by the evolution of computational techniques and experimental characterization that leads to a thorough understanding of tribological process on both macro- and microscales. The purpose of this book is to present recent progress of researchers on the hydrodynamic lubrication analysis and the lubrication tests for biodegradable lubricants.

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