Solid Bonded Films or Monolithic Ceramics in Tracked Chains of Construction Equipments for Wear Management

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ABSTRACT

Unlubricated tracked chains were realized using soft solid bonded films for the inner wear of the tribosystem of bushing/pin and monolithic ceramic bushings for the outer wear of the tribosystem bushing/sprocket.

Both novel approaches were tested on D6 22-to. dozers. Selected solid bonded films and specific monolithic ceramics, offer a potential for simplifying the design, reducing weight and designing a dry-running longlife chains. These results can be further transferred to high-speed running gears or belt drives .

1. INTRODUCTION

The tribosystems in construction equipment, where as they consists of many different metallic materials, are lubed using extreme pressure greases or oils. The thoughts to design them unlubricated were favored by the experience, that natural minerals act abrasive againts seals in polymeric materials, thus leading to leackage and limiting their life-time.

The wear of the sprocket and the bushing define the total wear of a tracked chains in contruction [1] equipment. In general for dozers and excavators, that the bushing wear of heat treated steels, depending from the operating conditions, is roughly the two to three times greater than the wear of the chain links.

To achieve at least close to equal wear resistances of bushing and track link, investigations have been started to substitute the steel bushing by ceramics.

It is common practice the “turn” weared bushing in order to use them a second time. Also the operators run the machine until the bushing is completely weared-off and the sprocket runs directly on the pin (See Figure 1 and Figure 2). The oil or grease lubrication will collapse. This motivated to study dry running tracked chains.

Another life-time criteria of tracked chains is the chain elongation due to the wear between the pin and the inner side of the bushing.

In order to solve the wear issues, the following generic questions raized-up, if

a. soft surfaces or
b. hard surfaces

have to be used.

Paper presented at the RTO AVT Specialists’ Meeting on “The Control and Reduction of Wear in Military Platforms”, held in Williamsburg, USA, 7-9 June 2003, and published in RTO-MP-AVT-109.

Figure 1 : D6D-Buschings in steel and monolithic ceramics having typical wear patterns and a weared D4D-Bushing

Figure 2 : Typical wear patterns observed in the field

These topics became predominating, since from research [2,14] it is known, that alternative high alloyed steels offer no significant potential for wear redudtion over the existing speciallized steels used in actual designs of tracked chains.

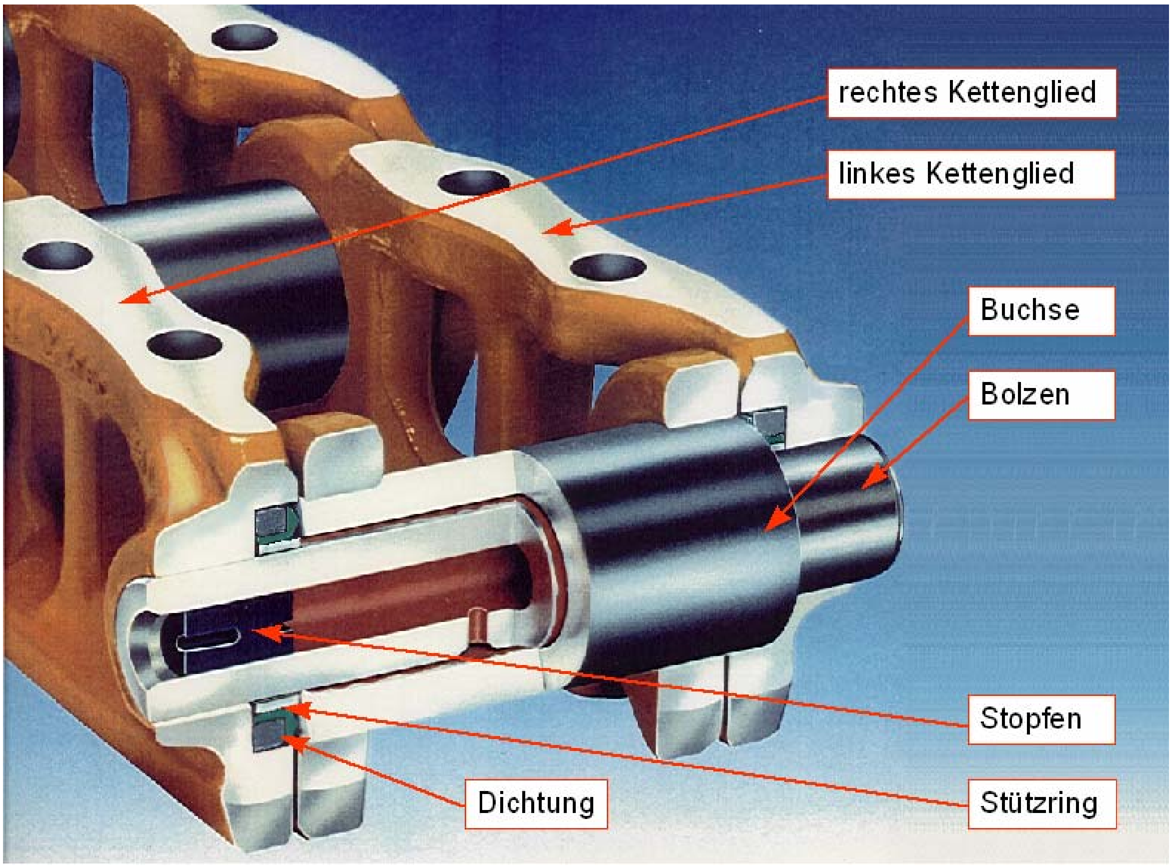

Figure 3: Section through a segment of an oil-lubricated crawler chain (Photo: Intertractor-Passini Group).

2. RUNNING TESTS OF CHAIN LINKS LUBED BY SOLID BONDED FILMS

2.1. Staring point

In the links of crawler and dozer tracked chains, the inside of the bushing form a tribological system with linear contact against the outside of the pin. In a typical "D6" chain size (Bushing $\varnothing_{outer}$= ~66,57 mm, length = ~171,45 mm), peak forces between 80 kN and 150 kN are exerted within this tribological system. To reduce the coefficient of friction, avoid adhesive wear and minimise the wear rate (chain elongation, extension of chain life), the links are individually greased or oil-lubricated in sealed systems (See Figure 3). The only friction condition obtaining is mixed or boundary lubrication. This type of lubrication requires sealing systems to prevent leakage of lubricants and the ingress of mineral particles. Special polymer radial shaft sealing rings seal off oil-filled chain links to the outside, and these seals are subject to abrasive wear.

The oil lubed chain guarantees a life-time operation, whereas the grease lubed chains gives more a life increase compared to dry ones. Both solutions reduce operating noises during bending of the chain links, but the seals are sensitive to abrasives.

2.2. Current technology

With undercarriages remaining unchanged in size, increased vehicle weights and increased driving speeds necessarily place greater stresses on the links in the tracked chains. To cope with these stresses, greases or oils containing MoS_2 or EP (extreme pressure) are now in standard use.

A disadvantage of grease lubrication is that, all of the greases of the various NLGI classes (consistency classes) cover only a restricted temperature range. For example, at temperatures up to minus 15°C an NLGI class 2 lithium-saponified, "soft" grease containing 3% MoS_2 by weight is used. There has therefore long been a desire to find a grease-free solution.

Table I: State-of-the-art grease concepts for tracked chains

Brand name of greases	NLGI-class	Base fluid	Additives	Thickener	Dropping point [°C]
Biotrac [3] (Blue Angel)	2	Rapseeded esters	:/.	Bentonite (gel)	n.d.*
Kubinol 3261	2	Mineral oil	MoS_2	Lithium soap	185
Komatsu [4] (Non-black grease)	2	Mineral oil	Phosphate glass	Lithium soap	>260
BEL-Ray [5] Molylube PA TP	0000	Synthetic hydro-carbon (PAO)	MoS_2 (~3 w.-%)	Aluminium soap (gel)	--
Remarks: * n.d., because operating temperature is limited to >95°C					

The greases of Komatsu, Bel-Ray and Kubinol states different lubrication concepts regarding the consistence of the greases. Only Bel-Ray favors a soft grease (flow grease), which will consequently flow into any place (especially at low temperatures and assure lubrication) and the synthetic hydrocarbon guarantees a higher thermal stability than the mineral oils. This philosophy reduces, when frictional overheating occurs, the formation of black residue coming from the mineral oil. The higher price for the synthetic hydrocarbon can be compensated with the cheaper aluminium soap. An aluminium soap grease is not a high quality high-temperature grease compared to the lithium soap ones.
If due to overheating the grease decomposes, than the MoS_2 particles will aggregate.
The degradation or leakage of grease or of oil results in wear and thus chain elongation, and generates unwanted noise, leading to customer complaints.

The original approach to using solid bonded films as a substitute for grease or oil-lubricated chain links was based on solutions used to remedy certain customer complaints, as well as on findings from tribotesting about the tribological behaviour of solid bonded films subjected to mineral dust. These had shown that solid bonded films containing MoS_2 [CAS no. of hexagonal MoS_2: 1317-33-5] in a poly(imideamide) binder proved to be exceptionally wear resistant when subjected to fine "Turkey" and "Arizona" sand. In other word: the dust didn ´t increase the wear rate compare to dust-free tribotests. The concept of a solid bonded film lubricated chain links was refined and patented as EP 1 065 138 A2 (JP2001080551, US 6,450,594).

Alternative to solid bonded films, hard thin film coating film were proposed with thicknesses of < 8 µm on the inner bushing side in patent US 6,045,200 by Caterpillar. They consist of chromium nitride and chromium carbo-nitrides. The deposition technique by spin-dipping of solid bonded films is more suited for large volumes and cost effective than a vaccuum based technique.

Figure 4 : Unstressed pin (D6) with Te'Strake 7409 heat curing solid bonded film

2.3. Objective

The aim of the project was to develop a dry-lubrication concept suitable for tracked chain applications, which could be used as a standard dry solution in any size of undercarriages over a temperature range from -20°C to +100°C, and which could also be extended for use in special versions from –40°C to +200°C, without exceeding the comparative component costs of the grease or oil-based options.

In the case of oil-lubricated chains, it was necessary to test whether a dry lubrication concept would also function on its own, or whether it would be useful only in terms of enhancing performance or extending chain life. Use of a dry variant on its own would allow the deep bore in the pin to be dispensed with, and would also remove the risk of internal oil pressure build-up.

The change in function from a grease or oil seal to a dust seal should allow additional cost savings to be made. The customary tribological properties (load-bearing capacity, chain elongation, low friction/heating-up of links) should be unchanged or improved.

2.4. Solid bonded film coated components

To provide a practical demonstration of the operational capability of the dry-lubrication concept, the outsides of the pins and the insides of the bushings were coated by Te'Strake Deutschland GmbH (S. Figure 3). The dimensions of the chain links conformed with "Pro6". The stylus profile measurements show a single solid bonded film on the steel substrates, with an optimum pre-coating roughness of C.L.A.~ 0.5 µm. The areas of the press fitting were not coated and no corrosion protection coating had been applied.

2.4.1. Solid bonded film

A solid bonded film, containing at least 20-25% MoS_2 by volume, is applied in a continuous process to the surfaces of the bushings and pins which form the tribological system. MoS_2 protects the tribological system from adhesive failure (EP function). This dispenses with the need for EP additives in oils. Use in tracked chains benefits the tribological behaviour of MoS_2, because the high loads or contact pressures ($P_H \sim 130$ MPa) permanently improve the film formation properties (extremely high load-bearing capacity [6] of MoS_2), resulting in a reducing wear curve or running-in.

Figure 5 : Solid bonded film pin after 280 operating hours in an unsealed chain section (top). Pin after 1,000 operating hours in an unsealed chain section (centre). Inside of bush after 1,000 operating hours (bottom).

2.4.2. Tribological properties of Te´Strake 7409

After the MoS_2 particles have aligned themselves in the film during the tribological running-in process, or after the "film" has formed, a coefficient of friction of < 0.1 can be assumed in the temperature range of -40°C to +150°C, relevant for construction machinery, which is comparable to grease or oil under mixed-/boundary lubrication. The coefficient of friction increases to a maximum of 0.18, when the tribosystem of the machinery is subjected to fine Arizona or Turkey sand. The low sliding speed of $v < 5$ mm/s, combined with a contact pressure of <130 MPa, works in favour of the solid bonded film.

It has also been shown that it is only the heat cured 7409 coating, with poly(amideimide)-based binding agents, which does not suffer a reduction in film life as a result of the fine Arizona or Turkey sand.

Depending on the geometry and working conditions, the film life of a single application of Te´Strake 7409 is 300,000 to 1,000,000 cycles at pressures of 1,000 MPa using the SRV™-test machine (See ASTM D6425-02 or DIN 51834-2 and –8) , and is therefore adequate for a crawler (< approx. 380,000 cycles in 6,000 operating hours, with a 10% driving proportion). The suspension of MoS_2 in polymer binding agents has tribological advantages in comparison with emulsification in a grease, because the polymer binding agents ensure better immobilisation of the MoS_2 in tribological contact on the surface. The overall result for the customer should be the creation of a silent "luxury chain" which can be used from low to high temperatures.

Table 2 . Structure and operating conditions of the tribological system

TRIBOLOGICAL SYSTEM	**Triboelement 1**	**Triboelement 2**
Designation	Inside of bush, made from drawn tube (Ra ~ 1.5-2 µm)	Outside of pin
Substrate	e.g. SAE 15 B 15-24 Cr(800-1000 HV)	42CrMo4, 35MnCr5, SAE1046, 40MnB4 (55-60 HRC),
Coating	Te´Strake 7409 a. uncoated b. coated	Te´Strake 7409 a. coated b. coated
Coating curing temperature	Approximately 200°C for 1 hour	
Coating thickness	7-8 µm per coating cycle (max. 2 coats)	
Surface roughness	CLA ~ 0.5 µm	CLA ~ 0.5 µm
Cleaning	Grease-free prior to coating	

Since the estimated number of cycles of the chain links on a bulldozer can be up to 2.5 million in under 2,000 operating hours, both surfaces need to be double-coated.

The x-ray diffraction diagrams of the D7409 low-friction paint coating indicate the crystalline constituents, graphite and MoS_2 without PTFE.

2.4.3. Environmental test conditions for the machine

The pins and bushings being tested were used in an unsealed segment and in various sealed, dry segments on a Liebherr PR732 Litronic (See Figure 4). The construction machine was carrying out clearing and grading work on a building rubble dump.

The XRD phase analysis of the sand adhering to the components (fine: grain sizes <50 µm) showed a composition of almost 40% quartz by weight, comprising (by weight) 21% coesite (synthetic SiO_2), 17.1% tridymite (SiO_2), 17.3% dolomite ($Ca,Mg(CO_3)_2$), 15.9 % SiO_2, 8% vaterite ($CaCO_3$) and a balance. Around 65 % of the composition of Arizona sand, by contrast, is quartz, with the remainder comprising chain and phyllosilicates, which explains the particularly abrasive effect only when the sand is dry. The "Turkey"-sand was composed of ~77 vol.-% of quartz, ~22 vol.-% Calcite and ~1 vol.-% Kilchoanite.

2.5. Morphologies of the tested solid bonded film components

The first sections of chain were removed after just 280 operating hours. The pin surfaces had no visible solid bonded films in the wear scars, and the surface roughness was reduced to C.L.A. ~ 0.25 µm without any indications of adhesive wear. A visual inspection of the pins and bushings revealed signs of tribo-corrosion (Rust). Corrosion processes are detrimental to coating adhesion and retention. For this reason, components will, in future, be phosphatised with "Endurion U.T.".

The XRD phase analysis of the tribologically stressed solid bonded films at 272 hours and 1,000 hours (See Figure 4) showed the formation of Fe_2O_3 and the degradation of the MoS_2 into $Mo_3O_8xH_2O$ (ilsemannite, JCPDS no. 210574). Ilsemannite, also referred to as a blue hydrogel of molybdenum oxide, is a naturally occurring degradation product of MoS_2, with a Vickers hardness of H_V ~ 4,800 MPa.

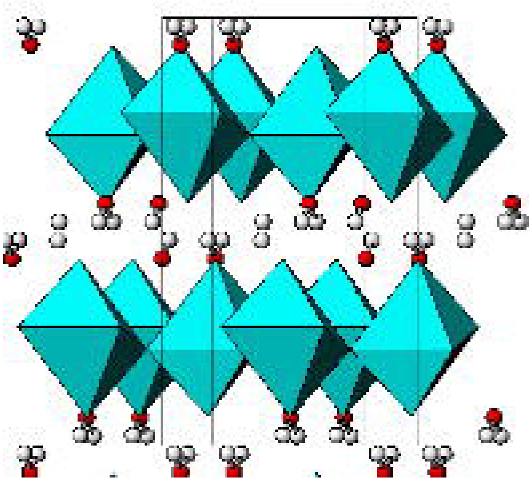

Figure 6 : Projection of the MoO_3x1H_2O structure in the [001] direction.

Layered structures have also been demonstrated in the hydroxides of molybdenum [7], such as Deca - Molybdate $MoO_{2.5}(OH)_{0.5}$ with a hexagonal crystal structure. These decompose at around 300°C.

In addition, the crystalline monohydrates [39082-25-2] and monoclinic dihydrates [25942-34-1] of molybdenum trioxide [8], [MoO_3 n H_20], with n= 1/3, ½, 1 or 2, are generally well known. They are also designated as molybdenum acids (Baker Chemicals), H_4MoO_5 or H_2MoO_4.

In these combinations (Figure 6), part of the H_2O molecule is octahedrally co-ordinated with the molybdenum in layers [9] of [$MoO_5(OH_2)$], while the other part is co-ordinated between the layers as a hydrate. Hydrogen bridged ring compounds connect the layers. Above a temperature of 450°C, the dehydration to $MoO_{2.8}$ is finished.

After 1,000 operating hours, no differences were discernible in the visual appearance of the chain sections in comparison to those inspected after 272 operating hours. However, a significant amount of MoS_2 was still in evidence in the wear tracks of the solid bonded film of the pin after 1,000 hours, indicating that not all the MoS_2 degrades. After 1,000 hours, wear had reduced the thickness of the inspected pin by less <0,8 mm (uncritical).

In air, the rate of oxidation [10] of MoS_2 does not start to rise exponentially until temperatures of above 300°C are reached, so that flash temperatures of more than 300°C in the solid bonded film of the internal surfaces can be assumed, particularly when the external temperatures of the bushings are >70°C. The dehydration of Ilsemannite is a slow endothermic reaction, which requires heat. Consequently, short-duration temperature peaks do not affect the thermal stability of ilsemannite.

In Germany, molybdenum trioxide [CAS: 1313-27-5] is classified in water hazard class 2 in accordance with German federal law VwVwS-99 [11], even though it is insoluble in water, since it is qualified by the R-phrases, "R36/37: Irritant to eyes and respiratory organs" and "R48/20/22: Hazard when subjected to extended exposure by inhalation or swallowing".

The following toxicity data [12] would justify classification in water hazard class 1 “slightly hazard” and would not be labelled with symbol “N” according to EC directive 1999/45/EC. Oral rat toxicity is LD_{50} >2,700 mg/kg (i.e. non-toxic) or >5,000 mg/kg. Aquatic fish toxicity is LC_{50} ~ 65-130 mg/l, daphnia toxicity EC_{50} = 150 mg/l, algae toxicity EC_{50} >100 mg/l, and the growth inhibition of bacteria EC_{50} = 820 mg/l (harmful to water organisms = water hazard class 1: "low water hazard").

2.6. Wear data of the tested components

Despite the increased abrasive wear resistance of the poly(amideimide)-bound solid bonded film, it is essential to prevent or at least minimise the penetration of minerals and contaminants into the "pin/bushing" tribological system. To this end, a number of different seals were tried out on the test chain in comparison with a standard oil-lubricated track:

a. metal seal washer/cup spring

b. seals for greased tracks (Freudenberg)

c. seals for lubricated tracks with metal spacer (Chicago Rawhide)

d. unsealed

Table 3: Increase in the divisions of chain lengths of different designs (division when new: 812.3 mm; maximum admissible wear length (Δ100%) or end of life: 824.5 mm)

Version of the Pro6 chain	**Increase in division after**	**(a) Change [in %]**		
	1,100 hours	1,100 h	1,350 h	1,830 h
Standard oil chain	812.0 mm	0	6	6
Solid bonded film with cup spring	813.0 mm	6	6	59
Solid bonded film with grease seal	813.5 mm	10	14	45
Solid bonded film with oil seal	812.0 mm	0	6	53
Solid bonded film, unsealed	814.0 mm	14	30	67

The standard oil-lubricated chain is naturally the most wear-resistant, but after 1,830 operating hours, non of the tested “dry” solutions had reached the wear limit. Interestingly enough, the cup spring and dry oil seal showed the same wear development up to 1,350 hours as the oil-lubricated chain.

Sand adhering to the segments counteracts the increase in the division, so that in some cases no change – or even a reduction – can be measured.

3. D6D-BUSHINGS MADE OF MONOLITHIC CERAMICS

It can be derived from tribological [13,14] studies, that the present metallic materials -primary steels- used for sprockets and bushings in worldwide serial applications (considering also heat treatments!) already represent the optimized wear solution, taking into account also economic factors.

However, wear still represents a problem and there do not seem to be alternative materials available in the area of metal materials, especially, since the machine weight continuously increases on unchanged chain sizes. Therefor, thought was given to the use of materials other than those normally used for bushings and sprocket teeth.

Today, fine ceramics are applied as “state-of-the-art” or commodity components for wear protection and for protection against corrosion. Few efforts are known to introduce full-ceramic parts in applications with simultaneous tribological and mechanical stresses because they seem to be too brittle and have a too low room temperaure strength compared to steels.

The novel engineering of fine ceramics offers an alternative. Therefore, the potential suitability of fine ceramics for the use in the rough environment of construction equipment was investigated.

It is common knowledge, that ceramic materials exhibit a high wear resistance against abrasive wear due to their high hardness, if the hardness of the abrasive particles (quartz sand = 7,500-12,000 MPa) is 20% lower than the hardness of the structural ceramics. Since quartz sand is the hardest natural mineral, beside diamond, the ceramics Si_3N_4 or Zirconia qualify as candidate materials. As it will be shown later, that silicon carbides, even hard, are to brittle.

Special steels, like X210Cr12 (1.2080), forming special carbides, like (Cr_xC_y), reach only Vickers hardnesses as maximum of 1.000 MPa.

Silicon nitrides and zirconias are the retained and suited candidate ceramics beside the zirconia toughened alumina (ZTA), since the ceramic bushings have to withstand additional structural (press fit and track force) and impact loading (sprocket).

With regard to this, the results of intensive research worldwide in the area of high performance ceramics are showing mechanical properties exceeding those from steels. In other words, the four point bending strengths for Si_3N_4 or Zirconia have more than trippled for in three decades.

For large volume components (greater than 200 cm^3), few top qualities garantied four point bending strengths at RT of greater than 1,000 MPa and the research level passed for both types of ceramic 2,000 MPa. The „top“ qualities of fine ceramic grades reached in 2003

σ_{4pb} ~ 2,100 MPa for Si_3N_4 and

σ_{4pb} ~ up to 3,000 MPa for ZrO_2-ceramics

The volume effect for the defect population in ceramics affects also the mechanical life-time prediction [15] (Weibull-diagramm). Also big attention was given to the pressfit between the bushing and the chain link, since continuous stresses are generate independent from the operation and the elastic moduli as well as thermal dilatation differ between both types of materials.

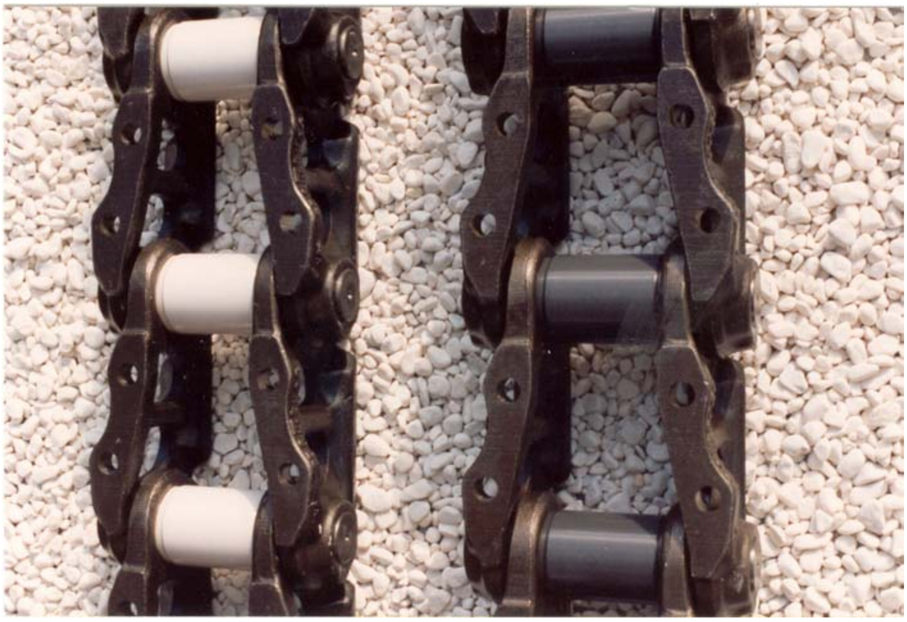

Figure 7 : Assembled D6D track chains with silicon nitride and zirconia bushings.

The successful machine trials on a 22-to dozer LIEBHERR 732BL with 234 kN pull force with monolithic ceramic bushings are reported elsewhere [16].

3.1. Abrasive wear of ceramics

In the following, the subsitution to ceramic bushing will be evaluated only under tribological considerations. The previously in the chapter of solid bonded films reported "inner wear" will be extended to the "outer wear" between the bushing and the sprocket, in which abrasive wear is predominant. According to Rabinowicz [17], the abrasive wear is shared into three regions of low wear/high wear transitions depending from the relation of hardnesses.

$$V = \tan\Theta \frac{F_N\, s}{3 H_w} \quad , \quad \text{for} \quad \frac{H_w}{H_a} < 0{,}8$$

$$V = \tan\Theta \frac{F_N\, s}{5{,}3 H_w} \left(\frac{H_a}{H_w} \right)^{2{,}5} \ , \ \text{for} \ \ 0{,}8 < \frac{H_w}{H_a} < 1{,}25$$

$$V = \tan\Theta \frac{F_N\, s}{2{,}43 H_w} \left(\frac{H_a}{H_w} \right)^{6} \ , \ \text{for} \quad \frac{H_w}{Ha} > 1{,}25$$

V, Wv	Wear volume of the wear piece
Θ,α	Sharp angle of the abrasive
Kc	Fracture toughness
E	Elastic modulus
F,F_N	Normal force
H_a	Hardness of abrasive
H_w	Hardness of working piece
S,s	Sliding distance

The methodology of Rabinowicz is more valid for metals and represents a simplification for ceramics.

Ceramics can exhibit a higher abrasive wear [18] rate than specific steels, since the fracture toughness has also to be considered. Metals tend to plastic deformation during ploughing and ceramics [19] to brittle fracture as well as to formation of radial and lateral cracks.

Assuming the growth of lateral cracks in the linear-elastic regime under a plastic deformed zone below the abrasive, the abrasive wear [20] volume correlates for low speeds with the hardness and fracture toughness as well as with sollicitation parameters (Load, sliding distance, sharpness of the abrasive) as follows:

$$Wv = \frac{2F^{5/4} s \sin^{5/4}\theta}{K_{IC}{}^{3/4} H^{1/2}}$$

W_V: Wear volume, F: Normal force, θ: half angle of abrasive, H: hardness, K_{IC}: fracture toughness, s: sliding distance

The Model [21] of Evans and Marshall concludes in a different way, but displays a similar relation:

$$W_V = \alpha \frac{F_N{}^{9/8}}{K_c{}^{1/2} \cdot H^{5/8}} (E/H)^{4/5} \cdot s$$

These relationships all indicate, that an increase of fracture toughness will reduce more the abrasive wear than by the hardness. This means, that a Zirconia Toughened Alumina or ZrO_2 with fracture toughnesses of $K_{IC} > 10$ MPa√m may be more resistant against abrasive wear than SiC or Si_3N_4.

3.2. Component test rig

The test bench (See Figure 8) described in detail in reference [14] is a computer controlled servo-hydraulic simulation test rig by means of which

a. force and motion between the sprocket and track bushing can be simulated for actual operating conditions,
b. quartz sand can be added as abrasive and
c. normal load and friction forces can be separated and measured in order to eliminate crosstalk.

Original full-size components can be tribologically stressed beyond operational conditions giving reporducible results in an accalerated timeframe. Primarily, force and movement chatracteristics between bushing and sprocket of tracks can be simulated operationnally, and quartz sand or other abrasives can be added in a defined manner.

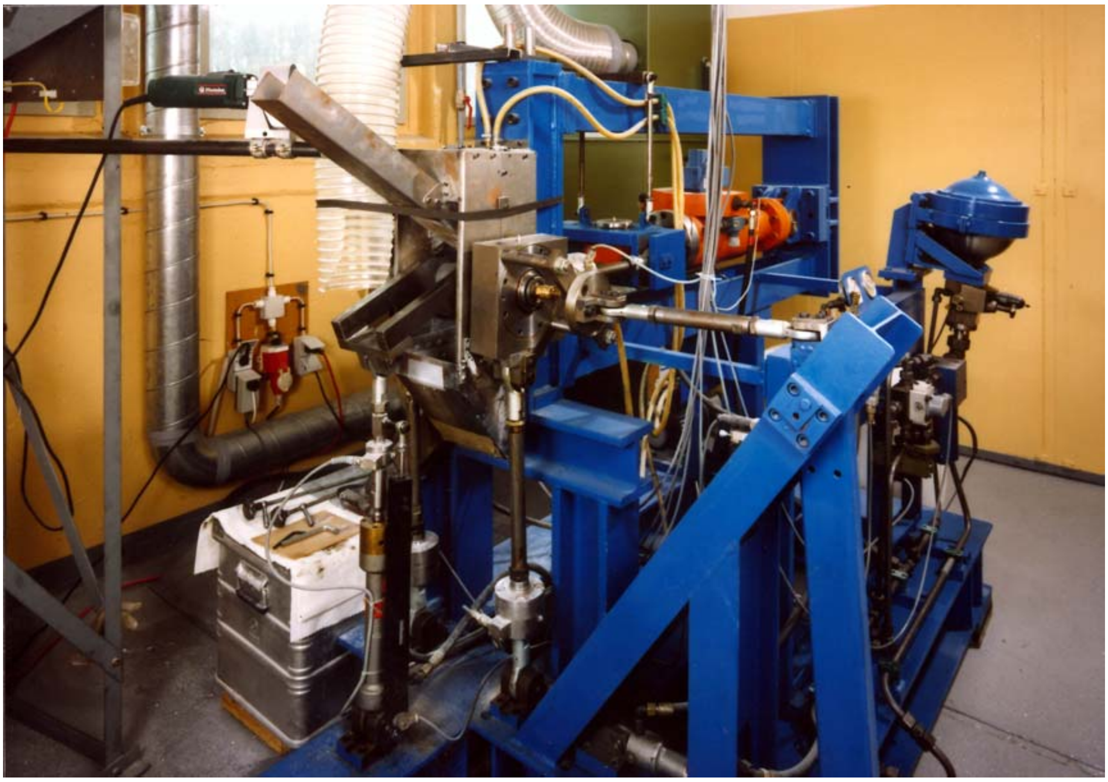

Figure 8 : Bench tester for D6- and D4 bushings

The main test condions are as follows:

Normal load :	30 kN (as average during loading)
Number of cycles:	10,000 (up to 100.000)
Simulated driving speed :	3 km/h
Swing angle :	30° at 1Hz

200 g/min fire dried quartz sand with a grain size distribution between 0,1 to 0,4 mm was used as “worst” case abrasive. The following experiments were performed as three-body abrasion and as unlubricated (dry) test without abrasive.

Under 30 kN, the initial Hertzian contact pressures are as follows:

Steel/steel	~ 630 MPa and
Si_3N_4/Si_3N_4	~ 720 MPa.

In this test programm, conventional metallic materials, like SAE 15B15Cr, GS37Mn5N, 30MnB4 (1.5526), 35MnCr5, 42CrMoV4 (1.7725) as swell as steels of type 100Cr6H (1.2067; AISI 51200), 51 CrMoV4 (1.7701) and X155CrVMo12-1 (1.2379) were tested.

3.3. Mechanical properties of ceramics

Beside the enormous potential for reduction of the abrasive bushing wear when using silicon nitride or zirconia, the question arises, whether the radial fracture load of the monolithic ceramic bushing is high enough, and whether the data from four point bending strength bars with ~540 mm³ can be transferred to D6D-bushings with ~301,160 mm³ stressed volume.

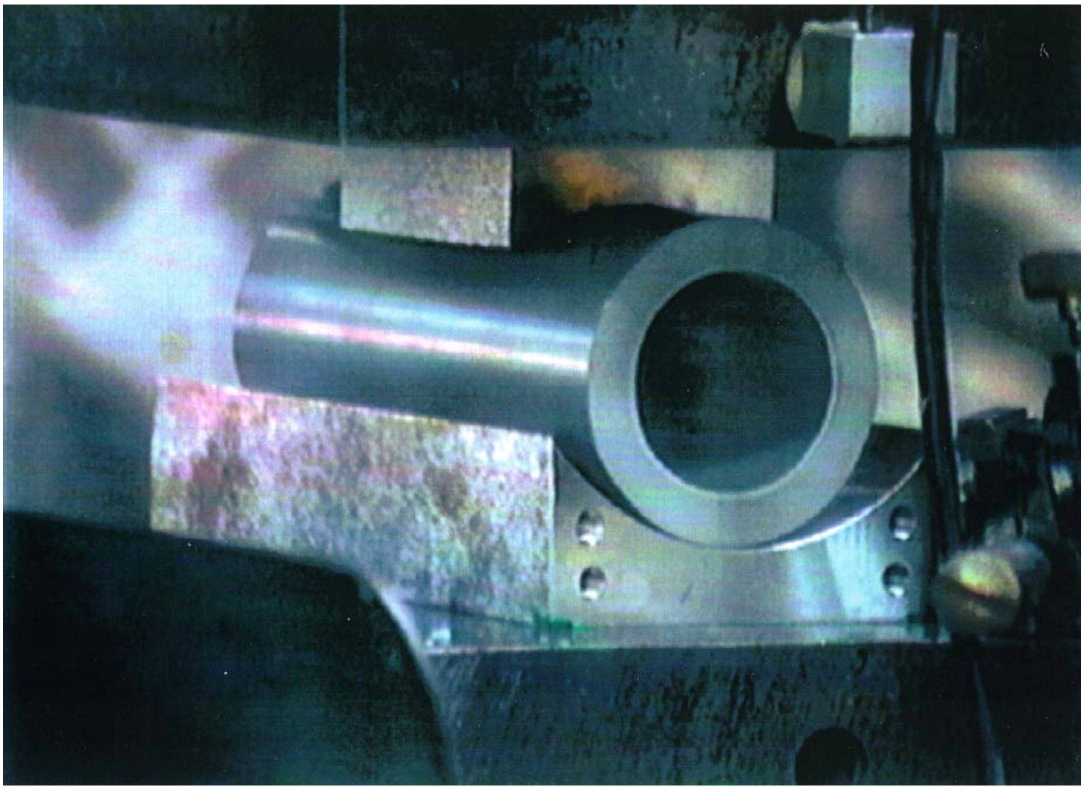

Figure 9 : Photograph of the configuration for radial fracture load tests

The Figure 9 shows the D6D bushing configuration during the test and the start of the bushing fracture. The fracture loads were increased continuously at rates of 10 kN/s until fracture occurred. The ceramic bushings were grinded to C.L.A. ~ 1,0 µm.

The radial fracture load (See Table 3) measured for silicon nitride and zirconia were quite high and reached easily 50% or 60% of SAE 15B15Cr and it has to be kept in mind, that the steel bushing had a greater diameter which is not necessary for the ceramics due to their wear resistance. The fracture load values apparently show sufficiently high values to withstand impact loading on a 22 tons dozer.

The weights of D6D bushing are as follows:

Steel ~ 2,4 kg,

ZrO_2 ~ 1,7 kg and

Si_3N_4 ~ 0,95 kg.

3.4. Wear testing

The wear rate was used in order to compared the wear levels of the different materials and to estimate the wear life using the wear rate. The wear rate is defined by dividing the wear volume by the acting normal force and the effective sliding distance. The wear volume was determined by means of stylus profilometry.

3.4.1. Abrasive wear

The following wear rates were evaluated under 30.000 N load after 10.000 cycles using fire dried quartz sand (granulometry: 0,1-0,3 mm).

The couples SAE15B15Cr/35MnCr5 and SAE 15B15Cr/GS37Mn5N in Figure 10 represent steels couples used in the stated of the art. The wear rates of the bushings using different silicon nitrides and zirconias and sliding against steels, like 100Cr6H (1.2067), 30MnB4 (1.5526), 35MnCr5, 42CrMo4 (1.7225) and X155CrVMo12-1H (1.2379) decreased using quartz sand for the Si_3N_4-bushings down to k_V = 2-7 10^{-5} mm³/Nm and for ZrO_2-bushings to k_V ~10^{-5} mm³/Nm, whereas the wear rates for the steels remain uninfluenced by the ceramics on a level of k_V ~10^{-4} mm³/Nm.

Table 3: Comparison of bending strength with radial fracture load of D6D bushings (∅= 66,6 mmx147 mm)

Ceramic	σ_{4pb} [MPa]	Fracture load [kN]	Supplier
SAE 15B15Cr bushings (∅= 69 mm)	900-1,300*	385-530	Intertractor
SiSiC	350	<15	HCT AG
HIP-ZrO_2 (Z703)	~2,000	245	KYOCERA
HIP-ZrO_2 (ZYFT)	~1,900	190-260	Saint Gobain
ND- Si_3N_4 (m~15)	800	70-92	CFI
S-Si_3N_4	750	102	ESK
GP-Si_3N_4 (SN235P; m~22)	~1,000	179-192	KYOCERA
GP-Si_3N_4 (K301)	~1,000	157-198	Saint Gobain

*traction

Using a full ceramic couple, like Si_3N_4/Si_3N_4 and ZrO_2/Si_3N_4, the abrasive wear of the flat sample (sprocket) can be lower considerably up to “zero wear”.

The Figure 11 confirms the relationships known from theory, that Si_3N_4 (H_V ~15,000-18,000 MPa) with a high hardness not consequently exhibit low abrasive wear itself compared to zirconia with lower hardnesses of H_V ~ 11,000-13,000 MPa and associated higher fracture toughnesses. The abrasive wear resistance of zirconia is superior to these of Si_3N_4.

The sintered silicon nitride bushing rubbing againt a silicon nitride flat exhibited an abrasive wear rate in the high wear regime, whereas the flat sample (sprocket) displayed no wear (See Figure 10 and Figure 11). The abrasive wear resistance of a silicon nitride bushing is lost under dry conditions without abrasive (See Figure 13).The wear resistance of gas-pressure sintered Si_3N_4 with better mechanical properties seems to be superior to the sintered Si_3N_4 (See Figure 10). In general, the lowest abrasive (sprocket) wear rate displayed zirconia

Wear test with silicon carbide (EkasicD and SiSiC) were of course performed, but are of limited meaning, since the D6D-bushing failure during tested with 30 kN. One results could be collected under 10 kN for the couple 100Cr6-bushing against SSiC flat sample: The wear rate of the SiC flat sample was 1,5 10^{-5} mm³/Nm, ranging between Si_3N_4 and zirconia..

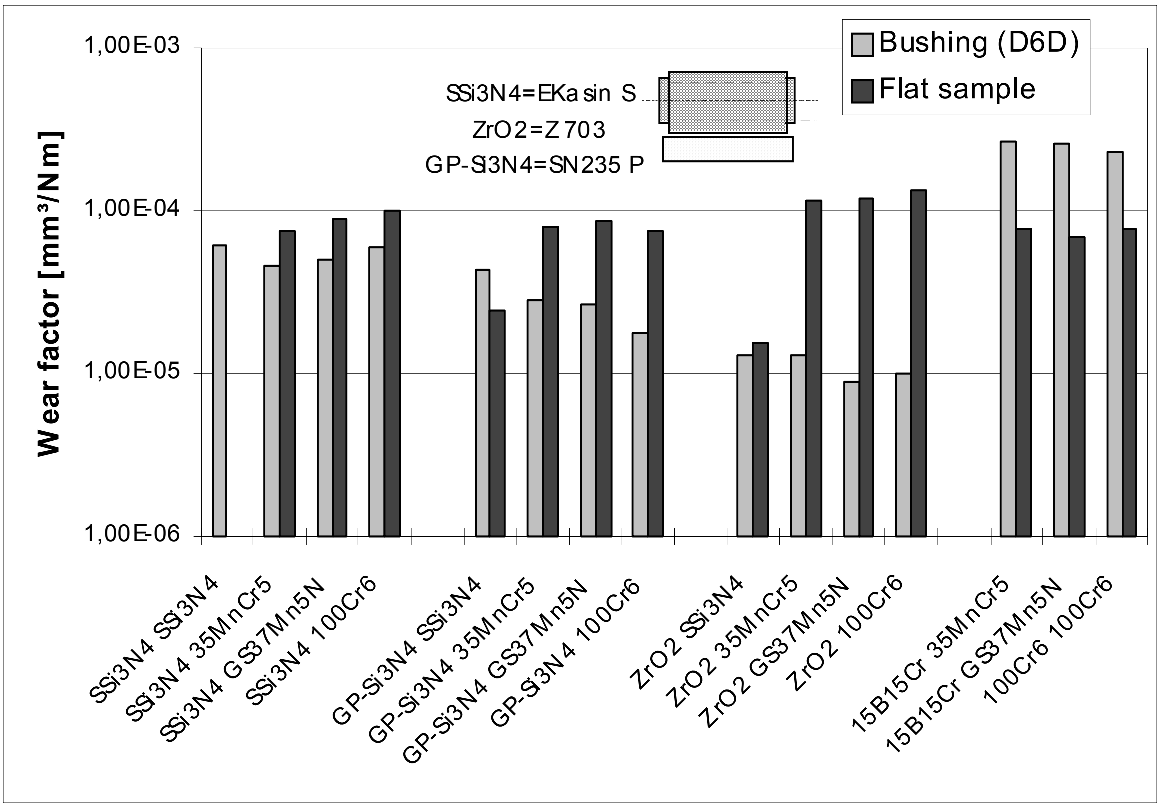

Figure 10 : Comparison the abrasive wear [16] rates of steels, Si_3N_4 and ZrO_2

3.4.2. Dry friction without abrasive

Under practical operation, the undercarriage and the tracked chain can be sujected to abrasives or non-abrasive conditions. In consequence, dry test without abrasive were conducted. Especially some metallic couples presented undesired adhesive wear mechanism (transfer).

The results in Figure 12 illuminate, that GS37Mn5N and SAE 15B15Cr represent steels with an optimal non-abrasive wear resistance also considering cost issues.

Comparing the abrasive wear rates in Figure 10 with non-abrasive one for steels in Figure 12, it can be concluded, that the quartz sand increases the wear roughly by two orders of magnitudes. The wear increase by quartz sand for the ceramics lie between two to three orders of magnitude. For 35MnCr5 and GS37Mn5N the wear rates ranged around kv ~ 3-4 10^{-6} mm³/Nm.

Zirconia bushings displayed the most benificial effects regarding wear reduction of the sprockets and the bushing wear itself. The observed wear rates falled below kv < 3 10^{-7} mm³/Nm (wear resolution limit using 30.000 cycles) and are considered as “wear free”.

It may be estonishing for the reader, that self-mated silicon nitride or mated against zirconia displayed for Si_3N_4 under non-abrasive conditions the high-wear regime and under abrasive a low-wear one (See Figure 13). This finding is on the other hand consistent with literature[22,23] on tribological properties of unlubricated sliding of silicon nitride.

35MnCr5 and GS37Mn5N fitted best with the ceramics regarding the wear rates of both bushing and sprocket and cost aspects.

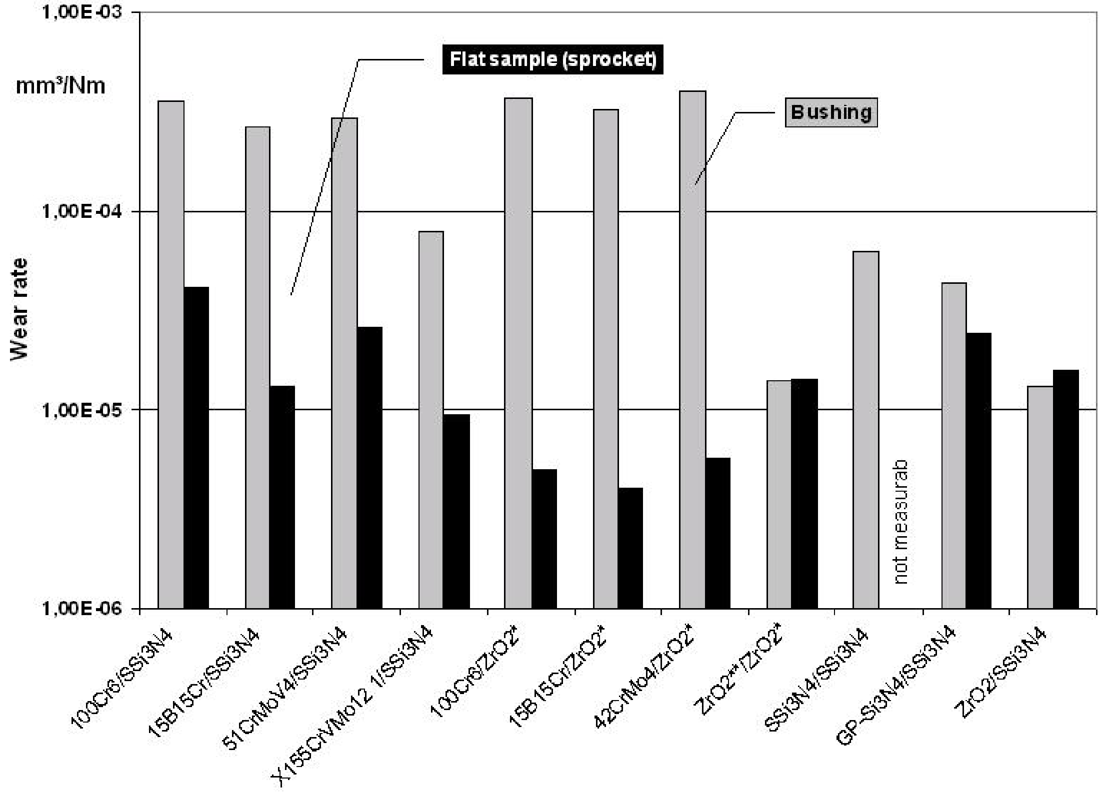

Figure 11 : Comparison the abrasive wear rates Si_3N_4 and ZrO_2 sprockets against steel bushings

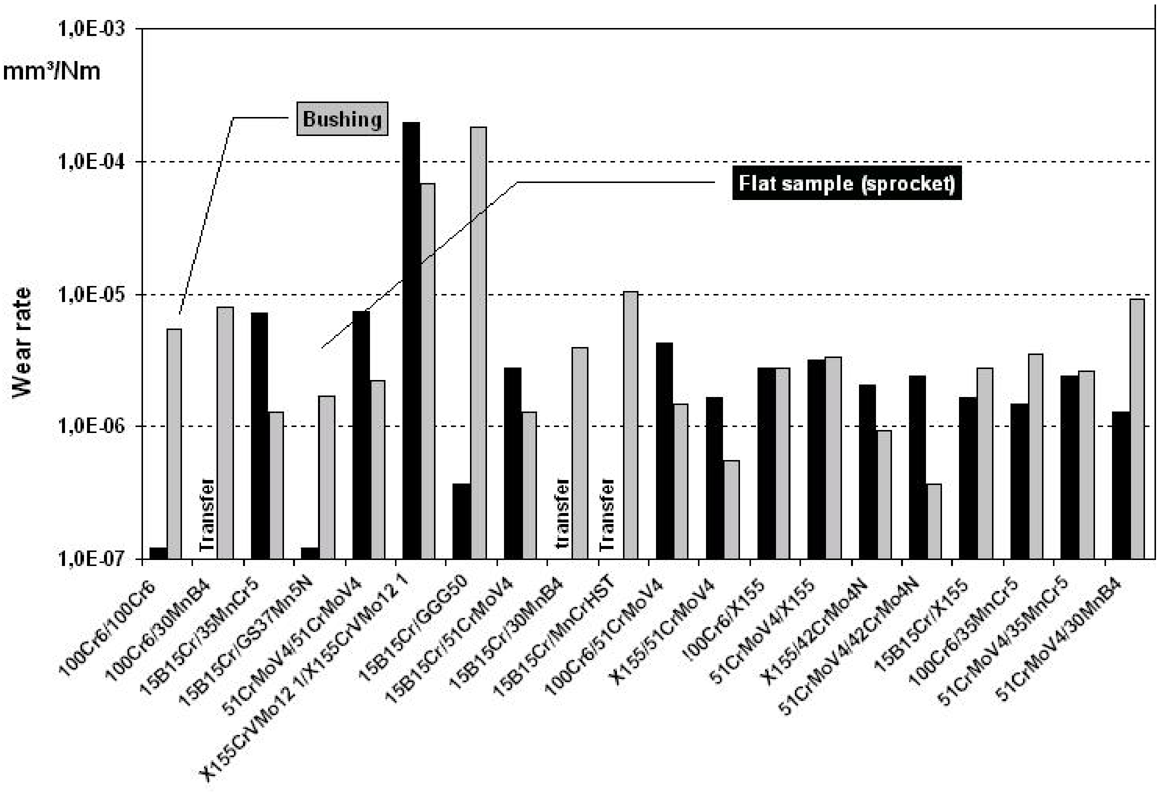

Figure 12 : Comparison the non-abrasive wear rates of steels

In general, the wear reduction potential of bushings made of Si_3N_4 and zirconia ceramics can´t be fully used so long other wear parts in an undercarriage or chain are made in steel. In consequence, the focus for using the wear resistance of both Si_3N_4 and zirconia should be oriented on new designs.

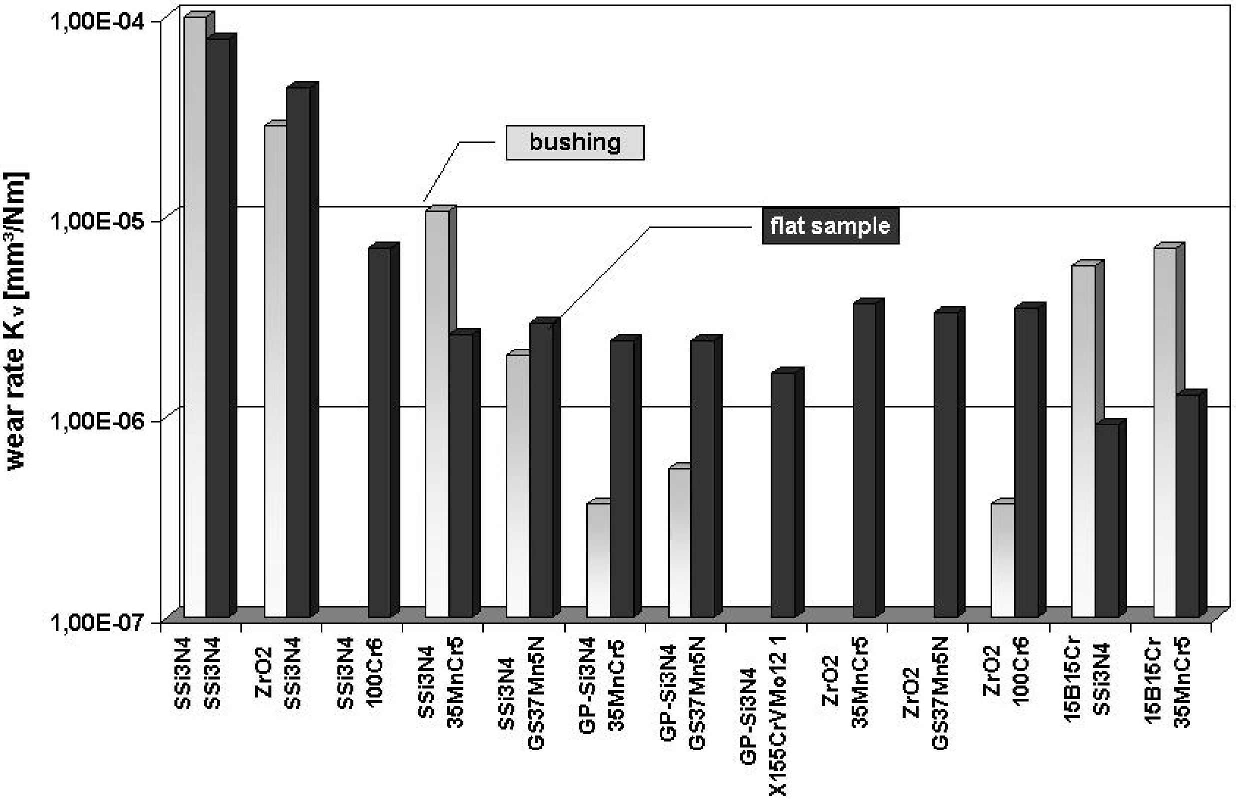

Figure 13 : Comparison the non-abrasive wear rates of steel-ceramic and ceramic-ceramic couples (no column= no wear detectable)

4. SUMMARY

Soft solid bonded films using poly(amid-imid)-binders in combination of simple dust seals are sufficient for dry lubrication of the inner tribosystems of tracked chains, even small amount of natural abrasive interfer. It seems, that poly(amid-imid) binder can embed small amount of particle. They offer a high potential to subsitute oil or grease lubricated chain links, since the tests have shown, that the oil lubricated chain is quasi overdesigned, because other metallic parts of the undercarriage or chain reach their life-end before.

Soft solid bonded films using poly(amid-imid)-binders increase under oil lubrication the load carrying ability, improve the corrosion protection, the running-in behavior and under deficient lubrication.

Under “pure” abrasive conditions, the abrasive wear rate can only be managed by increasing the hardness of the materials over the value of the abrasive or mineral, but the fracture toughness has to be considered as another important determinating material property. Selected ZrO_2 reduces abrasive wear up to a factor of 30 and Si_3N_4 up to a factor of 20 compared to steels used in construction equipments.

Trials with D6-dozers have underlined, that the known level of strength and subcritical crack growth velocity of selected Si_3N_4 and zirconia ceramics are considered to be sufficient for tracked chains.

Both approaches, selected solid bonded films and monolithic ceramics, offer a potential for simplifying the design, reducing weight and designing a dry-running longlife chain. They offer a weight reduction potential (inertia mass) for high-speed running gears and belt drives.

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