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SLIP-ROLLING RESISTANCE AND LOAD CARRYING CAPACITY OF 36NiCrMoV1-5-7 STEEL

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Abstract

The approaching CO_2 targets have now forced automotive OEMs to direct R&D efforts in the powertrain to reduce friction and increase lifetime as well as load carrying capacities of running systems. Martensitic steels such as 36NiCrMoV1-5-7 have a great potential to be used in automotive powertrain applications owing to their favorable mechanical properties. In order to realize lightweighting strategies it is essential that steels with improved fracture toughness values, as well as higher annealing temperatures with regard to higher contact pressures and possible thin film coating application, should be considered. State-of-the-art steels, like 16MnCr5, 21NiCrMo2, 30CrMoV9 and 100Cr6, are not able to sustain a further increase in torque or load during use, as well as annealing effects under higher oil or deposition temperatures. Therefore, recent research has explored the slip-rolling resistance, frictional and wear behavior of steels, such as 36NiCrMoV1-5-7, Cronidur 30 (AMS 5898), 20MnCr5 (SAE 5120) and 100Cr6H (SAE E52100), and this has shown that possible lean alloying concept alternatives with promising performance characteristics are already available.

Introduction

Highly concentrated or loaded contacts in powertrain, bearing and gear applications offer significant savings in CO_2 emissions. Today, thin film coatings, alternative base oils and new additives are popular as fields of work. In order to meet the CO_2 target of 2020 for passenger cars (95 g.CO_2/km), determined by the European Union [1], there is still a need for optimization of driving concepts. Although in public, the internal combustion engine is seen as the focus of efficiency gains, the whole powertrain offers at least the same scope for improvements. There are two reasons:

(a) Lightweight design;
(b) Reduction in friction without reducing the lifetime.

Lightweighting strategies increase the contact stresses above P_{0max} of 2.14 GPa (or FZG load stage 14) due to the reduction of component sizes. These demands directly raise questions about the suitability of the most promising technical solution. Steels with improved mechanical properties, ie. toughness values, which are offering a reduced coefficient of friction, resistance to high contact pressure and potential to apply a low friction surface coating represent a valid alternative to conventional gear and bearing steels. Traditional bearing steels, like 100Cr6

(SAE E52100) have reached their mechanical limits at contact pressures above FZG load stage 14. Furthermore, increased torques or contact pressures push the oil film temperatures on the gear tooth flanks to 200 °C, exceeding the tempering temperatures of state-of-the-art steels used in gear technology, like 20MnCr5 (SAE 5120), 21NiCrMo2 (1.6523), 30CrMoV9 (1.7707) or similar. In addition, the same tempering effect on steel surfaces can be observed during the deposition of thin film coatings, like DLCs or comparable coatings [2]. Figure 1 shows the influence of temperature on hardness values of different steels used for slip-rolling contacts. The real temperatures on surfaces during coating exceed in most cases 180 °C during deposition times ranging from five to eight hours. Both factors trigger metallurgical changes.

Nitrogen alloyed steels, like Cronidur 30 (AMS 5898, 1.4108) or XD15NW, which have a high annealing resistance of above 380 °C, are globally not widely available and are expensive due to their special manufacturing process, heat treatment and the N_2 furnaces needed. Embargo and Dual Use Regulations limit the direct and indirect use of some alloys, including Maraging steels. Therefore, alternative steels are required offering annealing temperatures far above 250 °C using simple production processes and heat treatment cycles. Higher deposition temperatures would be desired for enhancing metallurgical bonding of thin films through diffusion.

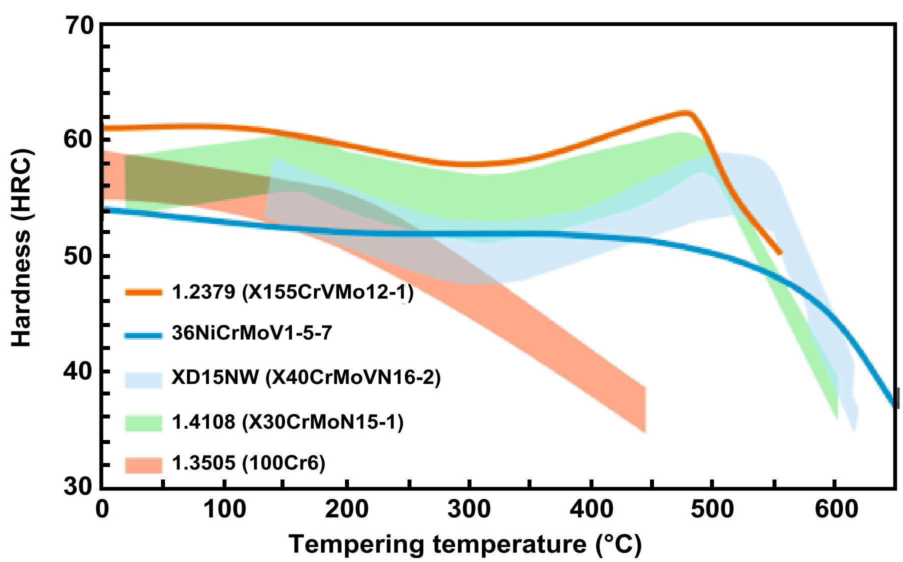


Figure 1. Tempering charts of different bearing and gear steels showing the influence of temperature on hardness.

Recent investigations on the slip-rolling resistance of silicon alloyed steels with improved toughness values and low contents of high-cost alloying elements showed promising test results [3,4]. Silicon alloyed steels V300 (1.8062) and NC310YW (40SiNiCrMo10) displayed also a load carrying capacity in the mixed/boundary lubrication regime up to 2.5 GPa. Furthermore, the steel V300 can offer a friction reduction of approximately 40% compared to commonly used steel-steel combinations.

The design recommendations in DIN 3990, part 5 and ISO 6336-5 mention only surface hardness and allowable stress. Gear applications, which require high toughness and long fatigue life at the very high loads impacting tooth flanks and toes of the gear teeth, cannot be realized by using the aforementioned low-alloy case hardening steels, such as 20MnCr5 (1.7147) or 27MnCr5 [5,6]. Distortion of parts, as well as grain growth, are enhanced by case hardening and thermochemical treatments.

Currently the molybdenum alloyed steel 18CrNiMo7-6 (<0.25 wt.%Mo) is used as standard for windmill gearbox applications. Alloying steels with higher molybdenum contents such as 2% instead of the standard 0.25% provides a hardness value above 700 HV even after tempering at 300 °C (see Figure 2). Thus, the tempering resistance of steel can be strongly improved by adding significant contents of molybdenum as well as optionally niobium, Figure 3. The effects of molybdenum and niobium alloying are shown in more detail in [7].

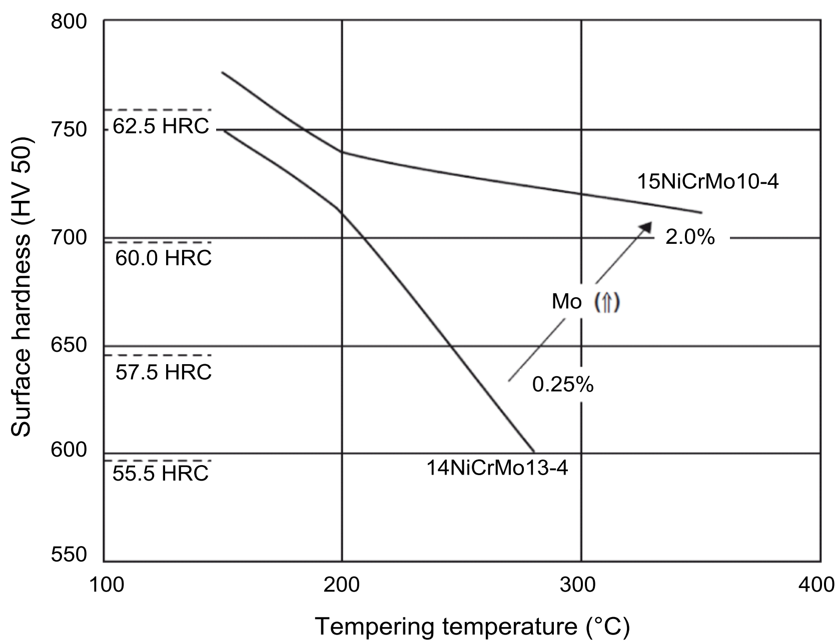


Figure 2. Effect of molybdenum alloying on the tempering resistance of case carburized, quenched and tempered steels [5].

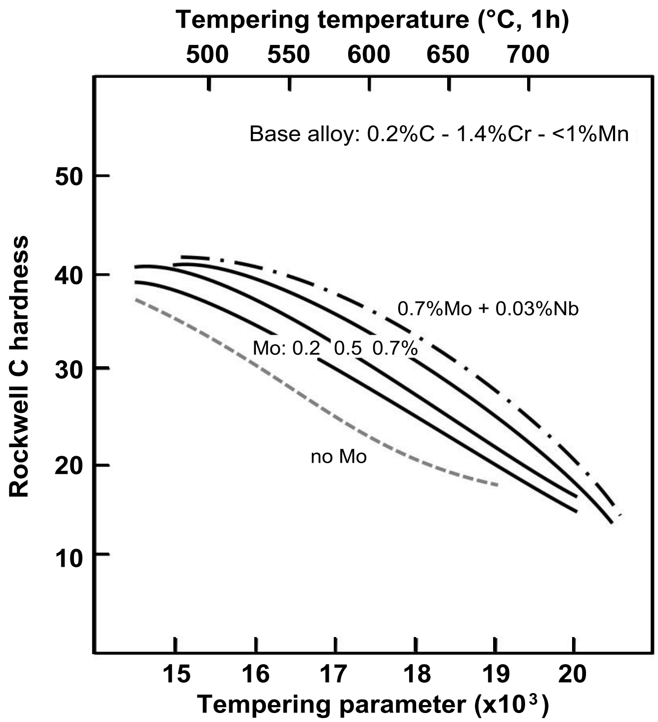


Figure 3. Effect of increasing Mo additions and Nb micro-alloying on the tempering resistance. (Tempering Parameter = (T(20+log(t)) where T is in Kelvin and t in hours) [7].

The present study investigates the slip-rolling resistance and load carrying capacity of the molybdenum alloyed steel 36NiCrMoV1-5-7 in comparison to 20MnCr5, Cronidur 30 and 100Cr6 for contact pressures (P_{0max}) of up to 3.8 GPa, in order to investigate its potential as an alternative steel for bearing or gear components.

Experimental Details

<u>Material Selection</u>

In previous investigations on the slip-rolling resistance of thin film coatings [8,9,10,11], the substrates were mainly made of the well-known bearing steels 100Cr6H (OVAKO PBQ, double remelted) and Cronidur 30 which is a martensitic cold working steel melted under pressurized nitrogen. Due to use of a PESR process (Pressure Electroslag Remelting) in combination with sophisticated rolling technology, extremely high cleanliness and a homogeneous structure with increased lifetime properties can be obtained in comparison to 100Cr6, at a maximum hardness of 60 HRC. Better corrosion and wear resistance can be achieved by partially replacing carbon with nitrogen which is retained in solution. Another positive aspect of this steel grade is its high temper resistance up to 500 °C [12]. Both steels 100Cr6H and Cronidur 30 are widely used in the bearing industry and were therefore selected as reference materials to 36NiCrMoV1-5-7.

Table I. Room Temperature Mechanical Properties of Materials Tested After Heat Treatment

Material	**100Cr6H (SAE E52100)**	**Cronidur 30 (AMS 5898)**	**20MnCr5 (1.7147)**	**36NiCrMoV1-5-7**
Density ρ (g/cm^3)	7.8	7.67	7.85	-
Young's Modulus E (GPa)	210	213	210	215
Elongation (%)	n.d.a.	<5	~ 10	~ 12.5
Hardness (HRC)	65.8	62.2	~ 47	~ 54
Fracture Toughness K_{IC} (MPa√m)	~ 16.5	~ 21	n.d.a.	120
Charpy Toughness KV (J)	-	-	25	30
Ultimate Strength R_m (MPa)	~ 2300	~ 2300	~ 900	1474
Residual Austenite (vol.-%)	6.8	22.5	6.3	<2.5
Maximum Service Temperature (°C)	150	475	180	510

n.d.a. = no data available

Table I summarizes the mechanical properties of the steels tested after heat treatment. The residual austenite contents of all tested materials were determined by means of X-ray diffraction (XRD) directly after receiving the samples from heat treatment.

Table II. Chemical Composition Determined by Spark Emission Spectroscopy of 100Cr6H, Cronidur 30, 20MnCr5 and 36NiCrMoV1-5-7 (wt.%)

Material	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**	**N**	**V**
100Cr6H	1.0	0.25	0.35			1.50				
20MnCr5	0.17-0.23	0.15-0.40	1.10-1.40	≤0.035	≤0.035	1.00 - 1.30				
Cronidur 30	0.25-0.35	<1.0	<1.0			14.0-16.0	0.85-1.1	<0.5	0.3-0.5	
36NiCrMoV1-5-7	0.3	0.25	0.2	0.002	0.002	1.50	0.8	3.0		0.3

Case-carburized 20MnCr5 is, in effect, a reference alloy for gear applications, comparable to AISI 52100 for bearings. In comparison to the other steels, 20MnCr5 is the only one which received a thermochemical treatment (case-carburization). Carburizing steels for gear components is a standard procedure in order to guarantee a hard and failure resistant material surface. It has to be noted that the carbon concentration in the surface region of 20MnCr5, ranging to slightly above 1.0 wt.% carbon, exceeds those stated in Table II due to case hardening. In ISO 6336-5 it is stated that the carbon content of the case area after carburization should lie in the range of 0.7 to 1.0 wt.%. The elemental concentrations in the carburized surface regions of 20MnCr5 were determined by SEM-EDX, spark emission spectroscopy and electron microprobe analysis. The carbon concentration ranged between 0.90 to 1.20 wt.%C. Finally, the surface of the case hardened 20MnCr5 is from a metallurgical point of view only slightly different from 100Cr6H (SAE E52100). The chemical composition of Cronidur 30, as well as 100Cr6H and 36NiCrMoV1-5-7, used as tribological test materials, are summarized in Table II. Using spark emission spectroscopy, the amounts of alloying elements in comparison to standard specifications were determined before tribological tests were conducted in order to guarantee the required quality of the materials. As mentioned in [9], the use of high quality substrate materials, ie. without segregation or porosity, impurities and defects due to the production process, is necessary for applications in highly loaded contacts to ensure the highest possible lifetime. With regard to a possible coating of the substrates, the selected steel has to withstand temperatures up to 300 °C without decreasing its hardness or changing its structural constitution.

Contrary to other state-of-the-art slip-rolling steels, 36NiCrMoV1-5-7 is a cost-attractive alternative offering several benefits, including:

- Elevated tempering temperatures above 300 °C, favoring the application of thin film coatings, such as diamond-like carbon or Zr(C,N) without causing microstructural changes in the substrate during deposition (see heat treatment chart in Figure 4);
- Simplified heat treatment cycles and manufacturing routes;
- Reduced friction for uncoated steel under mixed/boundary conditions;
- High load carrying capacity;
- Straightforward and simple heat treatment;
- Low wear as uncoated steel, similar to thin films;
- Tribological compatibility with state-of-the-art lubricants.

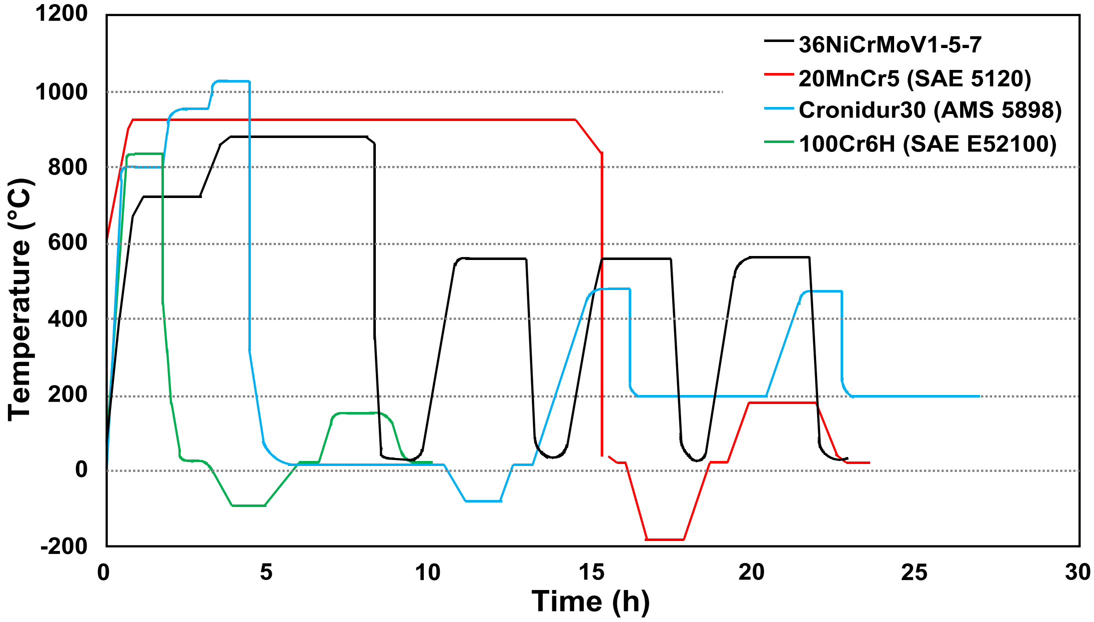


Figure 4. Schematic heat treatment curves of the steels 36NiCrMoV1-5-7, 20MnCr5, Cronidur 30 and 100Cr6H.

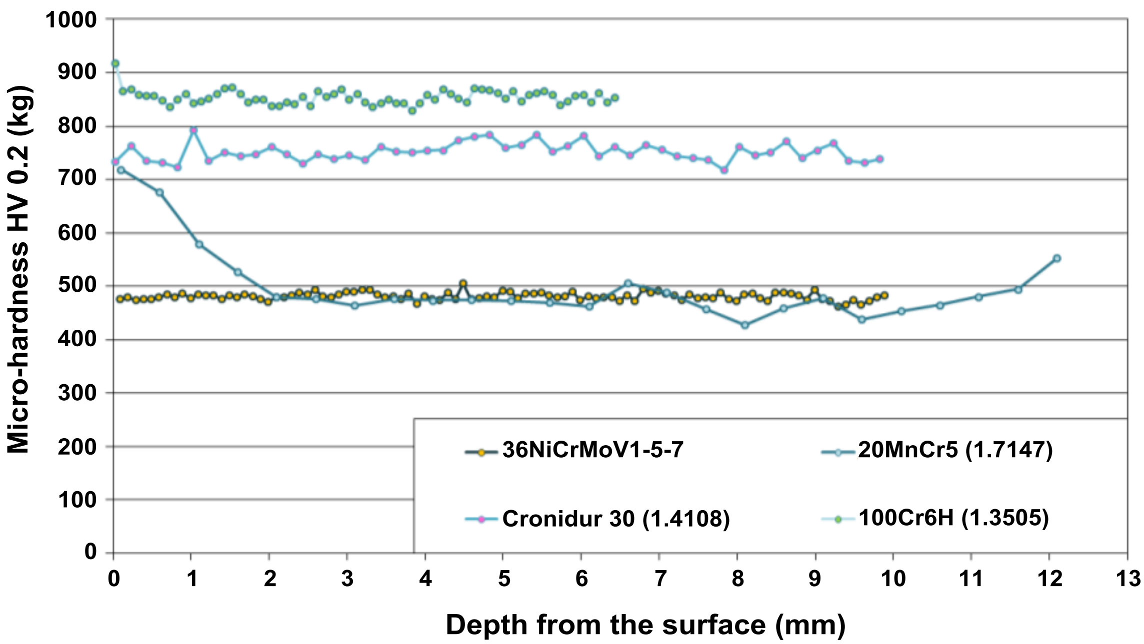


Figure 5. Hardness profiles of bearing and gear steels after heat treatment.

The hardness of the steels after heat treatment is shown in Figure 5. The high hardenability of the steels means there is little fall off in hardness below the sample surface except in the case of the 20MnCr5 which has received a case hardening treatment.

According to Figure 6, the metallographic analysis of the material structure, it can be stated that all steels show a broadly fine, martensitic structure. According to the aforementioned XRD analysis, Table I, Cronidur 30 contains a residual austenite content of 22.5 vol.%, which is not clearly visible in the micrograph. Inclusions within the structure were detected only in the case of 36NiCrMoV1-5-7. The influence of these inclusions in relation to the slip-rolling resistance will be considered below. Due to PESR (Cronidur 30) and VIM-VAR (100Cr6) procedures during the steelmaking process, nonmetallic inclusions could be minimized. 20MnCr5 revealed low amounts of manganese(II) sulfides within its structure.

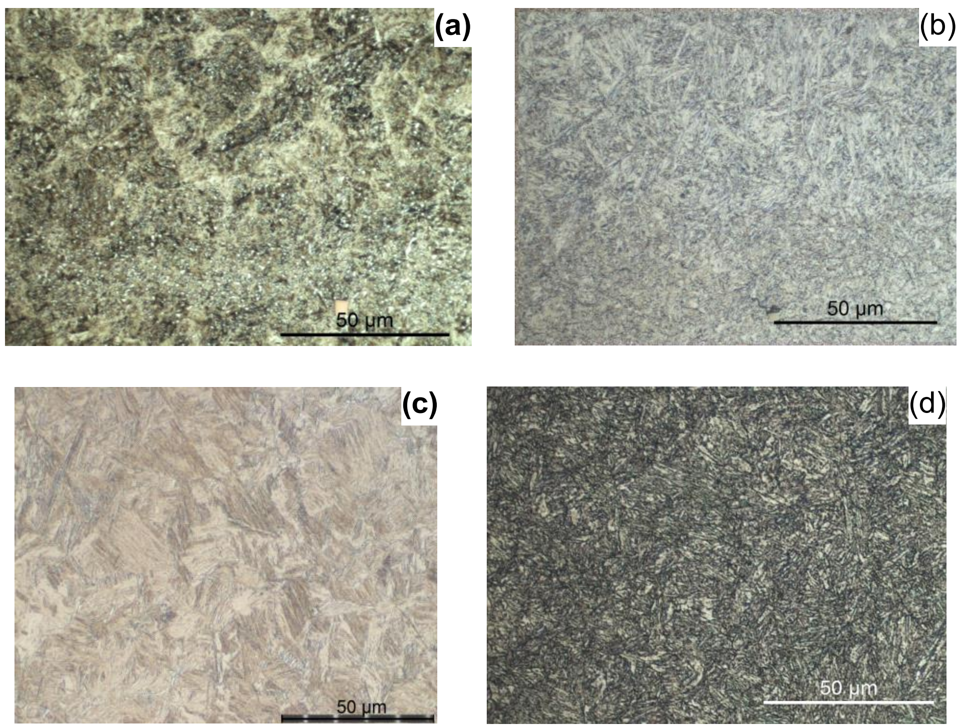


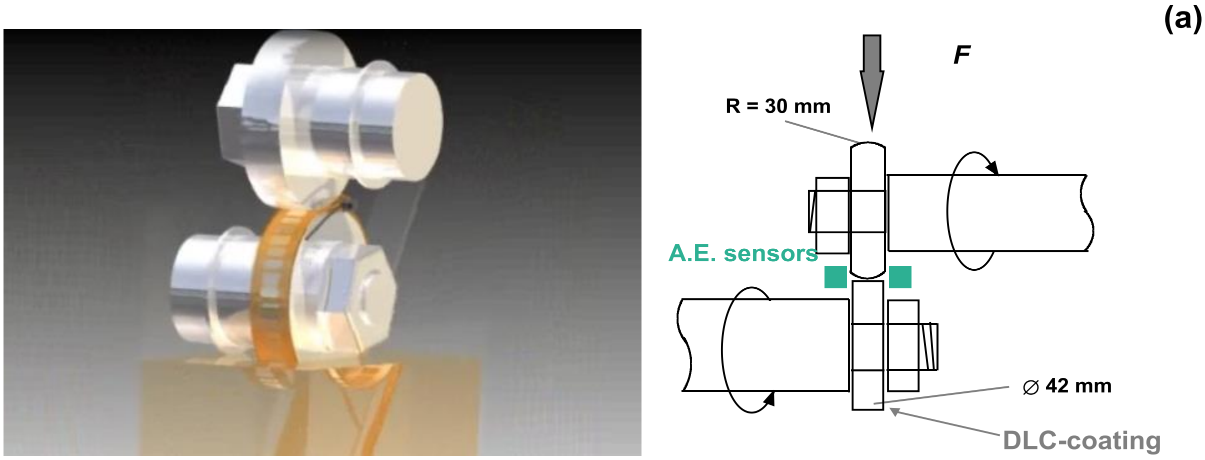
Figure 6. Optical micrographs of the etched material structure; (a) 100Cr6H, (b) Cronidur 30, (c) 20MnCr5 and (d) 36NiCrMoV1-5-7.

Slip-rolling Test Devices

All tribological slip-rolling investigations were carried out on an Amsler-type machine or on an Optimol 2Disk tribometer. Originally developed for simulation of wheel-rail contact processes, twin disk testing machines offer an optimal basis for experiments on highly concentrated contacts in combination with the selected surface roughness to operate in the mixed boundary lubrication regime. Nowadays, new twin disc machines can be used for the characterization of tribological systems under dynamic test conditions in terms of slip ratio. Mimicking the working conditions and contact configuration of gear teeth in contact and ball bearings, these testing machines are widely used.

In the Amsler and 2Disk tribometers, two discs with the same diameter roll against each other on their cylindrical surfaces. Using a single electrical motor and several coupling shafts, which ensure the mixed boundary lubrication regime at the start, the rotation speed is fixed at 390 rpm. To enable a continuous slip of 10%, the second disc, applied as the counterbody, is driven at a speed of 354 rpm. The exact sample configuration in this tribometer is shown in Figure 7.

For the Amsler machine the geometry of the discs, with an outer diameter of 42 mm and a width of 10 mm, generates a contact configuration of the ball-cylinder type. In order to avoid distortion of the test samples due to the heat treatment, pre-forms for the test samples were manufactured from the raw material (steel rod). These pre-forms have a stock allowance of approximately 0.3 mm on the diameter, width and inner hole dimensions. After the heat treatment the samples were processed by grinding and polishing to their final cylindrical and spherical shapes with the desired surface finish. In the present experiments the top, ball-shaped counter discs were mainly uncoated and only pre-polished or ground (R_a ~ 1.5 µm). The lower, cylindrical discs were used both in the coated and uncoated states with a highly polished surface (R_a ~ 0.005 µm). A normal force was applied by means of a spring, leading to a normal force up to 2,000 N (initial average Hertzian contact pressure P_{0mean} = 1.94 GPa) at the contact point (see Table III). The stiffness of the spring (14,650 N/m) and the lever action of the counterbody holder press the discs against each other. By controlling the compression of the spring the normal force can be adjusted in steps of 50 N. For comparison, an average contact pressure of P_{0mean} of 1.25 GPa corresponds to a maximum Hertzian contact pressure of P_{0max} = 1.875 GPa, which is equivalent to load stage 12 in the FZG test rig. According to the international standard ISO 14635-1, this load stage is the most demanding test procedure for gears using state-of-the-art gear oils. The hydrocarbon-based lubricant used was a synthetic factory fill-engine oil SAE 0W-30 named VP1 (ACEA A3/B4, long life, $HTHS^{150°C}$ = 3.0 mPas) with a content of sulfated ash of 1.20 wt.%. In general, engine oils have much higher additive treatment rates than gear oils, because engine oils require dispersants and detergents beside viscosity index improvers, as well as higher total base numbers (TBN). The kinematic viscosity at 120 °C was $\nu_{120\,°C}$ = 5.33 mPas and the pressure viscosity coefficient α for 1-1,001 bars at 120 °C was 12.8 GPa^{-1} [13]. The calculated value of minimum oil film thickness h_{min} at T = 120 °C and F_N = 930 N (or P_{0mean} = 1.50 GPa) is 0.027 µm, for F_N = 2,000 N (or P_{0mean} = 1.94 GPa) is 0.025 µm or for F_N = 5,000 N (or P_{0mean} = 2.62 GPa) is ~0.024 µm. The roughness values R_a of the uncoated steels ranged between 0.15-0.35 µm (spherical disk) and ~0.0035 µm (cylindrical disk) in the initial state resulting in a Tallian parameter, λ, between ~0.077 and 0.068, which denotes the regime of boundary friction. At 120 °C, the calculated oil film thicknesses are ≈1/10 of those at RT. The Hertzian contact stresses are at 120 °C, likely to be transmitted through the micro-asperities and not by hydrostatic pressure generated from a hydrodynamic oil film.



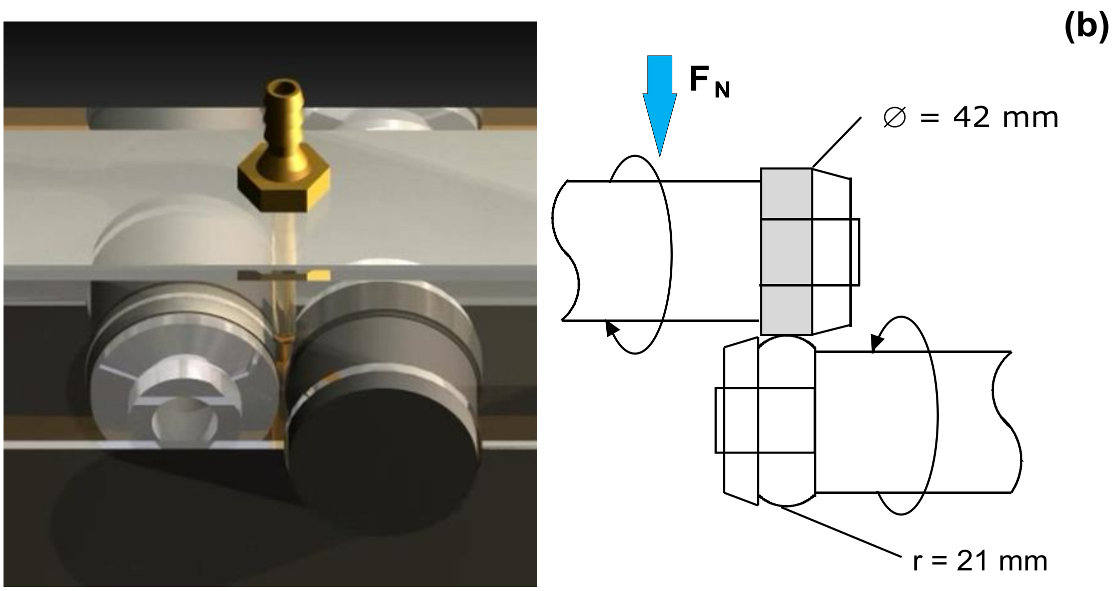


Figure 7. Sample arrangement in the twin disk tribometer; (a) AMSLER tribometer, (b) 2Disk from Optimol Instruments.

Table III. Experimental Conditions

Conditions	Parameter
Dimensions of the discs	Diameter: 42 mm; Width: 10 mm
Contact	Ground/polished curved disc (radius of curvature: 21 mm) against uncoated highly polished cylindrical disc
Substrate	36NiCrMoV1-5-7, 20MnCr5, Cronidur 30, 100Cr6H
Type of motion	Rolling with a fixed slip rate of 10%
Initial average Hertizian contact pressure P_{0mean}	1.5 – 2.62 GPa (F_N = 930 – 5,000 N)
Rotation at speed	390 – 354 rpm
Sliding speed at V_{diff}	0.08 m/s
Load cycles n_{tot}	Up to 10^7 or rupture (damaged surface area of >1 mm^2)
Effective sliding distance	Up to 132 km
Ambient temperature	120 °C oil bath temperature
Lubricant	BMW FF SAE 0W-30 'VP1' ACEA A3/B4 ($\nu^{120\ °C}$ = 5.33 mPas; $HTHS^{150\ °C}$ = 3.0 mPas)

In order to create experimental conditions as close as possible to real applications, the bath temperature of the oil is set at 120 °C. For safety, the temperature is controlled by a second thermal sensor couple with a programmable relay, reducing the temperature if it exceeds 140 °C. The lower cylindrical disc dips into the heated oil reservoir and drags the lubricant into the contact area due to the rotation. During the tests the friction torque can be measured by the axial torque of the lower shaft rotating at 390 rpm with use of a pendulum as well as a planetary gearing coupled with the mentioned axis. The coefficient of friction (COF) can be evaluated with the following equation:

$$\mu = M/(F_N \cdot r) \tag{1}$$

In this equation, M is the friction torque in Nm, F_N the applied normal force in N and r the radius of the driven sample in m. The deflection of the pendulum is converted into a translation movement for the measurement of the corresponding torque scale. A Linear Variable Differential Transformer (LVDT) permits the transduction of this movement into an electrical signal and records directly the COF [9].

The experimental setup in the newly designed Optimol 2Disk tribometer, similar to the Amsler type tribometer, generates a ball-cylinder contact mechanism using the same test samples. Designed for very high normal forces up to 5,000 N the tribological behavior of thin film coatings and their substrates can be tested under extreme conditions. This tribometer applies average contact pressures up to 2.62 GPa and can realize any slip ratio. Table IV summarizes the normal forces with the corresponding contact pressures (average P_{0mean} and maximum P_{0max}) and total deformation values of both samples according to Hertz' theory [14].

Table IV. Hertzian Contact Pressures for the Sample Geometries Tested

Normal force (N)	**930**	**2,000**	**4,400**	**5,000**
P_{0mean} (GPa)	1.5	1.94	2.5	2.62
P_{0max} (GPa)	2.25	2.91	3.75	3.92
Total deformation/flattening in the center of contact (µm)	13.4	21.2	37.8	41.2

The 2Disk test rig is powered by two electric motors, which rotate independently of each other. Thus, the slip rate of the two discs, as well as rotation speed, are freely adjustable, driven by an integrated computer control unit. In order to ensure the comparability and consistency of the test results obtained on both test machines, the experimental conditions (rpm, slip rate, lubrication and temperature) are always kept identical, with the exception of the Hertzian contact pressure. As shown in the test arrangement (c.f. Figure 7), the samples are positioned on the same vertical level, whereas the load application is induced by an electrical servomotor. This servomotor compresses a spring fixed between motor and axle of the cylindrical disc. It thereby adjusts the previously set normal force.

The test software is designed to measure the friction force as well as wear rates of both samples and plot it *in situ*. In contrast to the Amsler-type tribometer, the test sample does not dip into the oil reservoir. The oil is fed by a gear-type pump within a circular flow into the contact point of both samples in order to enable high speeds.

The quantification of the volumetric wear rates of the steel samples was taken to be the tribological criterion for the tests. Four profiles on each sample were taken by tactile profilometry perpendicular to the sliding direction, spaced at an angle of 90°. The measured average worn surface $\overline{W_q}$ permits the calculation of the volumetric wear rate, k_V, by the following equation:

$$k_V = \frac{V}{F_N \cdot L} = \frac{\overline{W_q} \cdot 2\ \pi\ r}{F_N \cdot n \cdot 2\ \pi\ r} \tag{2}$$

In this equation, V represents the worn material volume, F_N the applied normal force, r the sample radius, n the number of revolutions and L the distance run under sliding. Due to the low depth of the track, the wear volume V is equal to the planimetric wear surface $\overline{W}_q$ multiplied by the circumference of the sample.

Experimental Results

The slip-rolling tests were carried out by using the aforementioned test devices and conditions at four load stages. At P_{0mean} = 1.5 GPa and 1.94 GPa, the Amsler type tribometers were used. On increasing the applied contact pressure to 2.5 GPa and 2.62 GPa the tests were executed using the high performance Optimol 2Disk tribometer. Following the tests, optical microscopy images were taken of the wear track generated under the applied Hertzian contact pressure. In order to consider the performance of the different uncoated steels, the evaluated wear rates and coefficients of friction at the beginning and at the end of tests respectively were used for tribological assessment. Figure 8 shows the morphologies of the wear tracks on the cylindrical test sample and on its respective spherical counterbody at the four different load stages. In the case of steels 100Cr6H and 36NiCrMoV1-5-7 the tests at 2.62 GPa contact pressure were not conducted due to failures on the steel surface at a lower load stage.

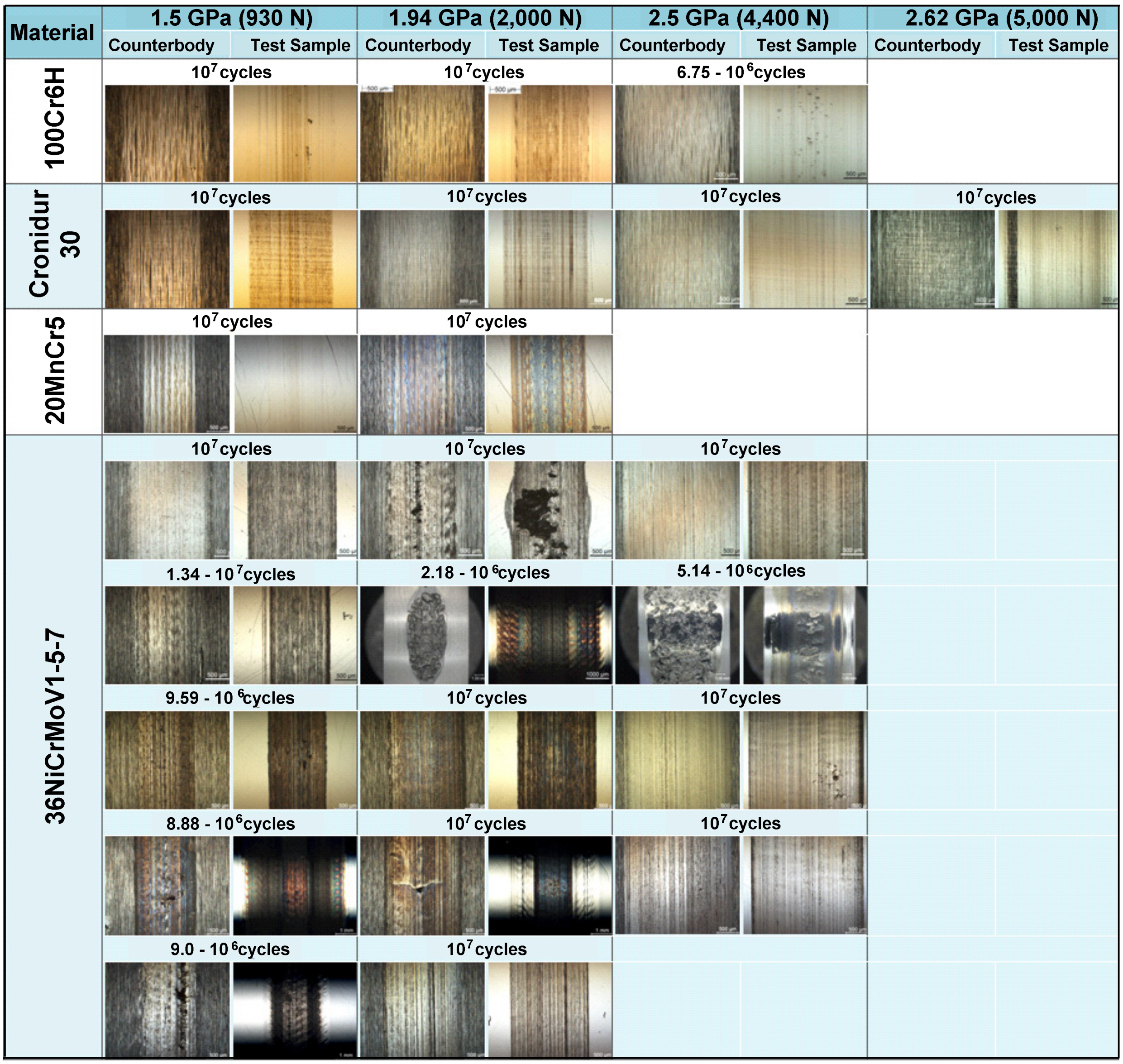


Figure 8. Optical light microscopy photographs of the typical wear tracks of rolling steel/steel contact displaying their morphology at different load stages, P_{0mean} = 1.5 to 2.62 GPa.

All optical pictures were taken after the upper testing limit of 10 million load cycles or upon the occurrence of the failure criterion (damaged area >1 mm²). In order to make the test results more comparable and reliable the candidate material 36NiCrMoV1-5-7 was tested at 1.5 GPa and 1.94 GPa in each case five times whereas at 2.5 GPa four tribological tests were conducted.

Considering the test results by looking at the light microscopy images taken after testing, it became clearly visible that 36NiCrMoV1-5-7 showed at all load stages a very inhomogeneous material behavior. 36NiCrMoV1-5-7 can be essentially slip-rolling resistant under P_{0mean} of 2.5 GPa, but individual samples failed at each loading level, or level of contact stress, before the end of the test at 420 hours (10 million load cycles) and showed serious damage to the surfaces. This behavior directly raises the question about the reasons as the slip-rolling resistances lie outside of the Lundberg-Palmgren relation.

All test results of 36NiCrMoV1-5-7 are shown in a summary diagram in Figure 9. The logarithmic y-axis indicates the number of cycles reached. In this figure, the load stages are represented by different colors, using at each stage the same lubricant SAE 0W-30 VP1. When the tested steel pairing reached the test end of 10 million slip-rolling cycles, a red dotted line symbolizes the good performance desired, with the indication that the steel could sustain the tribological stresses longer. In the grey boxes, top and bottom, the type of the steel counterbody and test sample are reported. At the base of the bars in the yellow boxes are the wear rates of the spherical and cylindrical samples determined after the tests. (In cases where fatigue failure occurred during the test, no wear rate was calculated.) The small vertical bars represent the coefficients of friction at the beginning (left) and at the end (right) of the tests.

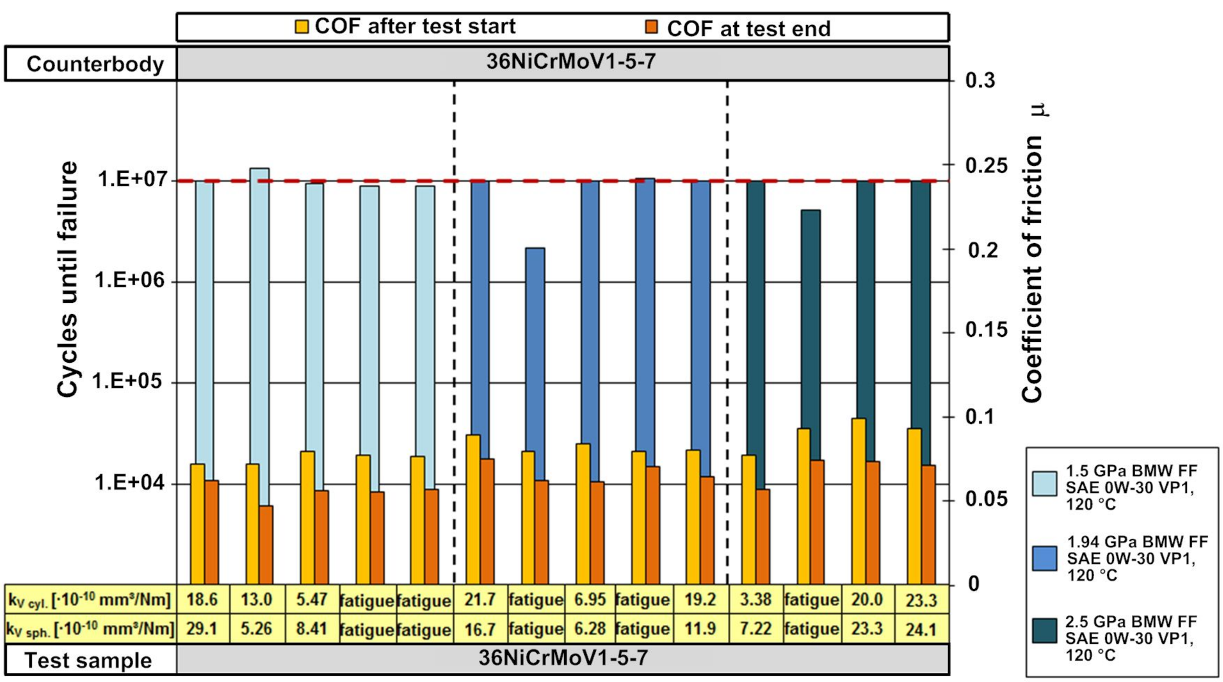


Figure 9. Number of load cycles reached, COF and wear rates of self-mated 36NiCrMoV1-5-7 samples under slip-rolling conditions.

Figure 9 illustrates once again the inhomogeneous test results for load cycles obtained as a function of contact pressure. Otherwise, the COF at test beginning and end shows good, reproducible and consistent results. At 1.5 GPa the initial COF ranges from 0.072 to 0.079 and furthermore the COF at test end lies between 0.047 and 0.062. On this occasion, a damaged and roughened surface does not seem to have any influence on the COF. A possible explanation of the inhomogeneous behavior of the 36NiCrMoV-5-7 alloy can be the presence of inclusions throughout the material volume (cf. Figure 10). The analysis revealed calcium sulfide (CaS) as well as aluminum oxide (Al_2O_3) and magnesium oxide (MgO) inclusions, see Figures 10(c) and (d), and alumina-silicates. These result from the calcium-argon treatment (CAB). The significant non-metallic and metallic inclusion populations act as crack initiators, especially when they are locally agglomerated directly beneath the stressed surface. Therefore, inclusions are able to initiate microcracks during the cyclic contact stresses introduced by the rolling load in the shallow layer beneath the raceways. Eventually, the microcracks can break through the raceway surface and spalling may occur, leading to the total failure of the material [15]. Non-metallic inclusions have their origin in melting and casting during the steelmaking process in an air environment. Thus, techniques such as vacuum induction melting (VIM) and vacuum arc remelting (VAR) are necessary to improve the cleanliness and homogeneity of highly stressed steels to avoid rolling contact fatigue.

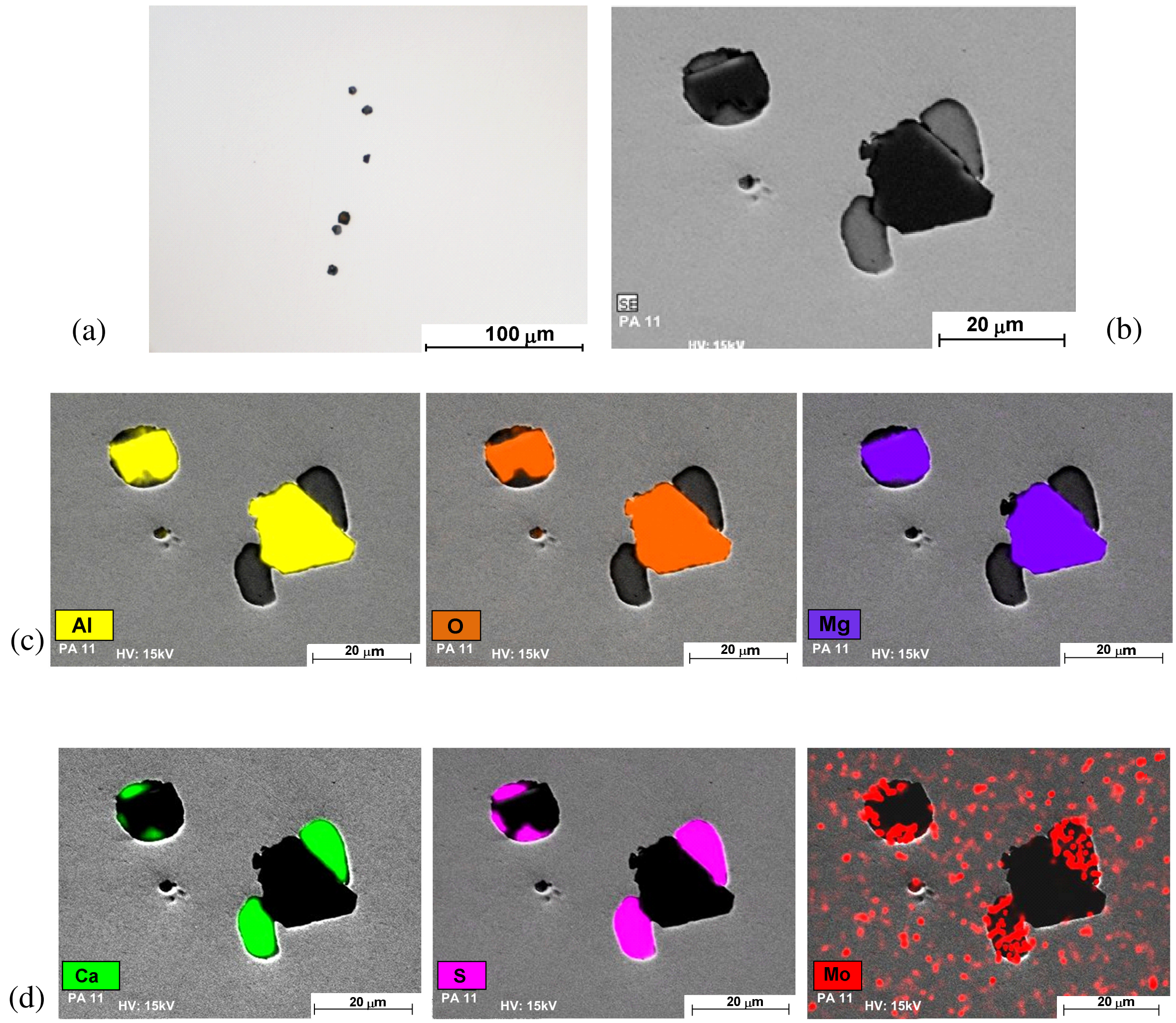


Figure 10. (a) Light microscopic image in cross section of 36NiCrMoV1-5-7 showing the presence of inclusions within the bulk material, (b) SEM image of inclusions in detail, (c) and (d) SEM/EDX element mapping images of inclusions.

Despite the question of "early" failures, the wear data in Figure 9 illustrate that the wear rates of 36NiCrMoV1-5-7 are more or less independent of the contact stress. This means that the load can be increased without compromising the load carrying capacity and wear as well as in terms of adhesive failures (seizures, galling). Furthermore, Figure 9 also reveals that the lower hardness level of ~ 480 HV 0.2 (see Figure 5) does not necessarily increase wear.

Considering the evolution of the coefficient of friction as a function of the test duration (10 million load cycles) in endurance tests conducted in the present work, the tribological benefit of the alternative steel 36NiCrMoV1-5-7 at $P_{0mean} = 1.5$ GPa becomes clearly visible (see Figure 11).

In comparison to conventional bearing steels, such as 100Cr6H and Cronidur 30 tested under identical conditions, 36NiCrMoV1-5-7 could reduce the friction values by approximately 30%.

In order to confirm these results, the test was repeated four to five times, using the same testing machine and conditions. Consequently, the low friction values of around 0.055 and down to 0.050 could be reproduced at $P_{0mean} = 1.5$ GPa. In the light of this comparison, it may be concluded that the reduction of friction by an optimal choice of the interaction between uncoated materials and lubricants could be achieved. Thus it allows the substitution of thin film coatings by an alternative steel, such as 36NiCrMoV1-5-7. However, the inhomogeneous slip-rolling resistance of 36NiCrMoV1-5-7 must be taken into account, which can be improved by different production processes to give a lower inclusion content.

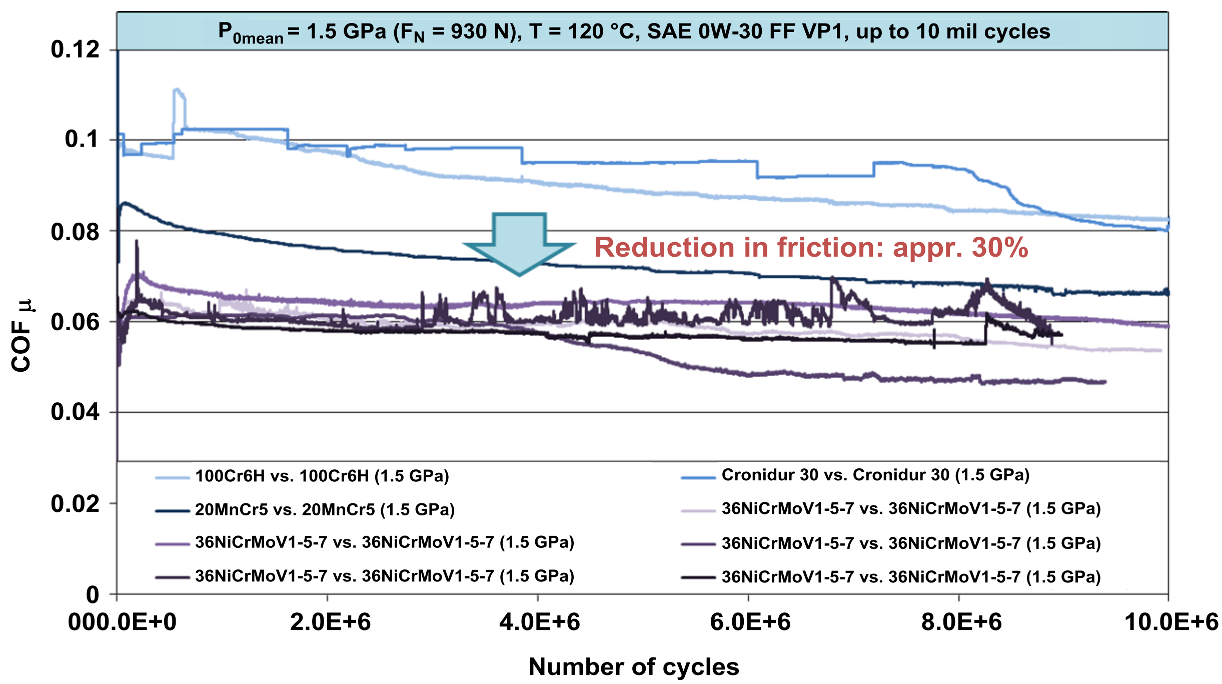


Figure 11. Evolution of the coefficient of friction over the test period of 10 million load cycles at $P_{0mean} = 1.5$ GPa and T = 120 °C in SAE 0W-30 VP1 oil.

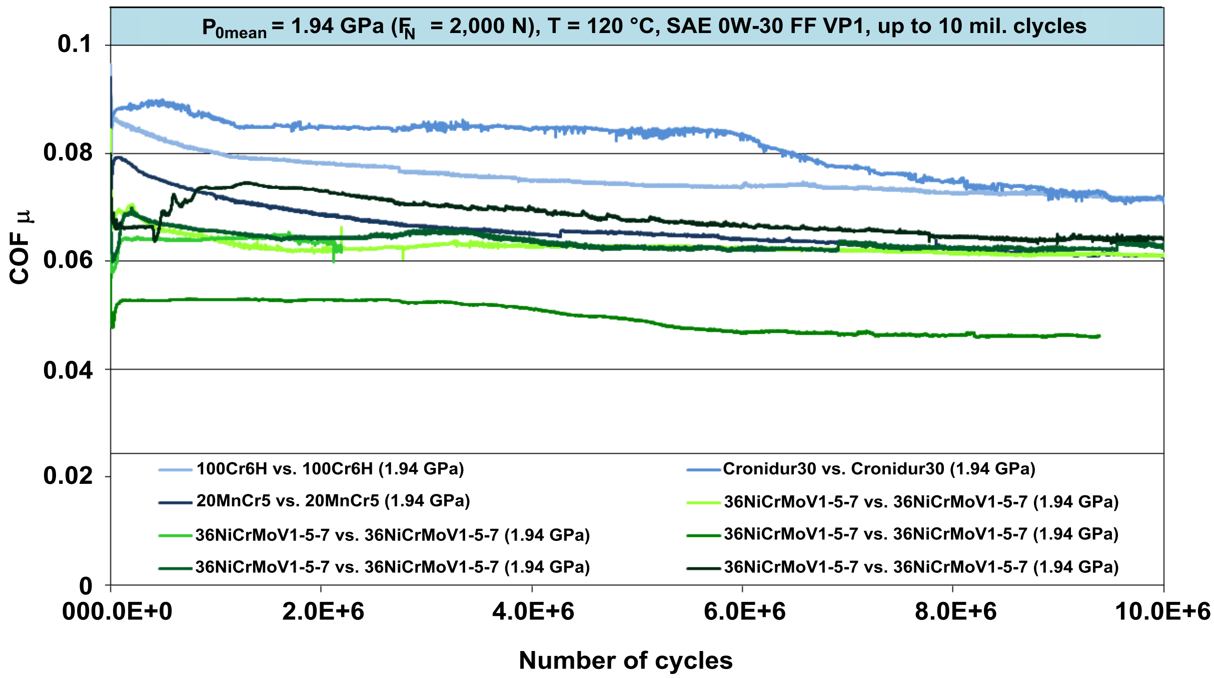


Figure 12. Evolution of the coefficient of friction over the test period of 10 million load cycles at P_{0mean} = 1.94 GPa and T = 120 °C in SAE 0W-30 VP1 oil.

Comparing the test results obtained at 1.5 GPa, to those at an average contact pressure of 1.94 GPa, Figure 12, the difference in friction values is less significant than in the case of tests at 1.5 GPa. Here again, 36NiCrMoV1-5-7 offers a friction reduction, in one case down to a value of 0.05. The repeat tests show that the coefficient of friction at test end is situated in most cases around 0.062, slightly higher than that at 1.5 GPa but still clearly lower in comparison to 100Cr6H and Cronidur 30. It was thus possible to show in ten tribological tests and under two contact pressures above FZG 14, using 36NiCrMoV1-5-7 as the test material, that the potential of reducing friction is realized by using the alternative steel without the need for coatings.

Looking at the evolution of the coefficient of friction at P_{0mean} = 2.5 GPa, the frictional advantage of 36NiCrMoV1-5-7 compared with 100Cr6H and Cronidur 30 is still apparent (cf. Figure 13).

As shown above, the frictional profile of highly concentrated contacts or systems can be optimized by a suitable material choice, for example, 36NiCrMoV1-5-7. Similar frictional results can be obtained by applying a highly wear resistant and low friction DLC coating. Therefore, an endurance test series was conducted, with different a-C:H thin film coatings of the BMW Group in order to distinguish the frictional potential of 36NiCrMoV1-5-7. The test series was separated into three parts. First the uncoated steel samples of the materials 100Cr6H, Cronidur 30 and 36NiCrMoV1-5-7 were tested at P_{0mean} = 1.5 GPa. The second part concerned the material pairing of uncoated steel (spherical disk) vs. DLC-coated steel (cylindrical disk). After finishing these tests, the third part followed comprising the DLC-coated steel (spherical disc) vs. DLC-coated steel (cylindrical disk). In order to guarantee the same adhesion properties of the coatings on the steel surface, the ground, spherical bodies were polished in the same manner as the cylindrical disks.

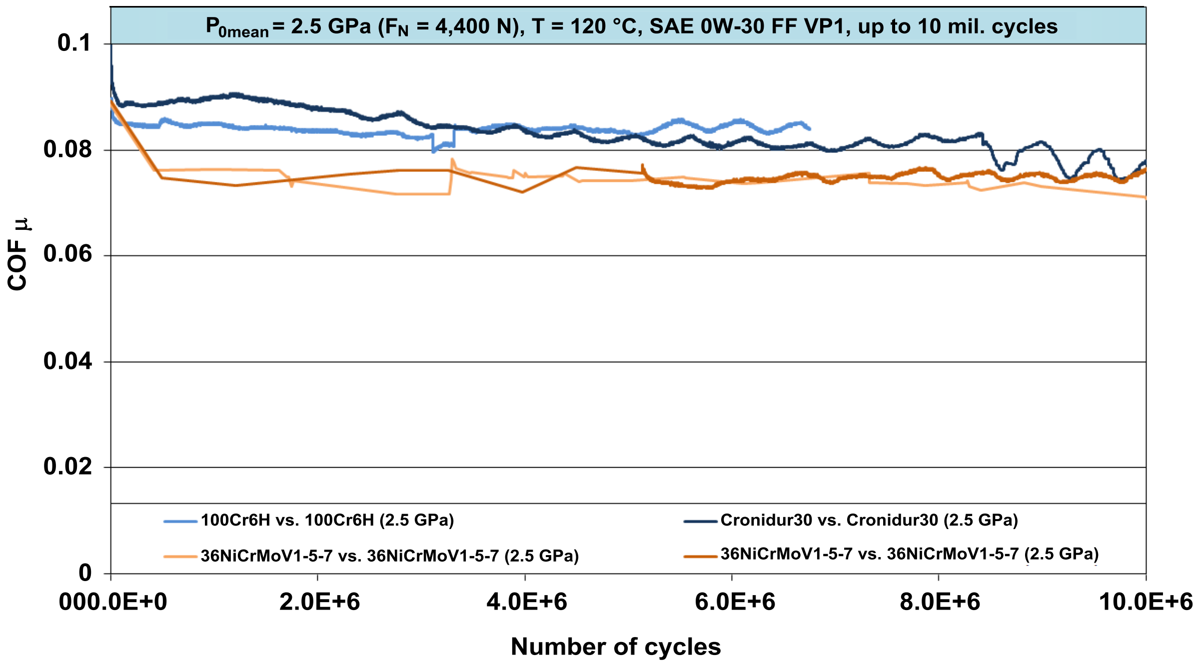


Figure 13. Evolution of the coefficient of friction over the test period of 10 million load cycles at P_{0mean} = 2.5 GPa and T = 120 °C in SAE 0W-30 VP1 oil.

The test results are presented in Figure 14, including one endurance test of uncoated Cronidur 30 vs. uncoated 100Cr6H as reference (red curve). Considering the evolution of the coefficient of friction over the test duration (10 million load cycles), this diagram revealed three regions.

The first region represents uncoated steel pairings with average coefficients of friction of 0.075 at test end. The application of a DLC-coating on the cylindrical test sample could reduce the friction values significantly, shown by the second region (green curves) in Figure 14. Considering the course of the pink curve (uncoated 36NiCrMoV1-5-7) it is remarkable that suitable, alternative and uncoated steels could offer the same potential to reduce friction as a DLC coating. When specifically designing the lubricant for such steels, the frictional benefit of uncoated steels could be more pronounced. The blue curves in Figure 14 represent the third region, ie. DLC vs DLC pairings, which showed the most promising results to reduce friction. In comparison to uncoated systems, the combination of DLC coatings in the contact region is, at the moment, the optimum. However, these results were obtained using perfectly finished steel surfaces before the coating process and showed what is potentially possible in future work.

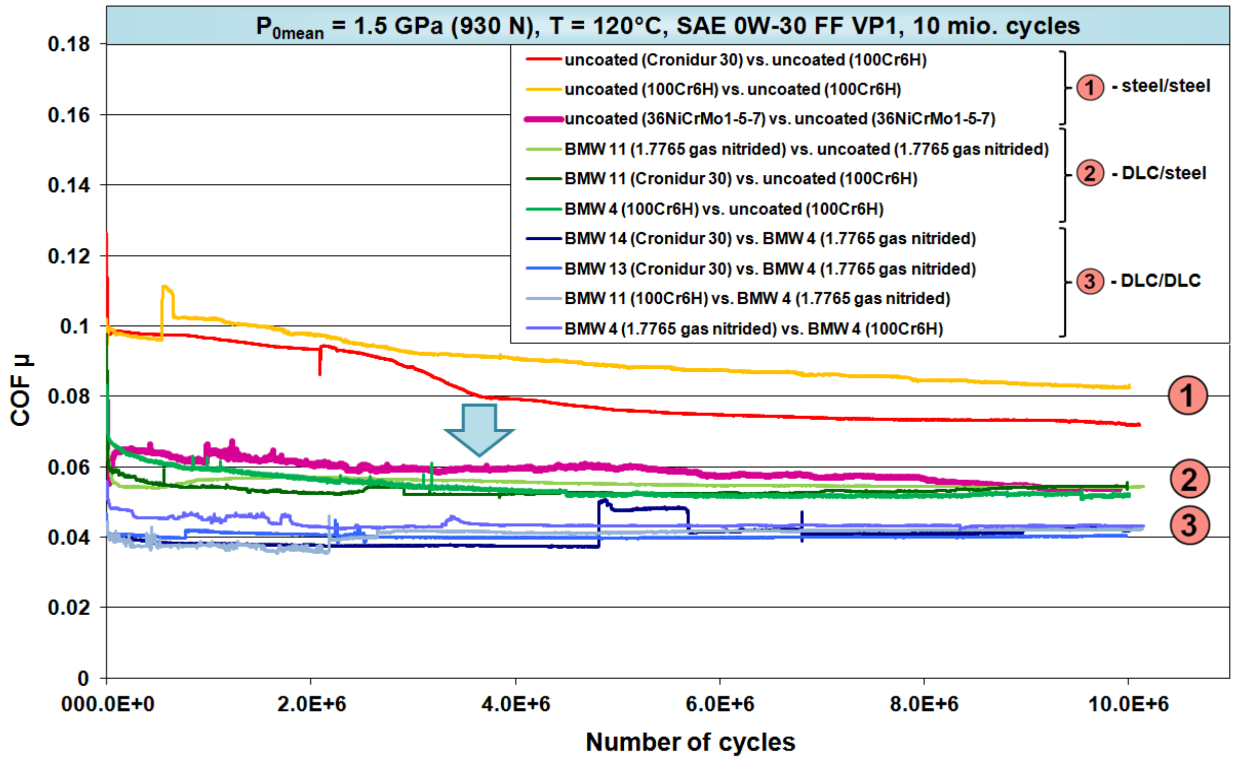


Figure 14. Comparison of friction coefficients of test pairings without any DLC coatings (100Cr6, Cronidur 30, 36NiCrMoV1-5-7), single coated samples and pairings with DLC coatings applied on both samples, tested at P_{0mean} = 1.5 GPa and T = 120 °C in SAE 0W-30 VP1 oil.

Figure 15 benchmarks the global impact of 36NiCrMoV1-5-7 in comparison to thin film coatings and a multitude of uncoated steels [3,4] on friction and wear under mixed/boundary conditions for slip-rolling motion lubricated by SAE 0W-30 FF VP1 oil at 120 °C. The steel 36NiCrMoV1-5-7 investigated in the current paper is compared with the following hardened and tempered steels:

(a) High carbon steels;
- 100Cr6 (1.3505, VIM-VAR)
- 102Cr6 (1.2067)

(b) Steels with advanced case hardening;
- 20MnCr5 (1.7147)
- CSS-42L (AMS 5932, VIM-VAR)

(c) Nitrogen alloyed steels;
- Cronidur 30 (1.4108, DESU)

(d) Silicon alloyed steels;
- NC310YW (40SiNiCrMo1)

Metallurgical details and detailed slip-rolling results are provided in the references [3,4,16]. CSS-42L is a Maraging steel requiring advanced case hardening, which takes some days. Hardening mechanisms based on silicon or nitrogen require both "clean" and "oxygen-free" melting and heat treatment cycles, keeping these alloying elements in solution without forming nitrides or silicides.

(In Figure 15 the horizontal bars represent the spread of results for all the hardened and tempered steels. The individual spreads for 100Cr6H and Cronidur30 in the uncoated condition are indicated by the dark green bars.)

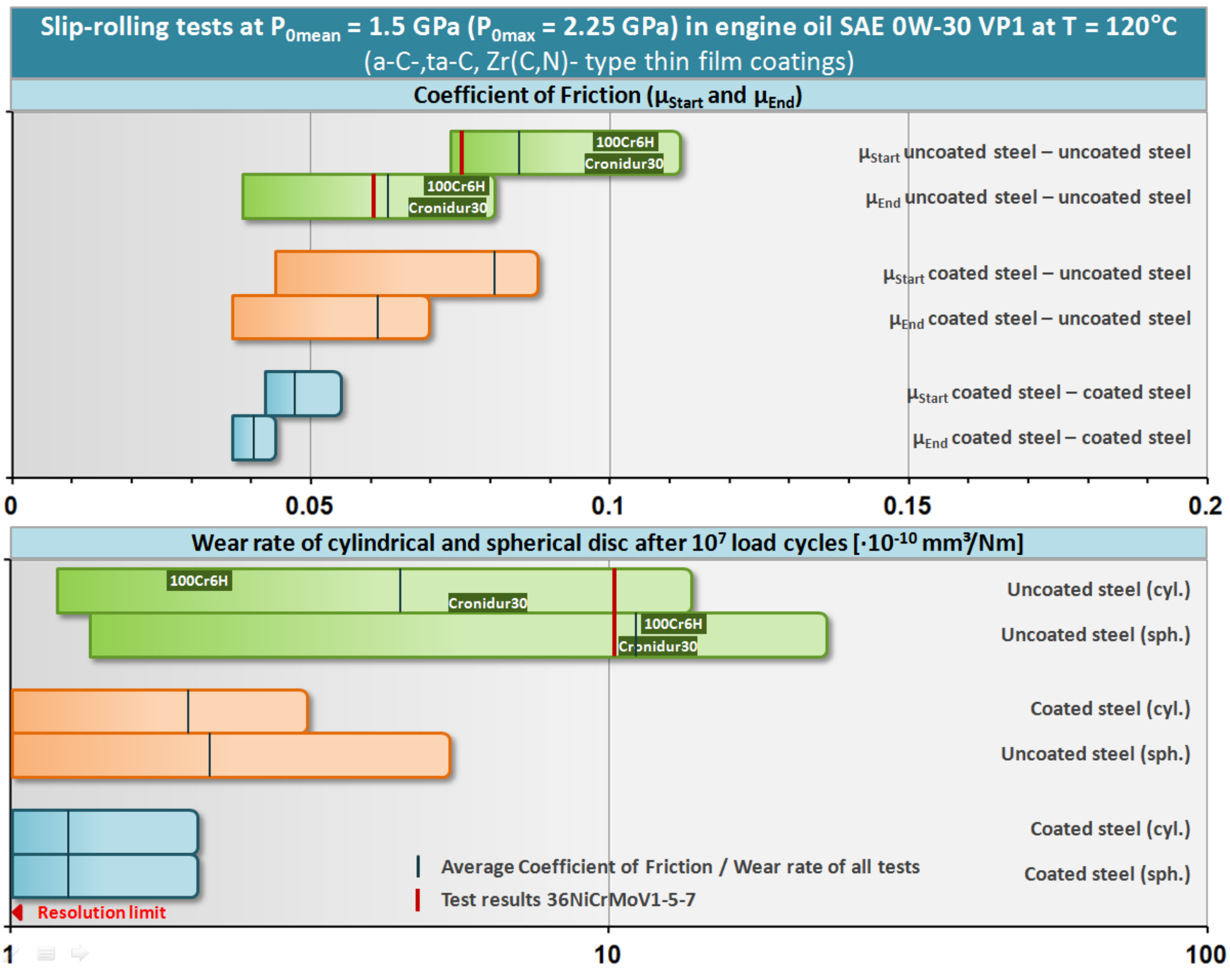


Figure 15. Comparison of friction and wear behavior of uncoated steel pairings, single coated pairings. [4,8,10,11].

It is instantly apparent from Figure 15, that the friction values of completely uncoated systems offered, on average, considerably higher friction coefficients at the beginning of the tests than systems where two DLC coated surfaces [11] are mated.

Conclusions

The majority of uncoated steels presented coefficients of friction between 0.06 – 0.09, but selected iron-based steel metallurgies, such as the high toughness steel 36NiCrMoV1-5-7, can also achieve low values of ~0.06 at test end, in the same range as test pairings rolling DLC against uncoated steel. From this point of view, it can be said that the application of thin film coatings on steel surfaces, with their difficult deposition and quality assurance requirements, can be avoided, if alternative steels are considered at the early design stage and appropriately used.

Basically, for wear resistance it is the same picture as for the frictional behavior. Thin films reduce wear rates by factors of 2–5, rather than by orders of magnitude. However, good slip-rolling resistance of 36NiCrMoV1-5-7 was demonstrated, but its variability needs to be improved by adequate steel production methods.

36NiCrMoV1-5-7 can substitute 100Cr6H and Cronidur 30 and offer similar load carrying capacity and slip-rolling resistance with associated lower friction coefficients.

It has to be noted that the wear resistance of 36NiCrMoV1-5-7 with a "quite low" hardness of 480 HV competes with those of hardened and/or case hardened steels.

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