lubricants

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Technical Note

Test Modes for Establishing the Tribological Profile under Slip-Rolling

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Abstract: The complex nature of slip-rolling contacts in many applications such as gear tooth flanks, rolling bearings, and heavy machinery often makes determining the friction and wear properties, as well as the fatigue resistance, of tribosystems difficult. The establishment of the tribological profile of a tribocouple under high Hertzian contact pressure and under slip-rolling will allow for the measurement and comparison of friction and wear coefficients as well as slip-rolling resistance by continuously monitoring the wear rate, coefficient of friction, temperature, oil film thickness, and/or electrical contact resistance using high-resolution signal analysis (HRA). A twin disc system can provide insight into the adhesive behavior of material and lubricant products such as alternative base oils and additives, ceramics, alloys, and thin film coatings. The strength and endurance of these products are often characterized through fatigue and resistance tests, which apply high Hertzian contact pressures to the rolling contact until seizure or failure is obtained. The further observation of the formation of tribofilms on the surface of contact yields information about the reactivity and thermochemical properties of additives. This review aims to illustrate how the implementation of different screening methodologies can be used as a meaningful tool for assessing the aforementioned tribological profile properties for the development of slip-rolling tribosystems.

Keywords: coefficient of friction; slip-rolling resistance; volumetric wear rate; Hertzian contact pressure; seizure load capacity; oil-film thickness; tribofilms; coatings

1. Introduction

A slip-rolling contact is one where the surfaces in contact with each other are rotating against each other with a specified percentage of slip. Examples of these contacts include tooth flanks, rolling bearings, cam-follower systems, continuous variable transmissions, toroidal gears, ball-screw and ball-nut drives, planetary roller screws, synchronous rings, and wheel–rail contacts. Due to arising ecological and energy concerns, improvements in lubricants and the load carrying capacity of tribological components is of global interest [1]. Lightweight approaches to develop cheaper machine parts and meet growing efficiency targets have placed strain on the physical capabilities of slip-rolling contacts in many industries, including heavy industry, the automotive industry, and metallurgy. In systems that involve the use of bearings and gear components, the pursuit of lightweight design has increased torque and Hertzian contact stresses, shortening the lifetime of these parts without proper lubrication [2,3]. Reducing the size of tribological components is seen as an important approach to both reduce carbon emissions and increase efficiencies, especially in the automotive industry [4,5].

However, recent advances in material composition, ceramics, and coatings have proved adept at slowing this accelerated degradation and improving the tribological properties of the material. Compared to steel ball bearings, ceramic ball bearings composed of silicon nitrides are high scuff resistant and generate low heat when operating under high loads and rotational speeds [6]. Furthermore, diamond-like carbon (DLC) coatings and, more recently, tetrahedral hydrogen-free amorphous carbon (ta-C) and hydrogen-free amorphous carbon (a-C) coatings, which do not dehydrogenate when exposed to hot oils or environments with low lubrication, are being used extensively in automotive applications for their low friction and wear properties [7,8].

The proper lubrication of slip-rolling contacts is essential to reduce harmful friction and wear, which extends the lifespan of these contacts and improves their efficiency [9]. Solid and liquid lubricants can react with the solid surface to create a tribofilm, with both physical and chemical properties that are characteristic to that tribofilm [10]. Some of these properties are measurable and can provide insight into the performance and behavior of the tribosystem, which is composed of the lubricant and contacts, such as the coefficient of friction (COF) and electrical resistance.

To study and reproduce slip-rolling contacts, twin disc tribometers are typically used. Generally, slip-rolling or highly-concentrated contacts are sensitive to wear under mixed/boundary lubrication regimes and fatigue over several load cycles [11]. The fatigue and crack growth of alloys can be enhanced by base oils and additives. Therefore, the twin disc tribometers must be capable of recreating the boundary lubrication regime. By varying the composition of the two contacts and lubricants, these types of tribometers can be an effective tool to further analyze the complex tribocontacts. This review paper will investigate the development of a new twin disc test rig, the Optimol 2disk tribometer, and will assess its effectiveness in analyzing the behavior of a tribocontact. Additionally, the paper will consider the test rig's capability to be used in research and development applications for the development of new lubricants, coatings, and tribocontacts.

2. Newly Developed Tribometer for Rolling Contacts

Two-disc test rigs are model tribometers, which drive two rotation symmetrical test specimens and press their cylindrical or spherical surfaces against each other. The most popular two-disc test rig is the Amsler test machine, type A135, which was introduced in 1922 [12]. The SAE EP test machine (SAE 2 machine) using Timken test cups was introduced in the 1930s. Twin disc tribometers are used to simulate the boundary lubrication of rolling contacts under a preset slip ratio. Lubricating oil is typically introduced to the tribocontact through an injector or from a thermostatically-conditioned reservoir below one of the discs. Compared to "historic" twin disc tribometers, the shaft in the 2disk is independently driven. Operation can either be synchronous or asynchronous, such that each disc can operate at different speeds since each disc is mounted on an independent drive shaft. A schematic of one of these tribometers is shown in Figure 1. The two shafts are water cooled in order to absorb the generated frictional heat.

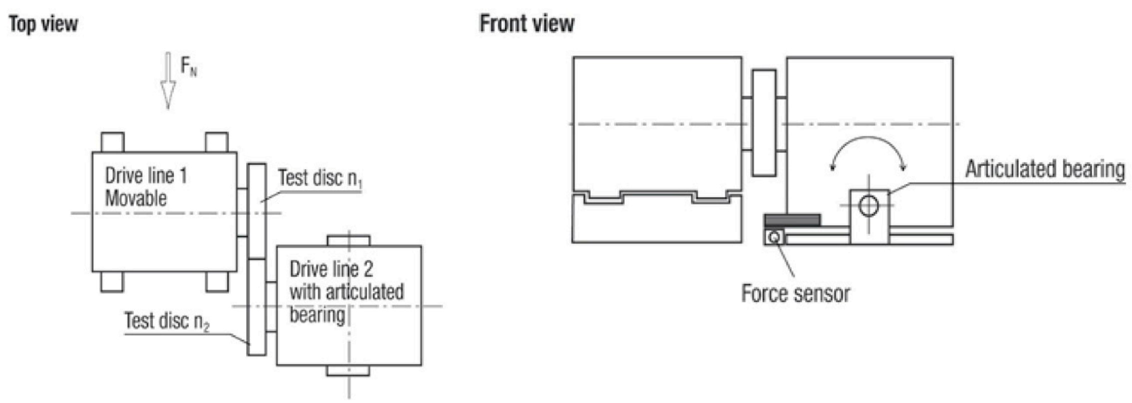

Figure 1. Schematic design of a twin disc tribometer.

Due to the development of higher performance lubricants, these tribometers must also be able to achieve high enough Hertzian contact pressures (P_0) for proper testing. Initial Hertzian contact stresses of P_{0max} < 4.2 GPa for F_N = 5000 N are achieved with the present spherical-cylinder contact geometry (for R = 21 mm and R1 = R2 = 21 mm). As components decrease in size and become more lightweight, Hertzian contact stresses have increased above P_{0max} ~ 2170 MPa, which correlates to an FZG stage of 14 [13]. Additionally, it would be ideal if the tribometer could be modified to exchange the discs to allow the testing of different alloys and coatings. A twin disc tribometer with these features can effectively analyze the tribological behavior of a wide variety of contact materials, lubricant formulas, and additive packages.

This paper will focus on one newly developed state-of-the-art twin disc tribometer, the Optimol 2disk test rig. This tribometer allows dynamic testing through high-speed stepless drives and a variable loading device, which can test at any desired slip-ratio from 0% to 100% using two cylindrical or spherical test discs with diameters of 45 mm and 60 mm. The test rig can variably change the contact load, temperature, drive speed and slip-ratio to analyze the tribosystems and enable dynamic test profiles. To do so, the test rig can measure the frictional force, wear rates, oil film thickness, acoustic emission, and electrical contact resistance for each test cycle, among other parameters. By measuring the planimetric cross area in the wear track of the test disk in four different locations, the average wear volume can be determined and can then be used to calculate the wear rate coefficient. In the 2disk test rig, the sliding of the test discs is parallel to the rolling motion, whereas other twin disc tribometers utilize sliding that is perpendicular to the rolling motion.

The Optimol 2disk tribometer can be used to analyze the tribological profile of a wide variety of tribosystems through endurance slip-rolling tests after more than ten million cycles. This test rig can be used for research and development for many tribological applications by monitoring the following properties: the evolution of the coefficient of friction, wear coefficients under a selected Hertzian contact pressure, load carrying capacity at different Hertzian contact pressures, formation of tribofilms through frictional analysis, and retention of additives and base oils through the frictional response.

3. Purpose and Methodology

This paper aims to illuminate different test modes of the 2disk tribometer as an example of a twin disc tribometer when examining the tribological profile of various coatings, additive packages for lubricants, and different types of steel. This will be accomplished by investigating and reviewing the published literature where this tribometer is used to evaluate the frictional and wear properties of the slip-rolling tribosystem. Three of these published papers were chosen for a detailed analysis: one paper regarding coatings, another about lubricant additives, and the third paper about steel heat treatment and pre-conditioning. For each of the three papers, important data and the main findings of the paper will be discussed in detail in the sections below. Conclusions will then be drawn, with regard to the 2disk test rig's capability to be used in research and development applications for a wide range of tribosystems.

4. Discussion

4.1. Coatings

Thin film coatings are viewed as a cost-effective way to reduce friction and prevent the adhesive failures of mechanical components. This is especially important in the automotive industry as emission and energy standards are becoming increasingly tight. Diamond-like coatings (DLC) are the fore-runners in this field, but the friction reduction is sensitive to the additive package and can be further improved by specific additives, like glycerol monooleate (GMO, 111-03-5) and glycerol monoisostearate (66085-00-6). Zr(C,N) inevitably forms ZrO_2 on its surface, which interacts with state-of-the-art additives tribologically in the same way as steels. Zr(C,N) coatings underwent fatigue tests for mean contact pressures ranging from ~1.5 to 2 GPa with a fixed slip ratio of 10%. Tests were carried out for two temperature regimes: room temperature and 120 °C. For the tests at room temperature, an unadditivated paraffinic oil in ISO VG46 ($\nu^{40\,°C}$ = 51.96 mm^2/s) was used, and for the tests at 120 °C, fully formulated motor oil (BMW SAE 0W-30) was used. The higher oil temperature intensifies the tribological stresses of the system, as oil film thickness decreases exponentially with temperature. For the fully formulated engine oil SAE FF 0W-30 ("VP1"; HTHS = 3.0 mPas, ACEA A3/B4; $\nu^{120\,°C}$ = 5.33 mPas), the calculated value of the minimal film thickness h_{min} is 0.0252 µm at T = 120 °C and F_N = 2000 N. The roughness values of the steel substrate (Ra cyl. = 0.0048 µm, Ra sph. = 0.17 µm) result in a parameter of Tallian of ~0.144, which denotes the regime of boundary lubrication. The same tests were also done using uncoated test discs and several ta-C and a-C coatings [1].

The study was interested in the failure of the coatings themselves and not the tribosystem as a whole, so the authors defined failure as when a damaged coated surface of 1 mm^2 appeared on the contact area. If there were no visible signs of failure, then the test would be stopped at ten million cycles. Among the variables monitored were hardness, oil film thickness, the coefficient of friction, contact pressure, the wear rate, and also wear tracks. The deposition of the various coatings onto the test discs proved to be extremely sensitive, requiring multiple batches to be tested. Coating deposition was carried out using the Cathodic Arc Plasma Deposition (CAPD) method at a process temperature of 400 °C. This temperature was chosen in reference to the high tempering temperature of the nitrogen alloyed bearing steel Cronidur 30 substrate used. To determine the advantages brought by the coatings, the 2disk test rig was employed to perform these endurance tests.

Figure 2 displays the results of the ten batches of coated samples when tested under the aforementioned conditions. The figure includes information for the number of cycles reached before failure according to Hertzian contact pressure, coefficient of friction, and temperature (color of the bars). The samples are also divided based on the batch number, lubricant, and testing configuration used. There are notable differences in the cycles reached between batches, an observation the authors reasoned could be from microstructural differences in the coatings. Even with performing pre- and post-mechanical surface treatments, these variations could not be eliminated and actually worsened the slip-rolling performance of the samples. However, three additional batches, Batches 8–10, were made using process-controlled nanolayering (pcnl) to attempt to replicate the results of the first batch, with much success.

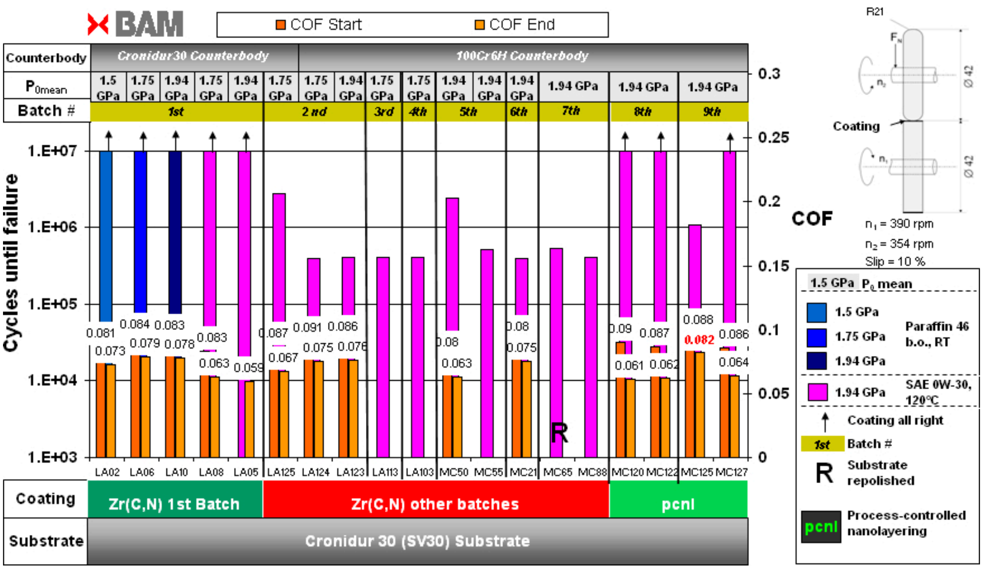

Figure 2. Slip-rolling results for Zr(C,N) coatings deposited on a Cronidur 30 substrate [1] from P_{0mean} of 1.5 GPa to 1.94 GPa.

The wear tracks of the steel counterbody and Zr(C,N) coating of the highly resistant first batch are shown in Figure 3, indicating no spalling or flaking. The oil temperature proved to have no negative effect on the magnitude of the wear tracks observed. Upon further examination of the wear tracks, the authors concluded that the additives contained in the motor oil at 120 °C formed a visible reaction layer after the tribological tests. This reaction layer is given by the color change along the raceways of the wear track. Scanning electron microscope tests show the presence of calcium, specifically calcium sulfonate or OCAB (overbased calcium alkyl benzene sulfonate), an additive with both extreme pressure and anti-wear properties, suggesting a possible reactivity with the Zr(C,N) coating. In the case of the unadditivated paraffinic oil, the same phenomena were observed, with evidence of higher tribological stress due to a higher surface roughness.

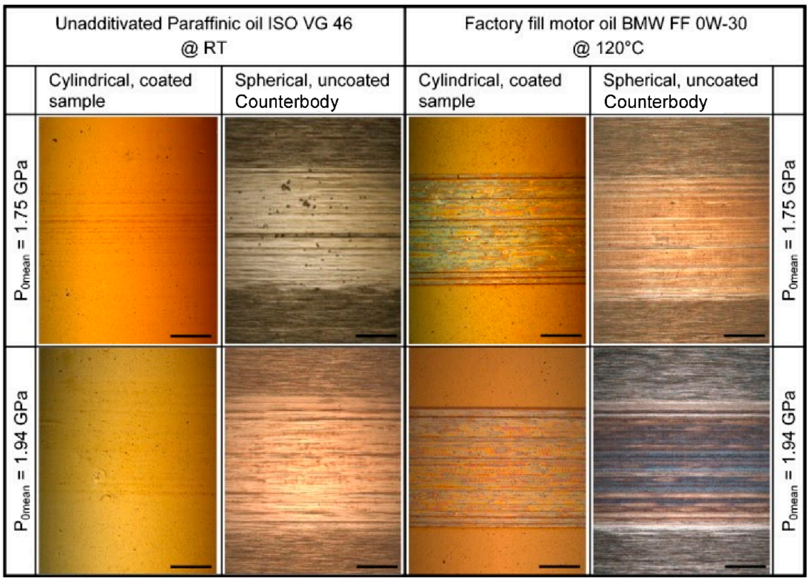

Figure 3. Microscopic images of the wear tracks on the uncoated counterbody and coatings after slip-rolling tests [1] at room temperature (RT) and 120 °C.

Comparisons with DLC coatings for the same test conditions in paraffinic oil, specifically those in the ta-C and a-C categories, show comparable slip-rolling resistances to the first batch of the Zr(C,N) coating. The initial and final coefficients of friction of these tests are displayed in Figure 4. However, when these ta-C and a-C coatings are paired with motor oil at 120 °C, performance decreases significantly, with no sample reaching ten million cycles. As with the Zr(C,N) samples, mechanical polishing to reduce the roughness of the deposited coatings had disastrous effects on the slip-rolling resistance and performance. Another important parameter considered was the frictional behavior of the thin-film coatings and how it contributes to the overall wear of the system. It was found that the highly resistant Zr(C,N) coating generated the lowest wear on the uncoated steel counterbody and also the lowest wear after ten million cycles, suggesting that Zr(C,N) was the most slip-rolling resistant of the coatings tested. However, with regard to the performance in a fully formulated motor oil at 120 °C, a-C:H:$_X$ coatings competed well with the Zr(C,N) coatings and offered the advantage of consistent reproducibility among batches. These conclusions drew from the results provided by the twin disc tribometer.

4.2. Lubricant Additives

The frictional response of new additives, like bismuth dimethyldithiocarbamate (Bi-dtc) and bismuth dodecylbenzenesulfonate (Bi-ddbsa), in comparison to molybdenum dithiodialkylcarbamate (Mo-DTC, $C_{11\text{-}14}$-branched and linear alkyl) [2] will be presented in this section. In the same test, the wear properties are also gathered and, if the test is executed to ten million load cycles, are also indicative of the slip-rolling resistance. Burbank and Woydt [2] determined if bismuth compounds can be used as a lubricating additive as an alternative to molybdenum-based additives, since some negative eco-toxicological properties of the molybdenum compounds are of increasing concern. Bismuth additives may participate in similar reactions to form tribofilms and could potentially offer improved tribological performance with a reduction in frictional losses.

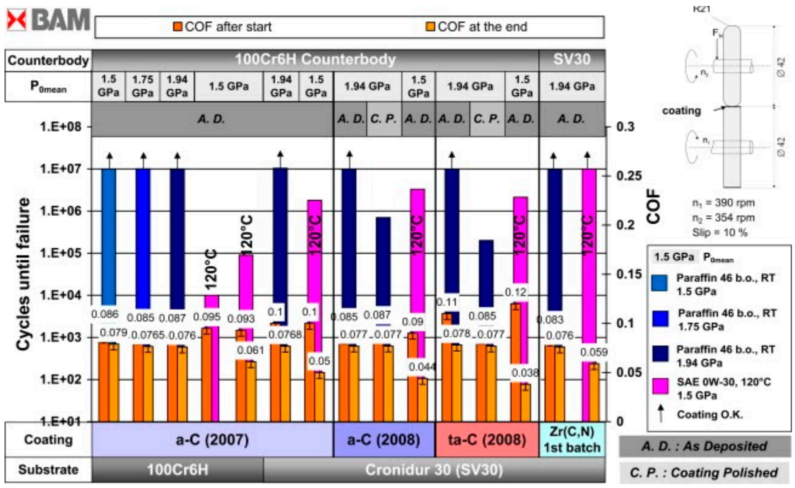

Figure 4. Slip-rolling results obtained with ta-C and a-C coatings [1] for different Hertzian contact stresses.

The authors use the 2disk tribometer for endurance testing to evaluate the friction and wear coefficients. Three additive packages were chosen to create a new tribofilm on cylindrical surfaces. Two of these contained bismuth compounds (Bi-ddbsa and Bi-DTC), while the third contained molybdenum compounds (Mo-DTC). Four different commercially available steel surfaces were tested for each tribofilm, with the steels being 20MnCr5 (SAE 5120H) with 6% and 14% residual austenite (RA), 36NiCrMoV1-5-7, and 45SiCrMo6 (1.8062). For each steel contact, one of each tribofilm was generated, then was tested using the 2disk test rig for its frictional and wear coefficients. The endurance testing lasted for 10^7 cycles, and SAE 0W-30 VP1 engine oil was used as a lubricant. The molybdenum and bismuth additive packages were not present in the lubricating oil, as the additives were only used to generate existing tribofilms before testing.

Burbank and Woydt found that all the steel contacts with and without tribofilms did not experience failure before the end of ten million cycles. The coefficient of friction (COF) was monitored for each contact across the test duration. The COF results are shown in Figures 5–7, for the 20MnCr5 (SAE 5120H), 36NiCrMoV1-5-7, and 45SiCrMo6 (1.8062) steel contacts, respectively.

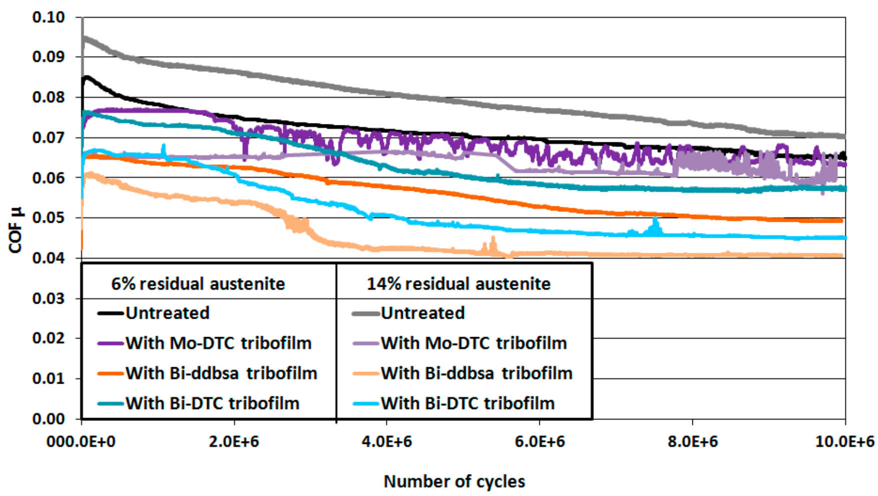

Figure 5. Evolution of the coefficients of friction in slip-rolling endurance tests of case-hardened 20MnCr5 (SAE 5120H) [2] under P_{0mean} = 1.5 GPa and 120 °C.

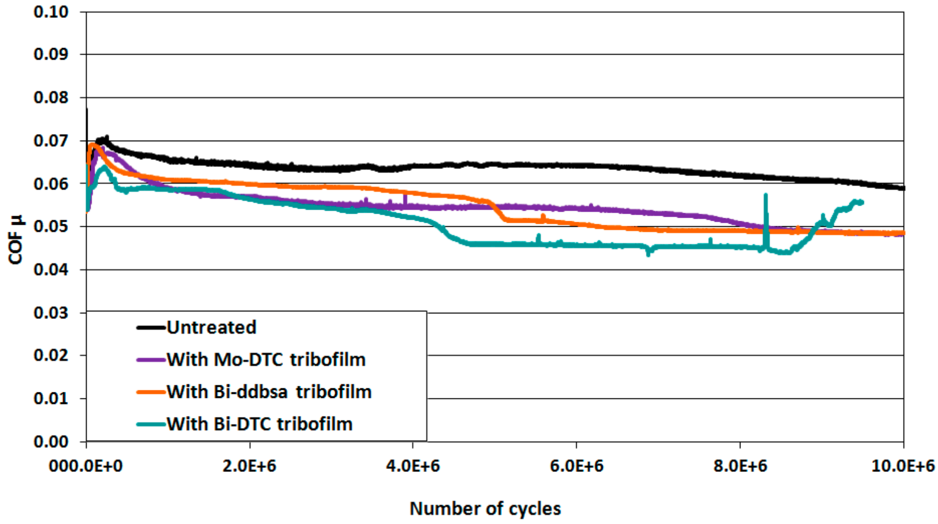

Figure 6. Evolution of the coefficients of friction in slip-rolling endurance tests of non-case-hardened 36NiCrMoV1-5-7 [2] under P_{0mean} = 1.5 GPa and 120 °C.

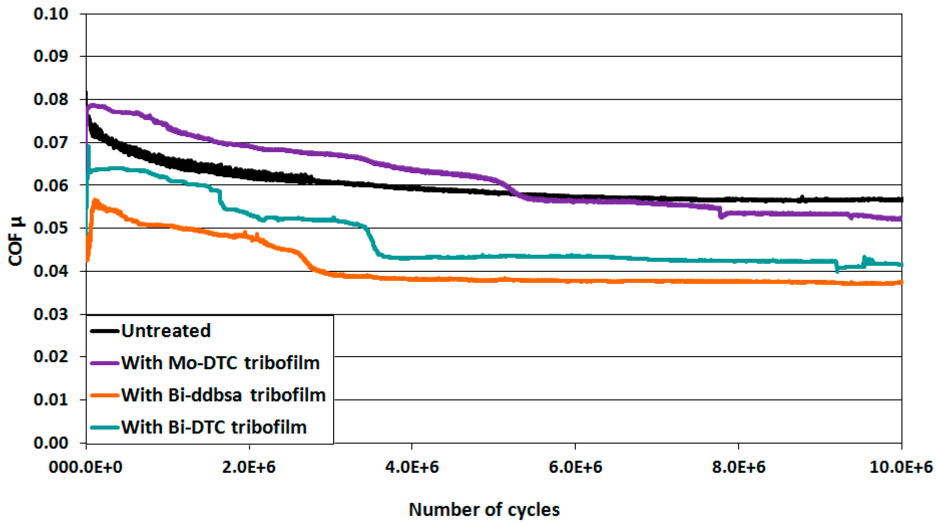

Figure 7. Evolution of the coefficients of friction in slip-rolling endurance tests of non-case-hardened 45SiCrMo6 (1.8062) [2] under P_{0mean} = 1.5 GPa and 120 °C.

Furthermore, the wear coefficient (k_V) was determined after the endurance testing for each steel contact and tribofilm. The wear coefficient results are shown in Figure 8.

The results from the COF measurements are fairly clear. For each of the three steels, the presence of a bismuth-based tribofilm (both Bi-DTC and Bi-ddbsa) resulted in a reduction in the COF. Additionally, the reduction in the COF from the bismuth-based tribofilms was greater than or equal to the reduction in friction from the molybdenum-based tribofilm (Mo-DTC) for each of the steel contacts. When looking at the wear coefficients, there is a significant reduction in the wear coefficients for every tribofilm when compared to the untreated steels. In some cases, such as the 36NiCrMoV1-5-7 steel, the bismuth-based tribofilms achieve a lower wear coefficient than the molybdenum tribofilms. Overall, the wear coefficients observed with the bismuth tribofilms are on par with those observed with the molybdenum tribofilms.

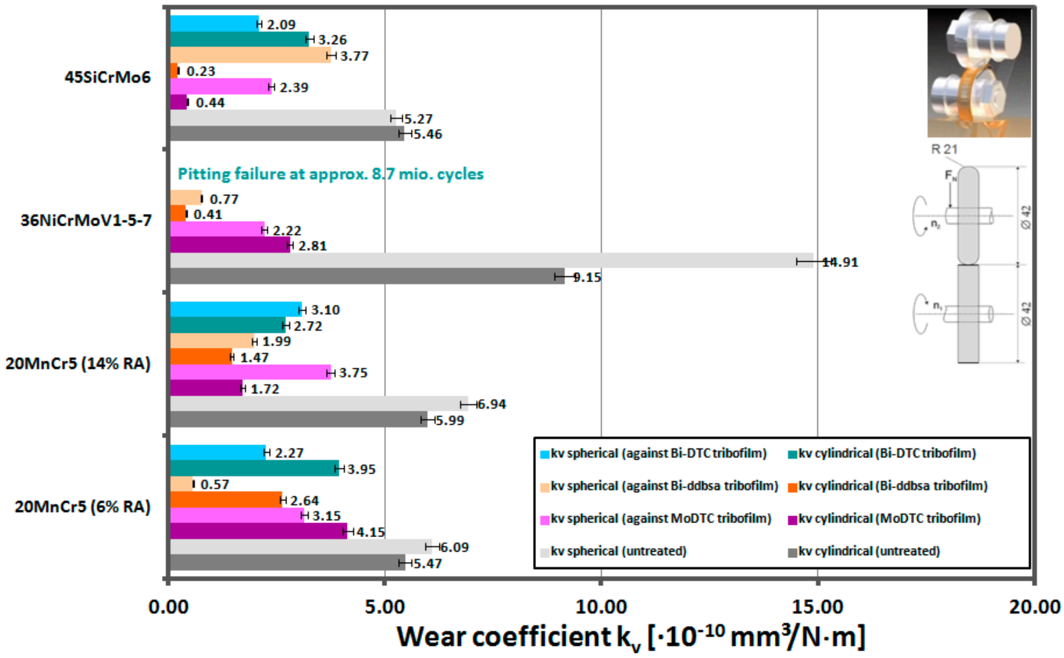

Figure 8. Wear coefficients of the cylindrical and spherical discs, with and without pre-conditioned tribofilms after slip-rolling endurance testing [2] under P_{0mean} = 1.5 GPa and 120 °C.

4.3. Pre-Conditioning of Steels

The benefits from the pre-conditioned cold work hardening of steel alloys were established in slip-rolling endurance tests using a twin disc test rig in combination with the residual stress depth profiles of subsurface regions and data for the hardness, wear coefficient, and coefficient of friction for both cylindrical and spherical configurations [3]. To avoid the critical material failure of mechanical components in tribosystems from increased residual stresses and the growth of microcracks, work hardening processes are sometimes used, known as "plasticity burnishing". The mechanism by which work hardening improves the strength of a material is on the microscopic scale, where deformations increase the dislocation density and/or trigger phase transitions. The aim is to produce, under controlled conditions, compressive stresses. This study sought to control the work hardening process through a pre-conditioned phase, in which experimental parameters such as contact pressure, rotational speed, and material lubrication are monitored.

Three steels were utilized to study the effects of work hardening on overall material strength and performance: the case-hardened gear steel 20MnCr5 (SAE 5120H) as a reference, hot working tool steel 36NiCrMoV1-5-7, and silicon alloyed spring steel 45SiCrMo6 (1.8062). The latter two steels were not case-hardened, for the purpose of comparing the properties of the steel before and after cold work hardening. The 2disk tribometer was used for the generation of cold work hardening in the contact zone of the cylindrical samples. Factory fill engine oil (BMW SAE 0W-30 VP1) was chosen for lubrication for its temperature resistance and kept at temperatures of 120 °C and above for all tests. The test discs used are realistic models for actual operational gear contacts and provide useful information as to how these material processes may improve the operation and longevity of internal combustion engine and automotive drivetrain components. The contact pressures ranged from 1.5 to 3.8 GPa, with tests running up to 10^7 load cycles and stopping when a damaged surface area of 1 mm^2 appeared, as was the case with the first study considered in this review.

Residual stress depth profiles were taken for the three steels both before and after cold work hardening and endurance testing. The alternative steels, 36NiCrMoV1-5-7 and 45SiCrMo6, however, were not able to provide residual profiles for after-endurance testing due to failure from the pre-conditioning stage. The residual profiles for 20MnCr5 steel and the two alternatives are shown in

Figures 9 and 10, respectively. The residual stresses generated in the pre-conditioning of 20MnCr5 proved stable up to 10^7 load cycles compared to the alternative steels, which did not meet this benchmark. The authors suggested lowering the mean contact pressure to 1.94 GPa, running surface treatments, and increasing the temperature to +140 °C in future studies to bring the compressive stress maxima closer to those of the shear stresses.

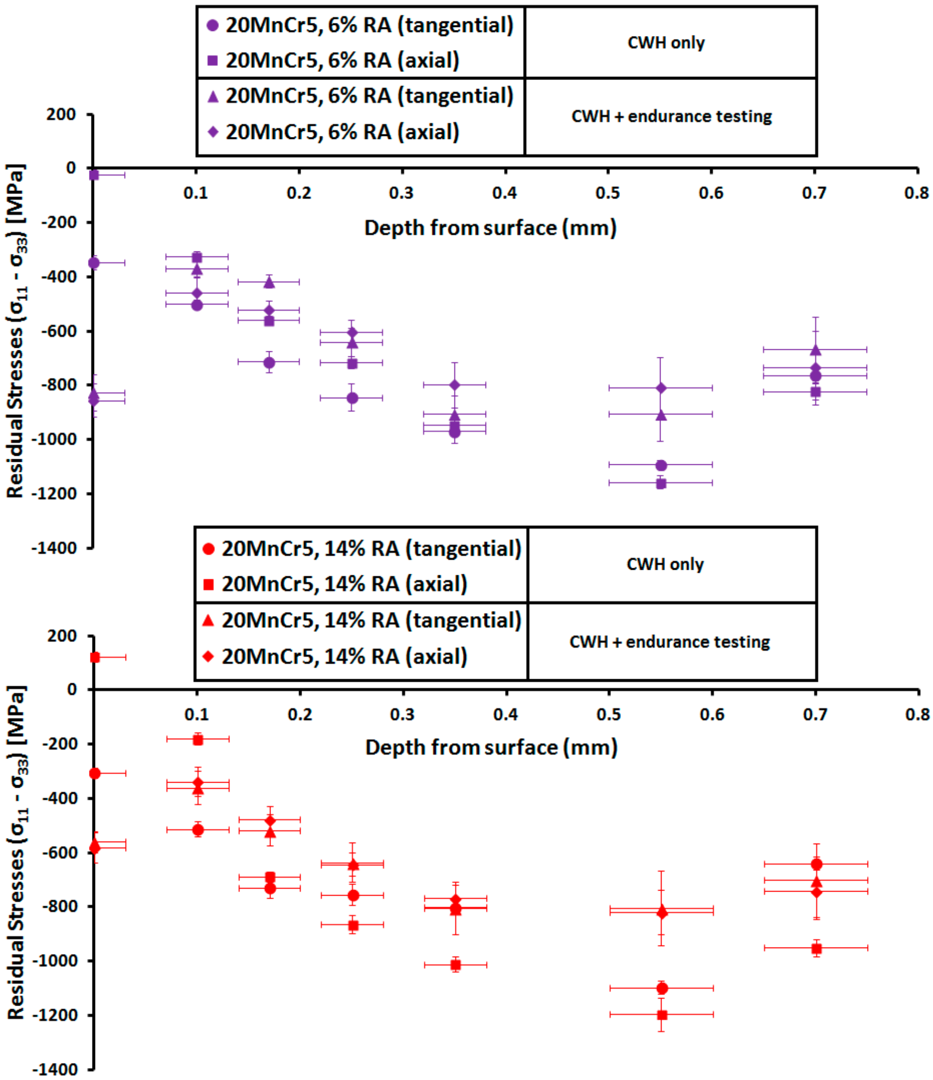

Figure 9. Residual stress depth profiles of 20MnCr5 after cold work hardening (CWH) and, additionally, CWH+slip-rolling endurance testing at P_{0mean} = 1.5 GPa [3].

The hardness profiles (Figures 11 and 12) reveal significant improvements in the surface layer hardness of the steels after cold work hardening executed only under short load cycles of thousands or tens of thousands. In the case of 20MnCr5, a maximum increase of 760 HV was observed. It is important to note that the percent residual austenite had an effect on the magnitude of the increase obtained for hardness, with higher percentages leading to stronger increases. The increases for 45SiCrMo6 were greater than those for 36NiCrMoV1-5-7; however, a thousand load cycles at high contact pressures (3.8 GPa) may not be enough to achieve the desired deformed surface profile. With the alternative steels containing less than 2% austenite, they rely heavily on grain refinement and less on the conversion of austenite to martensite to achieve work hardening, explaining why the reference steel was able to achieve better performance.

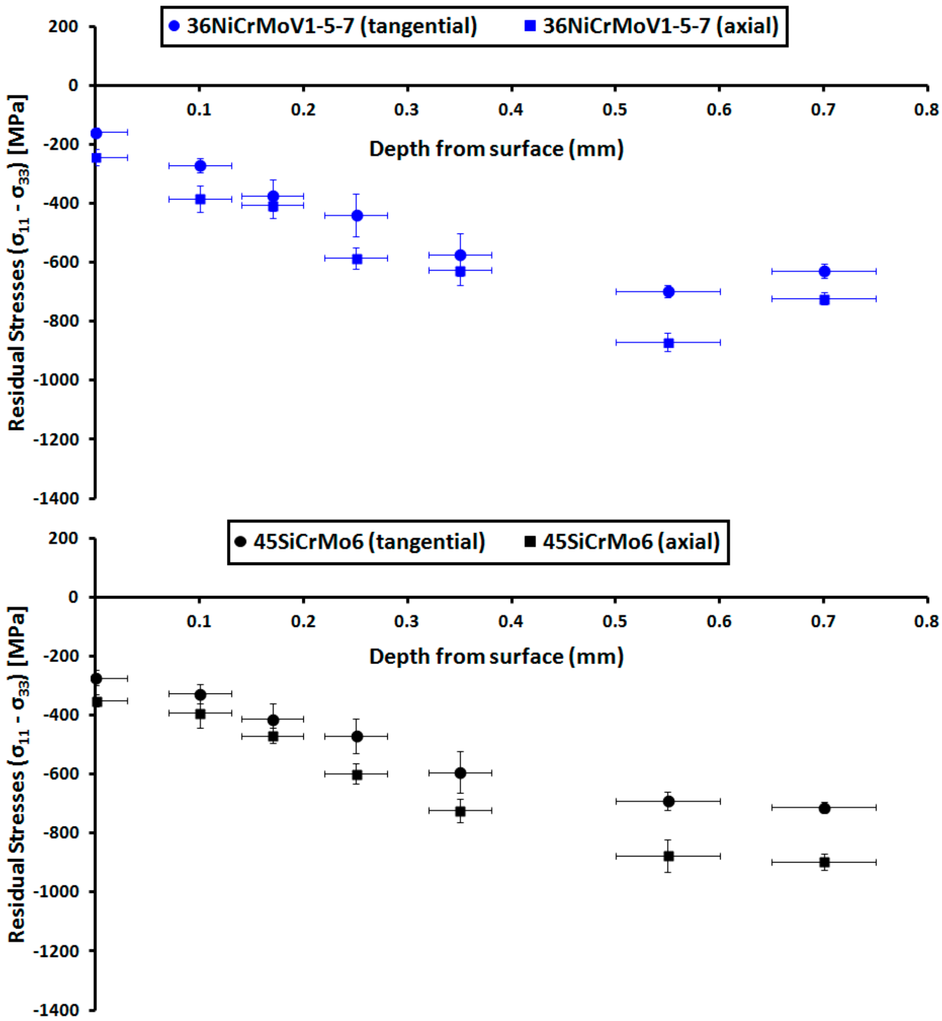

Figure 10. Residual stress depth profiles for 36NiCrMoV1-5-7 and 45SiCrMo6 after CWH [3].

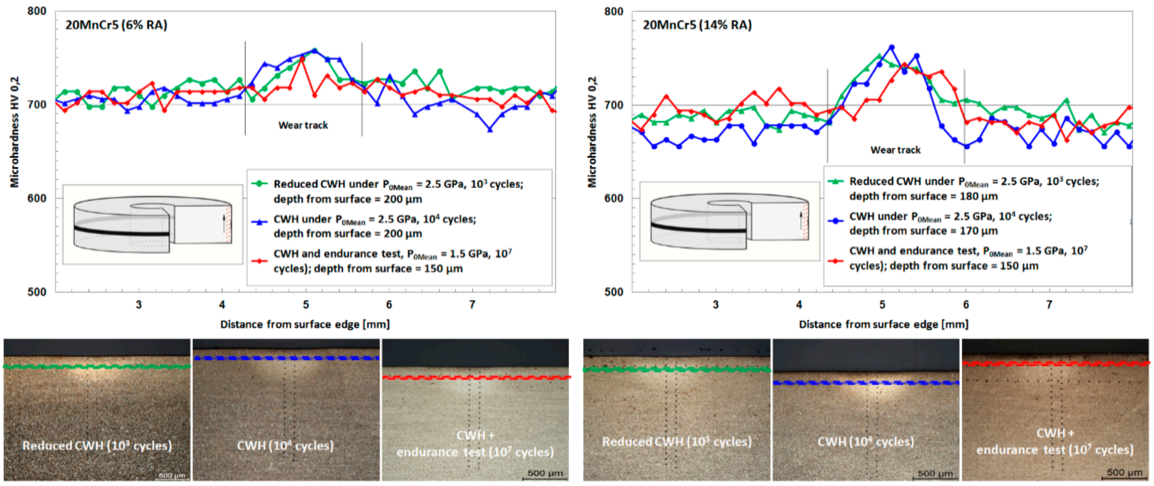

Figure 11. Microhardness profiles across sample surface of case-hardened 20MnCr5 after CWH, and after CWH+slip-rolling endurance testing [3].

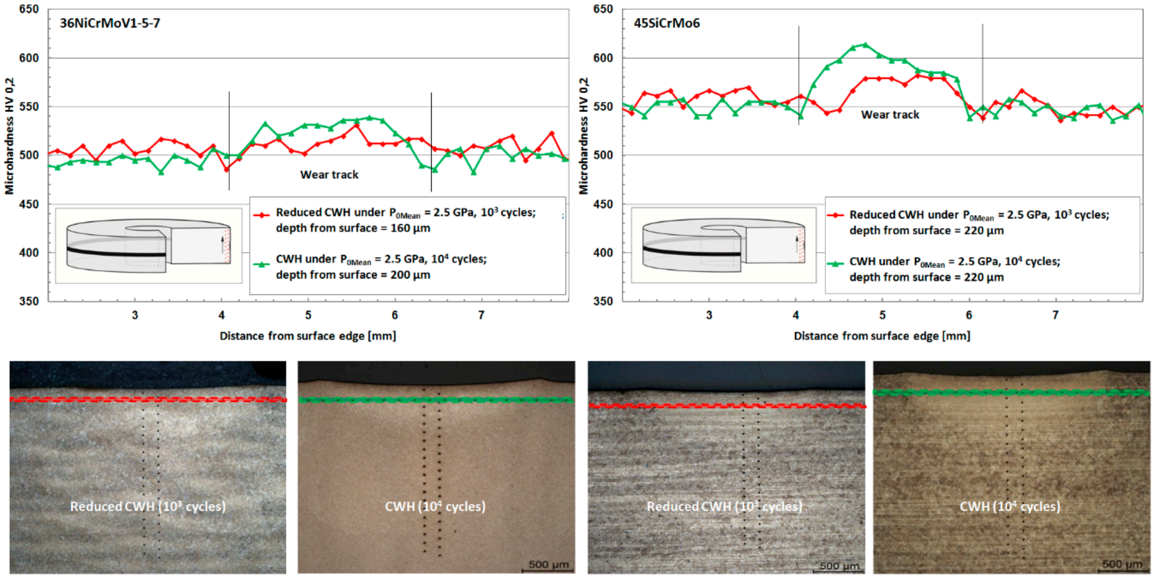

Figure 12. Microhardness profiles across sample surfaces of non-case-hardened high-performance steels, 36NiCrMoV1-5-7 and 45SiCrMo6, after CWH [3].

Further investigation into the frictional behavior of 20MnCr5, specifically with regard to the coefficient of friction and wear coefficient, shows that cold work hardening has no measurable effect on COF but causes an improvement in wear performance. This improvement was observed in all 20MnCr5 samples, but was the greatest for samples with 14% residual austenite, yielding a reduction of approximately 1/5 in the wear coefficient. As was the case with the residual stress and hardness profiles, the 36NiCrMoV1-5-7 and 45SiCrMo6 samples failed before 10^7 cycles during the endurance testing, producing no meaningful results for friction and wear. However, as loads were increased, 20MnCr5 began to break down in similar ways to the alternative steels. The results for 20MnCr5 are shown in Figure 13.

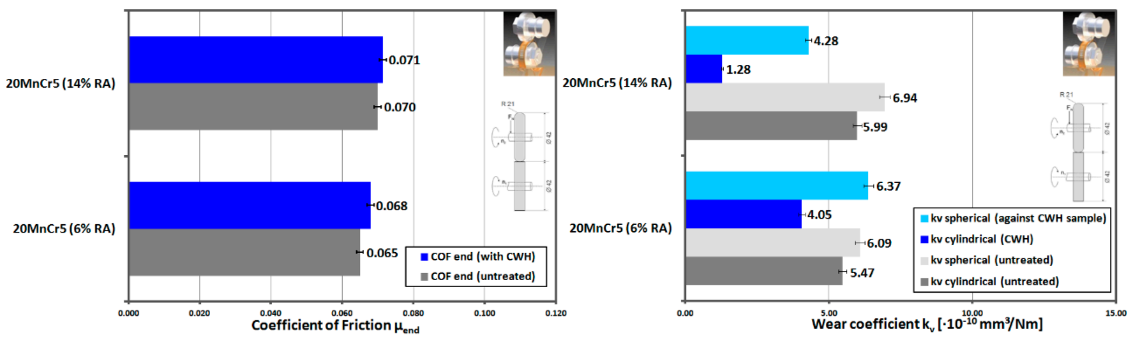

Figure 13. Coefficient of friction (COF) values at end of and k_V values after 2disk slip-rolling testing for case-hardened and cold work hardened 20MnCr5 [3].

After running into these mechanical failures with every steel tested, the authors decided to optimize the conditions for pre-conditioning to take into account the initial material hardness and tendency of the material to deform. This involved changing many of the experimental parameters, most importantly the radius of curvature of the cylindrical rollers. This change and others are summarized in Table 1. The most notable improvements these changes had were on the observed coefficients of friction of the non-case-hardened steels. With an optimized setup, all the steels were able to reach the required 10^7 cycles for the endurance tests. These results are shown in Figure 14. Additionally, improvements were found in the wear performance of the steels, with the greatest reduction being 1/10 of the original value from the untreated steel. These findings are summarized in Figure 15.

Table 1. Summary of optimized pre-conditioning parameters [3].

Initial Parameter	Optimized Parameter
Polished WC-6Ni roller (R_{WC} = 6 mm) Hertzian contact pressure P_{0mean} = 3.8 GPa (P_{0max} = 5.62 GPa) Lubricant temperature = +120 °C Rotational speed (cyl./sph.) = 390 rpm/387 rpm Duration of pre-conditioning = 25 min.	Polished WC-6Ni roller (R_{WC} = 21 mm) Hertzian contact pressure P_{0mean} = 2.5 GPa (P_{0max} = 3.75 GPa) Lubricant temperature = +140 °C Rotational speed (cyl./sph.) = 1200 rpm/1188 rpm Duration of pre-conditioning = 8 min.

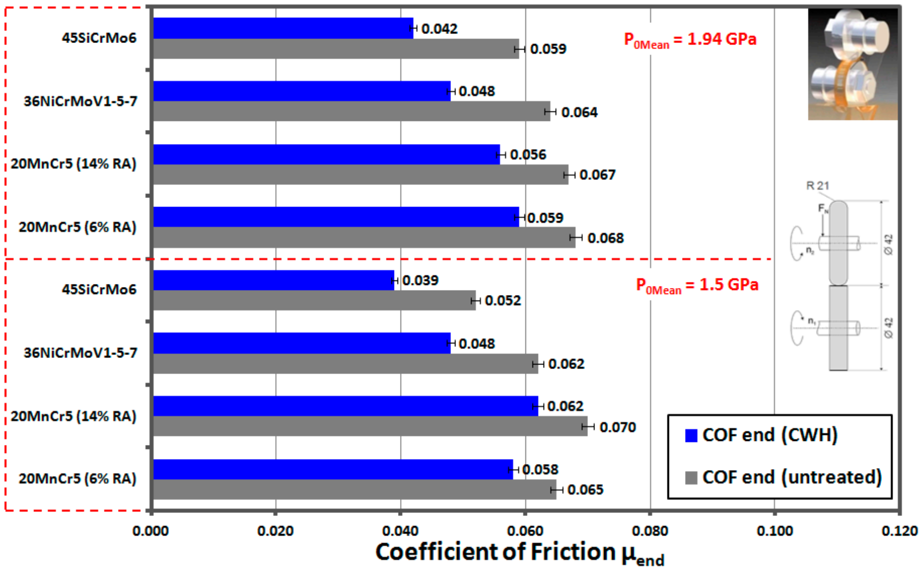

Figure 14. Coefficients of friction at the end of slip-rolling testing at 120 °C of samples, cold work hardened under optimized conditions [3].

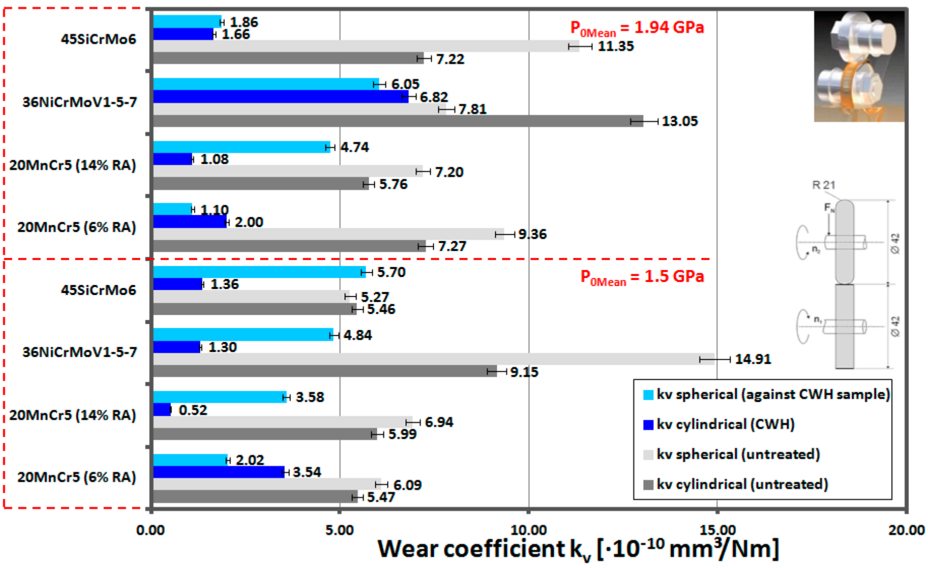

Figure 15. Wear rates of the spherical and cylindrical discs at the end of slip-rolling testing at 120 °C, cold work hardened under optimized CWH conditions [3].

Overall, in comparing the case-hardened reference steels to the non-case-hardened alternative steels, better friction and wear performance were observed without case-hardening, suggesting that pre-conditioning alone may be a viable alternative. Considering the high costs and intensive efforts associated with case-hardening, it may be beneficial to replace the old strategy with pre-conditioning for cold work hardening applications. Burbank and Woydt [3] proved using the 2disk test rig that cold work hardening, when paired with the correct metallurgies and optimized parameters, can improve material hardness, compressive residual stresses, and other tribological properties, such as the coefficient of friction and wear rate.

5. Conclusions

When considering the performance of materials under rolling-contact conditions, it is important to analyze tribological properties such as the coefficient of friction, wear rate, load carrying capacity, and lifetime through endurance testing. These tests are often performed using a twin disc tribometer. The application of coatings, additives, and steel treatment processes are some ways in which the previously mentioned properties can be improved. As shown in this summarizing paper, the wide array of measurement modes of the 2disk test rig was demonstrated to be an effective methodology for assessing the tribology profile of rolling contacts. Through the experimental tests done by Manier et al. [1], it has been shown that Zr(C,N) coatings are highly slip-rolling resistant, especially compared to commonly used DLC and ta-C coatings. With regard to the effect of additives, Burbank and Woydt [2] compared the effectiveness of bismuth-based additives to that of molybdenum-based additives and found that bismuth can provide comparable, and in some cases better, friction and wear performance and is less toxic to the environment. A third study determined that by preconditioning steel alloys, the cold work hardening process by which steels are strengthened can be made easier and cheaper, whilst, at the same time, meeting tribological requirements. Across these three highlighted papers, there is a variety of tribological systems under inspection. Despite these differences in tribocontacts, twin disc tribometers can still be used to reach a degree of measurement that other characterization methods cannot, since these tribometers can monitor many essential parameters for a tribosystem in real time, such as the coefficient of friction and wear coefficients. In analyzing the results of these three papers, it is demonstrated that a twin disc testing system is capable and effective for research and development applications for rolling contacts.

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