The effect of hard chrome plating on iron fines formation

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\textbf{ABSTRACT}

Scratch tests and reciprocating sliding tests were carried out under lubricated conditions to explore the influence of hard chrome plating on iron fines formation. In the scratch tests, the effect of hard chrome plating on iron fines formation at single asperity contact due to its inherent property have been investigated. In the reciprocating sliding tests, the initial roughness of the substrate and the roughness changes introduced due to the hard chrome coating have been taken into account. It was found that both the tribochemistry of the chromium layer and the smoothening of aggressive roughness features from the grinding process due to chrome plating play an important role in reducing iron fines formation.

\section{1. Introduction}

Cold rolled steel sheets are extensively used in many sectors such as automotive, packaging and electronics industries. The surface cleanliness of a rolled sheet is important for the functional and aesthetic properties of many sheet products and their downstream product process performance in forming operations \cite{1,2}. The generation of iron fines due to the ploughing action of the roughness peaks of the roll through the strip surface during cold rolling is one of the main factors that contaminate the strip surface \cite{3}. Iron fines originate mainly from the sheet metal being rolled, which is generally much softer than the roll \cite{3,4}. They can cause problems in fouling the cold rolling mill as well as negatively affect downstream processes such as annealing, galvanizing, filtration, forming and painting. For example, the iron fines that remain on the strip can reduce the adherence of zinc coating during galvanizing, and consequently, decrease corrosion resistance \cite{1}. A large amount of wear debris can block the filtration system. Moreover, cleaning the strips to remedy poor surface cleanliness incurs an extra cost and is environmentally undesirable.

The ever increasing demands on strip quality in terms of surface cleanliness require reducing the generation of iron fines during cold rolling. In order to achieve this, a thorough understanding of the rolling tribological system and the effect of rolling parameters is vital as these parameters play a decisive role in iron fines generation. The thickness reduction, rolling speed, and roll and strip roughness determine the lubrication regime and the ratio of metal to metal contact. The strip and the roll surface chemistry, and the lubricant and its additives define the physical and chemical interaction at the roll bite interface. These macro-scale rolling parameters create the environment at the micro-scale. The micro-scale is the scale where iron fines formation actually takes place. At micro-scale, the roll asperities plough through the strip surface. This ploughing could lead to wear particle formation depending on the wear regime \cite{5}. Methods that can be employed to enhance strip cleanliness include modifying pass schedules (e.g. reduction ratio per mill stand) \cite{6}, lubricant properties \cite{7,8}, strip properties (e.g. surface roughness resulting from pickling) \cite{4} and/or roll surface (e.g. hard chrome plating) \cite{9,10}. The focus of this study is on the influence of hard chrome plating the rolls on iron fines formation.

Chrome plating the rolls has been a common practice in the steel industry for a long time, both to increase the service life of the roll and to improve strip cleanliness. The high hardness of the chromium coating (up to 1200 HV) provides higher abrasion resistance, which helps to increase roll life time \cite{11}. Additionally, it helps against adhesive transfer for sticky alloys \cite{9,10,12}. It is reported that chrome plating could make a difference of up to 20% in reflection tape value, a method used to quantify iron fines generated \cite{3,13}. Although its positive influence on strip cleanliness has been known, there are only few studies on the governing mechanisms why this coating improves strip

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better adherence of oil to the chrome plated surface than to the steel to the improvement of strip cleanliness by chrome plating the rolls are: deposited. The authors attributed the decrease of friction to the formation under lubricated conditions. In their tests, chrome plated punches exhibited a cleaner strip and lower friction compared to the uncoated punches. The authors attributed the decrease of friction to the formation of a tribolayer on the chrome layer with positive tribological properties. Furthermore, they argue that strip cleanliness is not an intrinsic property of chrome plating but rather depends on the quality of the coating deposited.

In summary, the factors that are proposed in literature to contribute to the improvement of strip cleanliness by chrome plating the rolls are: (i) better adherence of oil to the chrome plated surface than to the steel surface [13]; (ii) the formation of Cr/CrOx tribolayer with desirable tribological properties [9]; and (iii) smoothening of the sharp and aggressive features from the grinding process with gentler features [10]. The first two are due to the inherent property of the chromium coating and the last one is due to its influence on the roughness features of the roll surface. In reality, the improvement could be due to some or all of these mechanisms acting simultaneously.

Besides the limited number of studies conducted on the positive influence of chrome plating on the rolls on strip cleanliness, there is a need to find a replacement for this coating due to health and safety regulations. The electrolyte used in the hard chromium plating process contains a hexavalent chromium (Cr(VI)) ion which is hazardous to human health and is environmentally harmful. For example, the products containing Cr(VI) are on the list of substances of very high concern and to be progressively eliminated under the REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) regulation by the European chemicals agency [14]. To systematically develop alternative coatings, a detailed understanding of the fundamental mechanisms behind the positive effects of chrome plating on strip cleanliness is necessary.

In this work, we explore experimentally the influence of chrome plating on iron fines formation. Two experimental techniques, namely scratch tests and reciprocating sliding tests, were carried out for this purpose to simulate the relative sliding of the roll and the strip in the roll bite. In the scratch tests, the influence of chrome plating on iron fines generation at singleasperity contact due to its inherent property excluding the roughness changes introduced during coating was investigated. In reciprocating sliding tests, the influence of chrome plating on iron fines formation taking into account the initial roughness of the substrate and the roughness changes caused by the hard chrome plating was studied.

2. Materials and methods

Both the scratch and the reciprocating sliding experiments were performed using a multi-purpose tribometer (UMT Tribolab from Bruker). The contacts in the current experiments were designed to resemble the roll-strip contact in the roll bite of cold rolling processes. Typically, in rolling processes the roll surface is prepared by grinding and it is continuously in contact with fresh incoming strip surface. An illustration of a roll-strip contact geometry is provided in Fig. 1a. In the roll bite, the speed of the strip equals the peripheral speed of the roll only at the neutral point. The roll moves faster than the strip before the neutral point and the strip moves faster than the roll after the neutral point. Thus, an asperity on the roll surface slides on the strip surface in the rolling direction before the neutral point and backwards after the neutral point. The sliding length depends on the thickness of the strip, the reduction ratio and the location of the neutral point. Rolling is commonly done with the neutral point kept close to the exit of the roll bite.

2.1. Scratch tests

In the scratch tests, a single asperity of a roll sliding on a strip material is simulated. The scratch tests were conducted under lubricated conditions using conical pins with a hemispherical tip. The hemispherical tip has a radius in the order of a single roughness asperity of a roll surface. The pin was fastened to a stage with a linear drive while the strip substrate was kept stationary. Each scratch was made by applying a normal load on the pin and sliding it 10 mm in the forward direction and 0.5 mm backward. Then, the pin is lifted and returned to the starting position and moved a distance of 1 mm perpendicular to the sliding direction to the side, after which the process is repeated (Fig. 1b). In this way it is ensured that the pin, which represents the roll asperities, is always in contact with a fresh strip surface, which corresponds to the rolling process. The sliding distance of the scratches corresponds to a typical slip distance of the first stand of a tandem cold rolling mill, where iron fines generation is a severe problem.

The scratch pins were made of a commercially available medium-alloyed cold work tool steel (Uddeholm Rigor®) that has similar composition to commonly used roll material. Chemical composition in wt. %: 1.0 C, 0.3 Si, 0.6 Mn, 5.3 Cr, 1.1 Mo, 0.2 V, balance Fe; hardness 60–62 HRC as supplied by the manufacturer. Three sets of scratch pins with a hemispherical tip radius of 225, 265 and 615 μm, two pins for each radius, were prepared. Half of the pins, one from each radius, were commercially hard chrome plated under usual industrial conditions and half of them uncoated for comparison. The average thickness of the coating is 5–10 μm. Coating thickness measurements were made using a magnetic induction method (DUALSCOPE® FMP20 from Fischer) according to ISO 2178. Prior to chrome plating, the hemispherical tips of all the pins were polished to a mirror like surface finish, see Fig. 2a. To remove the roughness changes introduced due to chrome plating and ensure that the chrome plated pins have the same surface finish as the uncoated pins, the former were polished again after the coating was applied. A section (50 mm × 50 mm × 3 mm) of industrially hot rolled and pickled Ti-stabilized ultra-low carbon (TISULC) steel strip was used as the counterface. This steel grade was chosen because it is extensively used in automotive applications owing to its high formability. It has also been observed to pose a high risk for poor strip cleanliness while rolling. The strip samples were polished to a mirror like surface finish.

Prior to the tests, the pins and the strip samples were thoroughly degreased and cleaned in isopropanol. Next, a film (1 g/m²) of a palm-oil based fully formulated industrial cold rolling oil containing anti-wear as well as extreme-pressure additives was applied on the polished side of the strip sample by smearing the oil using a clean rubber roller. The amount of oil film per unit area was determined by measuring the weight of the strip before and after applying the lubricant using a high resolution (10⁻² mg) microbalance. The load applied on the pins was selected so that the scratches are either in the wedge forming or cutting mode of abrasive wear in each case. This choice was made because wear debris generation occurs in these two abrasive wear regimes [5]. A normal load of 17 N, 25 N and 50 N were used for the pin radius of 225 μm, 265 μm and 615 μm respectively. A constant sliding speed of 1 mm/s was used. A total of 16 scratches were made by each pin. The scratches were done parallel to the rolling direction of the strip. The
The friction coefficient was measured with a sampling frequency of 1 kHz and the tests were monitored in-situ using a scientific camera to study the scratches. The worn surfaces were analyzed using an optical microscope (Keyence VHX-5000) and a scanning electron microscopy (SEM). In addition, X-ray photoelectron spectroscopy (XPS) analysis was done on the wear scar of the pins after the scratch tests to analyze the chemical nature of the tribolayer formed.

The XPS analysis was performed with Quantera SXM (scanning XPS microprobe) from Physical Electronics. Prior to the XPS analysis, the pins were thoroughly cleaned with acetone followed by 20 min ultrasonic cleaning with isopropanol in order to remove residual oil and wear debris. The sampling depth of XPS is generally few nanometers; therefore, the results reflect information on the uppermost pin layer including an adsorption film formed by the lubricant additives. The XPS spectra were acquired using a monochromatic Al Kα source with a spot size of 100 μm. First, a wide scan survey was done to see the gross overall atomic content of the surface layer. Afterwards, element spectra scans were made with a better energy resolution. Charge correction was done by setting the binding energy of C1s peak of aliphatic carbon at 284.8 eV. The identification of the tribofilm species is possible by comparing the peak spectra in the tribofilm to the same photon binding energies in the reference spectrum.

### 2.2. Reciprocating sliding tests

Reciprocating sliding tests represent the contact of a strip and a roll surface ground to several roughness values. In these tests, the strip substrate was fastened to a stage with a reciprocating drive while the pin was kept stationary. A self-aligning pin holder was designed to avoid edge scratches. The direction of sliding was along the rolling direction of the strip. Reciprocating sliding tests were carried out using pins with a squared cross section (5 mm × 5 mm). The tip of the pins on one side was shaped to have a cylindrical shape (diameter 50 mm) to resemble a fragment of a roll, see Fig. 2. The tips were ground and polished in the sliding direction similar to the grinding process of rolls. Three groups of pins in terms of r.m.s. surface roughness (Sq), approximately 0.03 μm, 0.3 μm and 1 μm were prepared. Four pins were prepared for each roughness value. Afterwards, two pins from each roughness group were chrome plated. No surface modification was done on the coated pins after the coating was applied, which is different from the scratch tests (section 2.1).

The counterface was a TISULC steel strip sample in as pickled surface condition. The strip samples were used in as pickled condition so that the surfaces of the contacting pairs of the tests are similar to that of the first stand of a tandem cold rolling mill. Both the pins and the strip samples were degreased using isopropanol prior to the tests. The tests were carried out under lubricated conditions using the same rolling oil as the scratch tests (section 2.1). The reciprocating sliding tests were done using a constant normal load of 100 N, a stroke length of 25 mm, a frequency of 3 Hz, and a duration of 5000 cycles (250 m) at room temperature. The friction coefficient was continuously monitored during the tests. The surface of the worn pins were analyzed using SEM.

The surface topography of the pins was measured using a non-contact three dimensional height profiler (Sensofar S-neox confocal microscopy). For the r.m.s. surface roughness analysis, 3 measurements at different locations with a resolution of 0.64 μm and a scan area of 877 μm by 660 μm were taken. The one dimensional (i.e. perpendicular to the grinding direction) power spectral density (PSD) of the pins surfaces was analyzed before and after hard chrome plating. Profile scans for PSD analysis were made with a resolution of 0.142 μm and a scan length of 146 μm. To average out the effects of noise, the PSD was obtained as an ensemble average of 30 profile scans at different locations. The PSD calculation was done using Welch’s method in MATLAB with a Hamming window.
The nanohardness of the strip sample, the uncoated and the chrome plated pins were measured using a Berkovich indenter (Nanoindentation tester NHT from Anton Paar). The measurements were made using a load of 40 mN (indentation depths less than 0.5 μm) to avoid the effect of the substrate for the coated pins. 20 measurements were made for each sample. The average nanohardness values are 10.7 ± 0.53 GPa and 12.2 ± 0.49 GPa for the uncoated and hard chrome plated pins respectively. The average nanohardness value of the strip sample is 2.2 ± 0.08 GPa.

3. Results and discussion

3.1. Scratch tests

The average steady state friction coefficient of the scratch tests is illustrated in Fig. 3a. The scratches made with the chrome plated pins showed lower friction coefficient on average compared to the scratches made with the uncoated pins. The distinct high friction coefficient of the chrome plated pin with a tip radius of 265 μm can be explained by the large amount of cracks observed on the chromium layer of that particular pin (not shown). This indicates that the quality of the coating is very important in terms of strip cleanliness, as has been pointed out by other authors [10].

Factors such as interfacial shear stress, ploughing and asperity deformation all contribute to friction. The contribution of asperity deformation may be considered negligible in the current tests as both the contacting surfaces were polished to a very smooth mirror like finish [15]. Thus, ploughing and interfacial shear stress may be considered as the only two contributing factors to the friction. The ploughing component of friction can be assumed to be the same for both the uncoated and the chrome plated pins, as the pin geometry, the applied load, the surface finish, the lubrication condition and the counterface material are the same. Therefore, the difference in the friction coefficient between the uncoated and the coated scratch tests can solely be attributed to the difference in the interfacial shear stress. This component of friction is sensitive to the material combination and the tribochemistry of the contacting pair. The following two phenomena can explain the low friction coefficient of the scratches made with the chrome plated pins. First, the extreme pressure and polar additives may react with the chromium/chromium oxide layer to form a tribochemical film with low shear, and hence, lower friction. Second, generally lower adhesion is expected between the contact of dissimilar materials (i.e. chromium - steel in the scratch tests with the coated pins) than contact interfaces with similar materials (steel - steel for the uncoated pins) [16].

The differences in the friction coefficient value for the different pin radii is related to the differences in the size of the pins and the applied load. The friction curves neither show any substantial difference among the different scratches nor exhibited any particular trend as the number of scratches increases, see Fig. 3b, c. It seems to be rather dependent on the local wear phenomena happening on each scratch. The large fluctuation of the friction coefficient for the uncoated pins most likely arises from the buildup and breaking of wear particles which was seen by the scientific camera observations.

SEM images of the pins after the scratch tests are provided in Fig. 4. Although abrasion of the strip is the main wear mechanism, material transfer occurred on the tip of the pins. The uncoated and the chrome plated pins showed different degrees of strip material transfer,
corresponding to their friction behavior. The chrome plated pins displayed a qualitatively significantly lower quantity of adhered strip material compared to the uncoated pins. Since all the test conditions are kept the same, the difference in the tribochemistry of the contacting pairs can be considered as the sole cause of this behavior.

For material transfer to happen, there should be a local breakdown of the lubricant film. In the scratch tests, a plastic wave is formed as the pin scratches through the strip surface. Due to the high contact pressure involved, lubricant failure can be expected at the contact spot. Depending on the strength of the boundary lubricant and the surface chemistry of the contacting counterparts, material transfer can happen. In the current tests, the lubricant additives may behave differently, in terms of physical and chemical interaction, towards the chromium layer of the coated pins and the steel surface of the uncoated pins. Probably, a tribolayer consisting chromium oxide(s) with positive effects on the tribological behavior is formed on the chromium surface, delaying the local failure of the lubricant, and subsequently delaying the initiation of adhesive wear. Once adhesive wear initiates, subsequent scratches may lead to build up of the transfer layer and lump growth. It has been shown in literature that the buildup of the transfer layer and the formation of big lumps is very sensitive to the material combination [17]. It is highly likely that the dissimilar steel - chromium material combination has a low rate of material transfer compared to the similar steel – steel contact pair.

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Optical microscopy images of the scratch grooves on the strip surface are given Fig. 5. The quantity of both loosely detached and adhered iron fines on the strip surface of the scratches made using the chrome plated pins is substantially smaller than the scratches made with the uncoated pins. This corresponds well to the friction measurements. The scratches made with the uncoated pins showed a higher friction coefficient, which means a higher friction shear stress at the contact spots. The increased tangential subsurface stress on the strip material due to the higher friction produces a greater surface damage on the strip. This leads to generation of more wear debris that contaminate the strip (Fig. 5) and more material transfer on the pin surface (Fig. 4). The camera observations also revealed that particle generation was accompanied by material transfer. Fig. 6 shows a snapshot of the scratch tests at the end of the forward movement of the 16th scratch. It can be clearly seen that
more wear debris was generated and loosely adhered to the uncoated pin than the clean hard chrome plated pin. Furthermore, the wear debris showed more adherence to the uncoated pins and were partly carried to the next scratch. On the contrary, the chrome plated pins remained clean with no loosely adhered wear debris at the end of each scratch during the whole duration of the tests.

XPS analysis was done on the worn tip of the pins to characterize the chemical nature of the tribofilm on the surface. The lubricant used in the current tests is a commercial fully formulated oil that contains friction modifiers, antioxidant, extreme pressure and anti-wear additives. The narrow scan XPS spectra of selected elements are provided in Fig. 7. A peak at 347.5 eV which corresponds to calcium carbonate ($\text{CaCO}_3$) and calcium phosphates ($\text{CaHPO}_4$ or $\text{Ca}_2\text{P}_2\text{O}_7$) was observed on the Ca 2p spectra of both the uncoated and the chrome coated pins [18]. However, the intensity of the peak on the chrome plated pin was significantly higher than the uncoated pin suggesting higher concentration (thicker tribofilm) of this species on the former. Overbased calcium sulphonate detergents are employed in industrial oils to act as extreme pressure and anti-corrosion additives. It is known that calcium detergent can interact with the surface and form a $\text{CaCO}_3$ pad like tribofilm that covers the surface [19–21]. In addition, calcium detergent and the phosphorus anti-wear agent generally have a synergetic effect and form a reaction film consisting of $\text{CaCO}_3$, $\text{CaHPO}_4$, $\text{Ca}_2\text{P}_2\text{O}_7$ and $\text{Fe}_3(\text{PO}_4)_2$ [18,21]. In the current tests, some calcium carbonate and calcium phosphates are likely to be generated on the worn surface due to the interaction of the calcium based detergents with the contacting surfaces and/or with other additives [18]. The presence of a sharp peak at the binding energy of 288.4 eV of the C 1s spectra, which is assigned to an O–C–O bond (carboxylate and/or carboxylic), in the case of the chrome plated pins but no distinct peak on the uncoated pin supports this claim [22]. The lack of a
distinct peak on the P 2p spectra corresponding to the range of phosphates (133.2 eV) suggests no presence of calcium phosphates on the surface. Hence, it is reasonable to conclude that calcium carbonate was likely deposited due to the interaction of the calcium detergent with the surface and/or with the other additives. In literature, it has been shown that the thickness of the calcium carbonate film depends on the material combination and the sliding speed [19]. Therefore, it is possible that a thicker protective calcium carbonate tribofilm was formed on the chrome coated surface than on the uncoated steel surface.

Another major difference between the XPS spectra of the uncoated and the chrome plated pins is the N 1s peak. A sharp peak at 399.7 eV was observed on the chrome plated pin surface but not for the uncoated one. The binding energies for nitrogen in organic compounds overlap significantly (399.0 – 400.6 eV) and can be difficult to decipher especially if there are multiple nitrogen containing groups. Nevertheless, this peak can be attributed to the amines species owing to their presence in the current lubricant as a friction modifier [22]. Organic friction modifiers such as amines are in general assumed to reduce friction by adsorbing/reacting on oxide covered metal surfaces [23]. Furthermore, they show competitive adsorption/reaction against other polar additives [24]. The adsorption and friction performance of amine based organic friction modifiers on surfaces has been shown to depend on surface chemistry and composition, its interaction with other additives, the bonding energy of the polar head to the surface, surface roughness and pressure [22,23]. The XPS results indicate that the amines adsorbed/reacted better to the chrome plated surface than the steel surface because of the different surface chemistry. This offers a possible explanation for the lower friction coefficient and less material transfer observed on the hard chrome plated pins.

The current tests were performed in the boundary lubrication regime. In this lubrication regime, friction and wear behavior strongly depend on the adsorption and the chemical reaction of the additives on the surface. A tribofilm can be formed in the frictional area through adsorption and/or tribochemical reactions with friction serving as the driving force. Some studies proposed a three layer model to characterize a tribofilm with the metal substrate at the bottom, a metal oxide/metal hydroxide in the middle and a reaction tribofilm on the top layer [25]. The compositional analysis obtained by XPS in the current tests suggested formation of a tribolayer consisting a carbonate and amine species on the chrome plated surface but not on the uncoated steel surface. This demonstrates that the surface chemistry of the chromium layer and its interaction with the additives plays an important role in reducing iron fines formation.

![Fig. 7. XPS spectra of the tribofilm on the worn pin surface.](image-url)
3.2. Reciprocating sliding tests

The r.m.s. roughness (Sq), the typical surface topography and the power spectral density (PSD) of the pins are illustrated in Fig. 8. Chrome plating did not significantly alter the average roughness of the pins (Fig. 8a). Nevertheless, a slight smoothening of the rough pins and a slight roughening of the polished samples was observed. Similar observation of roughness changes due to chrome plating is reported in literature [9,11]. Although chrome plating did not alter the average roughness value remarkably, the topography of the uncoated and chrome plated pins are visually distinct at sufficiently high magnification, Fig. 8b. The uncoated pin surface possesses sharp features from the grinding process which can be aggressive and induce intense abrasive wear on the strip surface during rolling. The sharp features are also the primary location for initiation of galling and a preferential locus for adhesion of fine strip wear debris. Chrome plating covers the sharp features and the prominent peaks from the grinding process with gentler patterns. It smoothen the short wavelengths while preserving the average roughness and the large wavelength of the topography. This was confirmed by the power spectral density analysis of the pins surface (Fig. 8c). The power spectrum of the pins with Sq of 1.0 and 0.3 μm show that chrome plating decreased the power at high spatial frequencies (short wavelengths), confirming that hard chrome plating smoothened the high frequency roughness features. The r.m.s. roughness amplitude (Sq) is mainly determined by the amplitudes at the low spatial frequency regions of the power spectrum [26]. Hence, even though the
high-frequency roughness is reduced by chrome plating, the long wavelength feature of the pins surface keeps the magnitude of the roughness height parameters unchanged. On the contrary, hard chrome plating increased the magnitude of the PSD for all the frequencies of the smoothest pins with Sq of 0.03 μm, indicating that it increased the amplitude of the surface at all frequency ranges of the current measurement. This corroborates the r.m.s roughness measurements (Fig. 8a). The effect of hard chrome plating is more pronounced at high frequencies. This asymmetry arises from the fact that the smoothing of the higher frequencies relative to the low frequencies. This change in micro roughness can influence the mechanical interlocking and accumulation of material transfer. The typical cracking of hard chromium deposits can also be observed on the coated pins [27].

The typical friction curves of the reciprocating sliding tests are presented in Fig. 9. At approximately a sliding distance of 75–100 m for pins with Sq of 1 μm and 175 m for pins with Sq of 0.3 μm, a sudden increase of friction coefficient was seen. The sudden increase of friction is generally associated with a transition to severe adhesive wear and gross macroscopic surface damage, also known as galling. This was confirmed by post-test SEM analysis of the pins. For lubricated contacts, like the current tests, local failure of the lubricant is a necessary condition for galling to occur. The local lubricant failure is generally related to frictional heating [28]. No such transition of friction was observed for the tests done using chrome plated pins and pins with Sq of 0.03 μm. This is similar to previous publications on the influence of roughness on galling behavior, smooth roughness delaying the initiation of galling [29,30].

The minimum sliding distance needed for the transition in friction to occur varies depending on the roughness of the pins. The dependence of the minimum sliding distance to galling on roughness can be attributed to the quantity and severity of defects serving as a spot for the initiation of galling. The rough pins have relatively coarse grooves and surface irregularities from the grinding process which may act as spikes making scratches on the strip surface and serve as a location for the initiation of galling. On the other hand, the surface of the smooth pins is relatively defect free because the coarse protrusions and irregularities are removed by polishing. In literature, it has been shown that surface roughness has a crucial effect on the friction and the ability of a material to prevent pickup of counter material. The rougher the surface the sooner the transition occurs, which is attested by the friction graphs (Fig. 9). Both substrate polishing and polishing the surface after a coating is applied has been shown to improve the galling resistance of coated surfaces [29].

None of the chrome coated pins showed such a transition in friction. Both the tribochemistry of the chromium layer as well as the smoothing of the aggressive roughness features due to the chrome plating may contribute to this behavior. However, the contribution of each component cannot be isolated in these tests. Scratch tests indicated that tribochemistry plays a big role in terms of material transfer due to the formation of a protective tribolayer on the chrome plated surface. Concurrently, smoothing of the sharp roughness features on the pin surface reduces the number of galling initiation points. For the tests which did not show any sign of galling i.e. the tests with stable friction throughout the whole test duration and no transition, the chrome plating did not alter remarkably the friction. The friction coefficient remained at a steady value of approximately 0.05 for all roughness values. These results are in agreement with previous findings [9,12].

The worn surface morphologies of the pins after the reciprocating sliding tests are provided in Fig. 10. Fig. 10a, b shows the SEM image of the worn pins ground to Sq of 1 μm. The SEM image of the uncoated pins that showed a transition of friction coefficient revealed a massive strip material transfer (Fig. 10a). This observation correlates well with the friction measurements. On the contrary, no such material transfer was seen on the chrome plated pins (Fig. 10b). However, abrasive scratches can be seen on the pin surface. The abrasive scratches are possibly caused by the wear particles generated during the test and remain within the contact area. At some locations, the abrasive scratches lead to coating damage. These wear induced defects may act as the initiation point for galling and accelerate material transfer and formation of lumps on the
Fig. 10e-f illustrates the worn surface of the pins ground to Sq of 0.3 µm. In addition to macro galling (Fig. 10c), SEM analysis of the uncoated pins revealed multiple galling initiation sites with small fragments adhered locally to the pin, see Fig. 10d. The fragments are situated on the valleys from the grinding process. A collection of fine wear debris are also gathered at these spots, which may promote mechanical interlocking and trigger formation of large lumps [31]. Additionally, coarse abrasive scratches that are originated by detached wear particles are visible on the pin surface (Fig. 10c). The abrasive particle is seen embedded to the pin surface at the end of a scratch. The hardness of the wear debris that stayed within the contact may increase due to extensive plastic deformation during their formation or as a consequence of repeated plastic working during sliding. They could become even harder than the pin material and act as a third body abrasive and scratch through the pin material with subsequent sliding, such as the one shown in Fig. 10e. Fine abrasive scratches are seen on the chrome plated pins, see Fig. 10f. The scratches on the chrome plated pins are milder than the uncoated pins owing to the higher hardness of the chromium coating. Nonetheless, at some locations the abrasion resulted in coating spallation.

The brittle nature of the coating wear can be explained by the high degree of residual stress in the coating layer which is indicated by the presence of cracks [27].

The smooth pins with Sq of 0.03 µm did not exhibit any material transfer, see Fig. 10g, h. This can be attributed to the very smooth roughness of the pins. The surfaces of these pins are relatively defect free as the coarse protrusions and irregularities are removed by polishing, reducing the potential initiation sites for strip material transfer. Despite no changes in friction, mild fine abrasive scratches could be seen on the surface of the pins. This might be caused by fine wear particles generated during the test and remain within the contact area. The fine scratches are more pronounced for the uncoated pins. This is expected as the hardness of the uncoated pins is lower than the chrome plated pins.

The wear mechanisms for the uncoated pins in the current reciprocating sliding tests resemble the wear mechanisms reported elsewhere for generalized lubricated contacts where adhesive wear is dominant and the influence of roughness of the harder counterpart was demonstrated [32]. The wear process of the tests can be summarized as follows.

At the beginning stage of the tests, abrasive scratches are formed on the soft strip surface by the roughness peaks of the hard pin with mild adhesive wear and material transfer on the pins. As the sliding proceeds, the transferred layer builds up on the pin surface. The local contact changes from pin-strip material to a self-mating contact with the strip material in both contacting bodies, which is known to give an unfavorable contact with high adhesion. Further adhesion and mechanical scratches promote accumulation of the transferred material and formation of lumps on some of the initiation points. These lumps act as a protruding abrasive scratching features and create coarse macroscopic scratches on the strip surface. These coarse scratches eventually lead to unstable friction and severe adhesive wear.

The wear mechanism for smooth pins is dominated by plastic deformation and flattening of strip asperities with some fine abrasive scratching. The hard smooth pin surface causes plastic deformation and flattening of the soft strip asperities in the initial stage. Repeated sliding leads to concentration of sub-surface shearing strain, fatigue, delamination wear or detachment of oxidized particles. These wear mechanisms can result in wear debris generation. Partly, wear debris are removed from the contact by subsequent sliding movements and some stay within the contact. The hardness of the debris remaining within the contact could possibly increase due to work hardening and oxidation, causing the micro-scratches seen on the pins surface.

In summary, the scratch and the reciprocating sliding tests demonstrated that hard chrome plating delays initiation of galling, reduces the rate of material transfer and improves abrasive wear resistance. This behavior can be attributed to the combined effect of better adsorption/reaction of the additives to the chromium surface providing protection against galling, the smoothening of aggressive roughness features from the grinding process by gentler features due to the chrome plating, and low adhesion of the strip material to the chromium layer. The most important finding of this work is that the tribochemistry of the chrome plated layer plays an important role in reducing iron fines formation. Uncoated pins showed severe galling and material transfer. Galling deteriorates the surface finish of the strip. In rolling processes, this implies that the roll has to be changed by then. Chrome plating and the tribofilm formed act as a protective layer, delaying galling. The improved abrasive wear resistance due to chrome coating implies that the roughness peaks will wear out slowly with a longer rolling distance, and hence, longer roll life. In the search of an alternative for hard chrome coating, in terms of strip cleanliness, the current tests demonstrated that it is important to consider both the tribochemistry and hardness of the coating. No direct comparison between the scratch tests and the reciprocating sliding tests was performed, owing to the different test geometries and scales. Further research is necessary to investigate whether the type of lubricant and additives affect the performance of chrome plating on strip cleanliness.

4. Conclusion

Scratch and reciprocating sliding tests were carried out to gain a detailed insight regarding the positive influence of hard chrome plating the rolls on iron fines generation in cold rolling processes. The scratch tests quantitatively confirmed lower friction, lower amounts of iron fines and less material transfer occur when using chrome plated pins than those made using uncoated pins. The scratch tests also confirmed that the tribochemistry of the chromium layer plays an important role on reducing friction and iron fines generation. Furthermore, the current work revealed new insights in the analysis of these contacts as follows:

- XPS results showed that chrome plated surfaces promote the formation of a tribofilm consisting of a carbonate and amine species.
- Scratch tests can be used to evaluate the potential performance of other coatings on strip cleanliness in cold rolling processes.
- Chrome plating did not significantly alter the average roughness of the pins. However, a smoothening effect of the sharp surface irregularities and protrusions from the grinding process is seen.
- In the reciprocating sliding tests, chrome plated pins exhibited reduced scratches, delayed initiation of galling and low rate of material transfer. This indicates that chrome plating has a positive influence in terms of both abrasive and adhesive wear resistance.
- The combined effect of the surface chemistry of the chromium layer and the smoothening of sharp features from the grinding process due to chrome plating contribute to the improved strip surface cleanliness.

Declaration of competing interest

I, Melkamu Awoke Mekicha, hereby confirm on behalf of all authors that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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