IN-SITU INVESTIGATION OF THE EFFECT OF HARD CHROME PLATING ON IRON FINES FORMATION *

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Abstract

One of the main factors that reduce strip cleanliness are iron fines, which are formed due to the abrasive interactions of the roll surface and the strip in the roll bite during cold rolling. They can cause a problem in fouling of the cold rolling mill as well as downstream processes. It has been repeatedly observed that chrome plating the work roll improves strip cleanliness. In the present work, scratch tests and reciprocating sliding tests were carried out under lubricated conditions to explore the influence of chrome plating on iron fines formation. Scratch tests were conducted to study the influence of chrome plating on iron fines formation at single asperity scale due to its intrinsic property. Reciprocating sliding tests were performed to study the influence of chrome plating a rough surface on iron fines formation, taking into account the initial roughness. The scratches made using chrome plated pins showed lower friction, generated less iron fines and exhibited lower material transfer. Reciprocating sliding tests done using the uncoated pins showed galling at different sliding distances depending on the roughness of the pin. On the contrary, reciprocating sliding tests with the chrome plated pins exhibited no galling irrespective of the roughness.

Keywords: Chrome plating; Scratch tests; Iron fines; Cold rolling.

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1 INTRODUCTION

Surface cleanliness is an important measure of the quality of a cold rolled sheet metal. Strip cleanliness is important not only for aesthetic reasons but also for the functional performance of sheet metal products. Additionally, poor strip quality negatively affects downstream processes such as annealing, galvanizing, forming and painting. One of the main factors that reduce strip cleanliness are iron fines. Iron fines originate mainly from the sheet metal being rolled, which is generally much softer than the roll, as a result of the abrasive interaction of the strip surface and the roll roughness asperities in the roll bite [1–3]. Iron fines can cause inadequate zinc adherence in galvanizing lines. Furthermore, large quantities of iron fines interrupt the filtration process [4–6].

Chromium plating the work rolls has been a common practice in the steel industry for a long time both to increase the service life of rolls and to improve strip cleanliness. Although it has been repeatedly observed that chrome plating the rolls improves strip cleanliness by reducing iron fines generation, only few studies have attempted to systematically investigate the fundamental mechanisms by which chrome plating improves strip cleanliness.

Jacobs *et al.* [7] performed experiments on a specially designed plate-out tester to study the influence of chrome plating the work rolls on the efficiency of oil adherence to the roll or strip surface. They found out that the amount of oil that adheres to the chrome coated samples is at least twice the amount of oil on the uncoated samples. The authors pointed out that the increased oil adherence on chrome plated rolls could be one of the deciding factors why it results in cleaner strips. However, they did not examine the influence of chrome plating on the roughness of the roll surface. In another study, De Mello *et al.* [8] investigated the combined influence of shot peening and hard chromium coating on the wear behaviour of cold rolling mill rolls. They showed that the influence of chrome plating on the wear rate varies depending on the initial roughness of the surface being coated. Chrome plating done on polished surfaces reduced the wear rate of the counterbody. On the contrary, the wear rate of the counterbody increased when chrome plating was carried out after shot peening. The authors emphasized that wear is controlled by the generation and stability of a tribolayer formed on the surface of the contacting pairs. In their recent work, Montmitonnet *et al.* [9] studied the effect of chrome plating on strip cleanliness by performing plane strain compression tests under lubricated conditions. Their results showed that the tests done using chrome plated punches exhibited a cleaner strip. They argue that the improvement in strip cleanliness due to chrome plating is not an intrinsic property of chrome plating but rather depends fundamentally on the smoothness of the coating deposited.

In summary, the mechanisms proposed in literature for the positive influence of chrome plating on iron fines formation are: (i) improved wettability of the chrome plated surface by lubricant emulsion; (ii) formation of a tribolayer on the chromium layer with positive tribological properties and (iii) it provides smoother roll surface with less high frequency sharp components from the grinding process. In reality, the improvement could be due to a combination of these mechanisms acting simultaneously.

So far, no research has been conducted to study separately the contribution of these mechanisms on iron fines formation. In addition, the increasing requirements in terms of better strip surface quality and the health and safety regulations towards banning Chrome (VI), which is used in the hard chrome plating process, means there is a need to find a replacement for this coating. For example, the European Union REACH (regulation concerning the Registration, Evaluation, Authorization and Restriction of Chemicals) safety regulation on chemicals requires Chrome (VI) to be removed from manufacturing processes [10]. To look for substitutes in a systematic way, a detailed understanding of the fundamental mechanisms behind the positive effects of chrome plating on iron fines formation is necessary.

The objective of this work is (a) to investigate the influence of chrome plating on iron fines formation at single asperity contact and (b) investigate the influence of chrome plating on iron fines formation taking into account the initial roughness of the surface being coated. For this purpose two sets of experiments were conducted: scratch tests and reciprocating sliding tests. Scratch tests were carried out to examine the effect of chrome plating on iron fines formation at single asperity contact due to its intrinsic property by excluding the effect of roughness. In reciprocating sliding tests, the roughness changes introduced during chrome plating are taken into account.

2 MATERIAL AND METHODS

Both the scratch tests and the reciprocating sliding experiments were performed using a multi-purpose tribometer (UMT Tribolab from Bruker). The contacts in the current tests were designed to resemble the roll-strip contact in the roll bite of cold rolling processes.

2.1 Scratch tests

In the scratch tests a single asperity of a roll sliding on a strip material is simulated. The scratch pin, which represents the roll asperity, slides against a polished flat strip substrate. The tests were done under lubricated conditions using conical pins with a hemispherical tip, see Figure 1. The hemispherical tip has a radius in the order of a single roughness asperity of the roll. Three sets of pins with different tip radius (225, 265 and 615 µm) were prepared. Two pins were prepared for each radius, one used in the uncoated condition and the other one chrome plated under usual industrial conditions with a coating thickness of approximately 7 µm. To ensure that chrome plated pins have the same surface finish as the uncoated pins, the coated pins were polished again after the coating was applied.

Prior to the tests, the pins and the strip samples were degreased and cleaned with isopropanol. Next, a film of 1 g/m^2 rolling oil was applied on the strip surface using a clean 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. Then, 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 on the strip surface. A total of 16 scratches were made by each pin. The load applied on the scratch pin was selected so that the scratches are either in wedge forming or cutting mode of abrasive wear in each case [11]. The friction was measured and the tests were monitored in-situ using a scientific camera. The worn surfaces were analyzed using an optical microscope, a non-contact three dimensional surface profiler and a scanning electron microscopy (SEM). A summary of the test parameters for the scratch tests are provided in Table 1.

Figure 1. Pins used in the scratch tests (L) and reciprocating sliding tests (R).

Table 1. Materials and test parameters for the scratch tests

Pin material	• Medium alloyed cold worked tool steel, Uddeholm Rigor®: 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 • Surface condition = polished
Strip material	• TiSULC steel (50 mm x 50 mm x 3 mm). • Surface condition = polished
Lubricant	• Bonderite 93TP (fully formulated rolling oil) • Oil film thickness = 1 g/m^2
Scratch test parameters	• Sliding speed = 1 mm/s • Scratch length = 10 mm • Number of scratches = 16 • Spacing between scratches = 1 mm • Load = 17 N (225 µm), 25 N (265 µm), 53 N (265 µm)

2.2 Reciprocating sliding tests

Reciprocating sliding tests were designed to represent the contact of a pickled strip and a roll surface ground to several roughness values. Reciprocating sliding tests were carried out using pins with a squared cross section (5 mm x 5mm x 30 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 Figure 1. The tips were ground and polished in the sliding direction similar to the grinding process of rolls. Three sets of pins in terms of r.m.s. surface roughness (Sq), approximately 30 nm, 0.3 µm and 1 µm were prepared. Four pins were prepared for each roughness value. Afterwards, two pins from each roughness group were hard chrome plated. No surface modification was done on the coated pins after the coating was applied. The counterface was a TiSULC steel strip sample in “as pickled” surface condition.

Similar to the scratch tests, both the pins and the strip samples were degreased using isopropanol prior to the tests. The strip substrate was fastened to a stage with a reciprocating drive while the pin was kept stationary. The tests were carried out under lubricated conditions using the same oil as the scratch tests. The tests were carried out 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 at room temperature. The friction coefficient was continuously monitored during the tests. The pins were analysed with SEM after the tests.

The nanohardness of the uncoated and the chrome plated pins were measured using a Berkovich indenter (Nanoindentation tester from Anton Paar). The measurements were made using a small load of 40 mN (indentation depths less than 0.5 µm) to avoid the effect of the substrate. 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 chrome plated pins respectively.

3 RESULTS AND DISCUSSION

3.1 Scratch tests

The average steady state friction coefficient of the scratch tests are presented in Figure 2. The scratches made using chrome-plated pins exhibited lower average friction coefficient as compared to the uncoated pins. Roughness can be assumed to have little influence on the friction as both the contacting interfaces were mirror polished. Additionally, the applied load is the same for both the uncoated and chrome plated pins for a given radius. Thus, the ploughing component of friction can be assumed to be the same in both cases. Hence, the difference in the friction coefficient could only be attributed to the difference in the interfacial shear stress in the contact. The possible causes for this difference in the interfacial shear stress include; (i) the extreme pressure and polar additives react with the chromium layer to form a tribochemical film with low shear and (ii) lower adhesion between the dissimilar chromium – steel interface than the steel – steel interface. The higher friction coefficient of the coated pin with a tip radius of 265 µm was found out to be due to the large amount of cracks observed on the tip (not shown). This confirms that the quality of the coating plays an important role in terms of strip cleanliness as has been already indicated by Montmitonnet *et al*. [9].

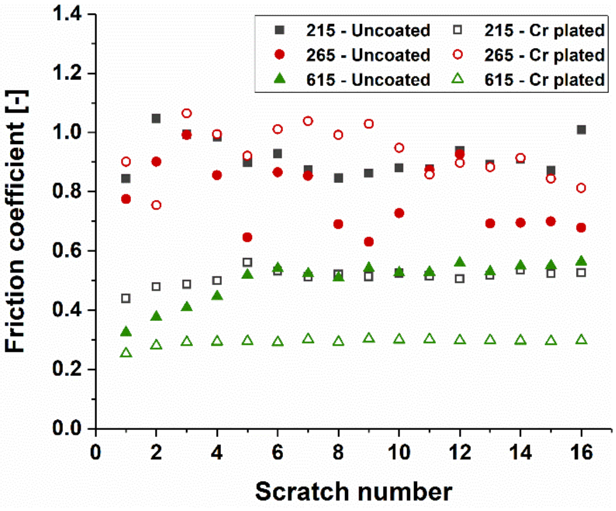

Figure 2. Friction coefficient of the scratch tests.

An example of the SEM image of the pins after the scratch tests and the optical microscopy image of the corresponding scratches on the strip surface are provided in Figure 3. The uncoated and chrome plated pins showed different degrees of material transfer, corresponding their friction behavior (Figure 3(a)). Chrome plated pins showed a significantly lower quantity of adhered strip material as compared to the uncoated pins.

For material transfer to happen, there should be a local breakdown of the lubricant film. As the pin scratches through the strip surface, a plastic wave is formed. Due to the high contact pressure involved, lubricant failure is therefore likely at the contact spot. This might give adhesion and material transfer between the strip and the pin depending on the strength of the boundary lubricant and the surface chemistry of the contacting counterparts. The lubricant additives may adsorb and react differently to the chromium layer of the coated pins than to the steel surface of the uncoated pins. Probably, a tribolayer with positive tribological behavior is formed on the chromium surface, delaying and/or preventing the local failure of the lubricant, and subsequently delaying the initiation of severe adhesive wear.

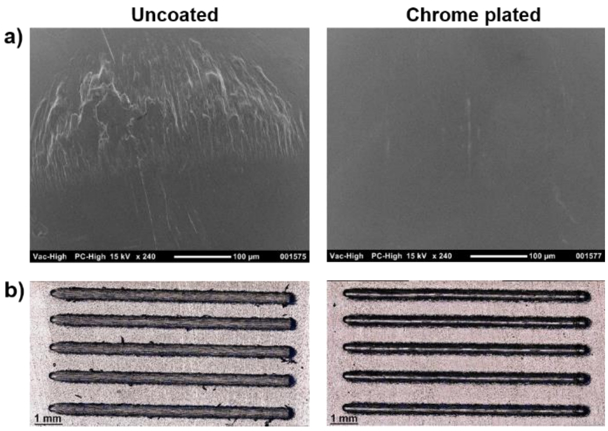

Figure 3. (a) SEM images of the pins with a tip radius of 615 µm after the scratch tests, (b) Optical microscopy images of the scratches made by the pins with a tip radius of 615 µm.

As can be clearly seen from the optical microscopy images of the scratch grooves on the strip surface (Figure 3(b)), the quantity of both loosely detached and adhered iron fines on the surface of scratches made using the coated pin is remarkably smaller than the scratches made using the uncoated pin. This could be related to the higher friction coefficient of the scratches made with the uncoated pins, which means higher subsurface shear stress at the contact spots. The increased subsurface shear stress on the strip material produces greater surface damage on the strip. This leads to generation of more wear debris that contaminate the strip surface (Figure 3(b)) and more material transfer on the pin surface (Figure 3(a)). These findings suggest that the tribochemistry of the chromium coating plays an important role in reducing iron fines formation and friction in the boundary layer lubrication regime.

3.2. Reciprocating sliding tests

Table 2 presents the r.m.s. roughness value of the pins. Chromium coating did not significantly alter the average roughness of the pins. Only a slight roughening of the polished samples was observed. A similar observation of roughness changes due to chrome plating is reported in literature [8,9]. Although chrome plating did not alter the average roughness value substantially, the topography of the uncoated and the chrome plated pins look different at sufficiently small scale. The typical surface topography of the uncoated and chrome plated pins are presented in Figure 4. Chrome plating made the prominent peaks, which can be aggressive on the strip surface during rolling and induce more intense abrasive wear in the strip surface, gentler. 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 [12].

Table 2. Effect of chrome plating on the average roughness of the pins used in the reciprocating sliding tests

Nominal Sq	Uncoated (µm)	Cr plated (µm)
1 µm	1.06	1.00
0.3 µm	0.28	0.31
30 nm	0.034	0.061

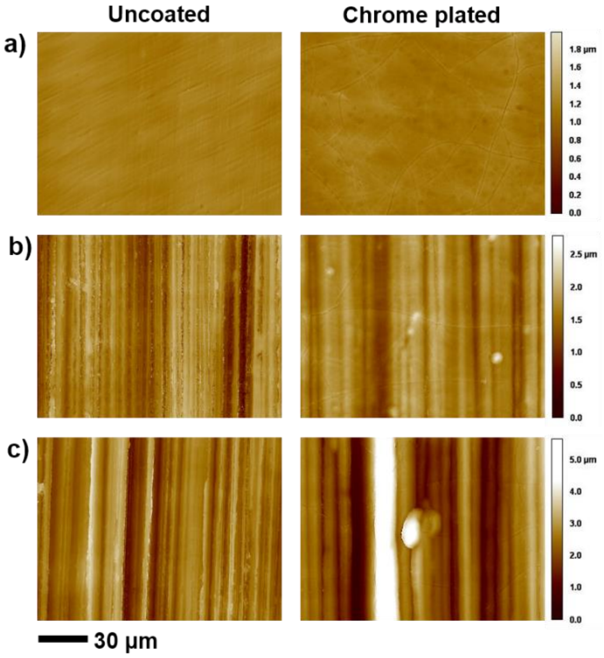

Figure 4. Typical surface texture of the uncoated and coated pins used in the reciprocating sliding tests, a) Sq = 1 µm, b) Sq = 0.3 µm, c) Sq = 30 nm.

The friction curves of the reciprocating sliding tests are presented in Figure 5. At approximately a sliding distance of 75 m for uncoated pins with Sq of 1 µm and 175 m for uncoated pins with Sq of 0.3 µm, a sudden increase of friction coefficient was seen. The tests conducted using the pins with Sq of 30 nm did not show such a transition in friction. This type of sudden increase of friction is generally associated with a transition to severe adhesive wear (also known as galling) and gross macroscopic surface damage [13]. For lubricated contacts, like the current tests, local failure of the lubricant is a necessary condition for galling to occur. The local lubricant failure, in turn, has been related to frictional heating [14]. The difference in the critical sliding distance for the sudden increase in friction to occur at different roughness levels can be attributed to the amount of defects serving as a spot for the initiation of galling. Rough surfaces have coarse surface protrusions and irregularities, which may act as a galling initiation point as compared to the smooth surfaces. This is similar to previous publications on the influence of roughness on galling behavior, smooth roughness favoring better galling performance [15,16].

None of the chrome coated pins showed such a transition in friction. Both the tribochemistry of the chromium layer as well as the smoothening of the aggressive rough ness 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, possibly due to the formation of a protective tribolayer on the chrome plated surface. Concurrently, smoothening of the aggressive roughness features on the pin surface reduces the number of galling initiation points. In all the reciprocating sliding tests that did not show galling, the friction coefficient remained at a steady state value of approximately 0.05 for all the three roughness values.

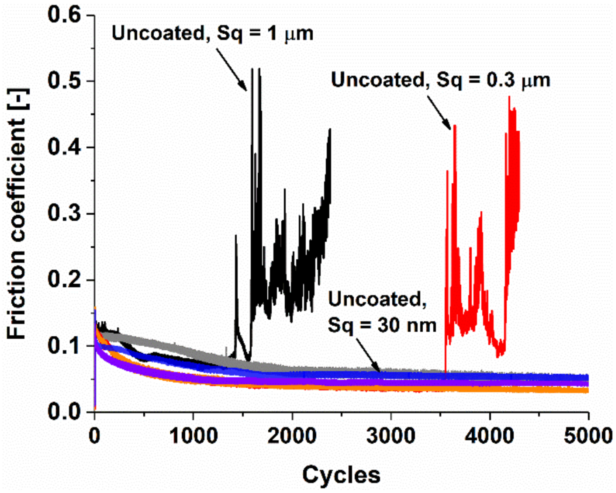

Figure 5. Friction coefficient graphs of the reciprocating sliding tests.

The worn surface morphology of the pins after the reciprocating sliding tests is illustrated in Figure 6. A massive material transfer with several initiation points was observed on the pins that exhibited a transition to severe adhesive wear, corroborating the friction measurements (Figure 6(a, b)). On the contrary, no such material transfer was observed on chrome plated pins irrespective of the roughness.

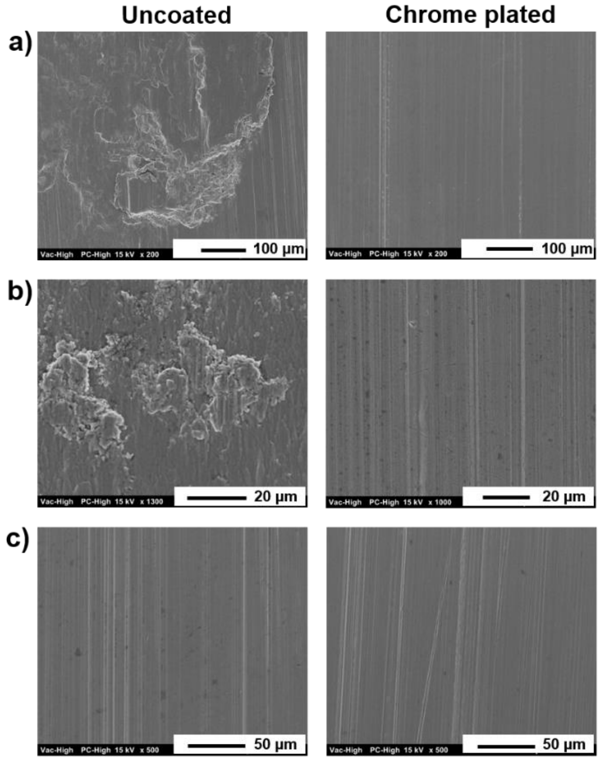

Figure 6.SEM images of pins after reciprocating sliding tests, a) Sq = 1 μm, b) Sq = 0.3 μm, c) Sq = 30 nm.

The wear mechanisms for the uncoated pins in the current tests resemble to the wear mechanisms reported elsewhere for lubricated systems where adhesive wear is dominant and the influence of roughness of the harder part is demonstrated [15–17] . At the beginning stage of the tests, abrasive scratches are formed on the softer strip surface by the roughness peaks of the harder pin accompanied by mild adhesive wear and material transfer. As the sliding continues, the transferred material accumulates on the pin surface and forms macroscopic lumps. At the lumps, the local contact changes from a pin-strip material contact to a self-mating contact with the strip material in both contacting bodies. This is known to give an unfavorable contact with high adhesion [18]. These lumps, which gain hardness by strain hardening and/or oxidation, scratch the strip material with subsequent sliding. When the lumps reach a critical size, coarse scratching of the strip substrate begins, which eventually transforms into severe adhesive wear and unstable friction. In this stage, a high rate of material transfer is accompanied by wear particles generation. In rolling processes, this implies that there is deterioration of the strip quality and loss of the desired roughness transfer. Hence, the roll has to be changed by then.

The smooth pins with Sq of 30 nm (Figure 6(c)) did not exhibit any material transfer. This can be attributed to the very smooth roughness of the pins. These pins are relatively defect free and there are few initiation points for galling to happen. No material transfer was seen on the chrome plated pins irrespective of the roughness value. This is possibly due to the combined effect of the tribochemichal reaction of the chromium layer with the lubricant and the smoothening of the aggressive roughness peaks from the grinding process. It is difficult to distinguish the contribution of each factor from these tests.

In summary, both the scratch and reciprocating sliding tests demonstrated the significance of chrome plating on adhesive wear and consequently iron fines formation. No direct comparison between the scratch tests and the reciprocating sliding tests was performed owing to the different scales and test geometries. Whether the type of the lubricant and the chemistry of the additives affect the performance of chrome plating on strip cleanliness is a subject of current and future research.

4 CONCLUSION

- Scratch tests done using chrome plated pins showed lower quantity of iron fines, less material transfer and lower friction.
- Scratch tests indicated that the tribochemistry of the chromium layer plays an important role in reducing iron fines formation.
- Scratch test can be used as a method to evaluate the performance of other coatings with regard to strip cleanliness in cold rolling processes.
- Reciprocating sliding tests done using the uncoated pins showed galling at different sliding distances depending on the roughness of the pin. However, none of the reciprocating sliding tests with the chrome plated pins exhibited galling irrespective of the roughness.
- Both the tribochemistry of the chromium layer and the roughness changes due to chrome coating play a role in reciprocating sliding tests.

Acknowledgments

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