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Surface Microstructure of Normal and Defected Cold Rolled Sheet, Investigated by SEM/EDS and Surface Profilometry

This paper features the deviating surface microstructure of some common lubrication-related surface defects such as mottling and "white marks," as well as heat scratches and frictional pickup. In addition, defects attributable to rolled-in dirt and rolled-in scale are discussed, in which the local surface morphology is often indicative of a deviating local lubrication regime. Possible remedies for these surface defects are discussed.


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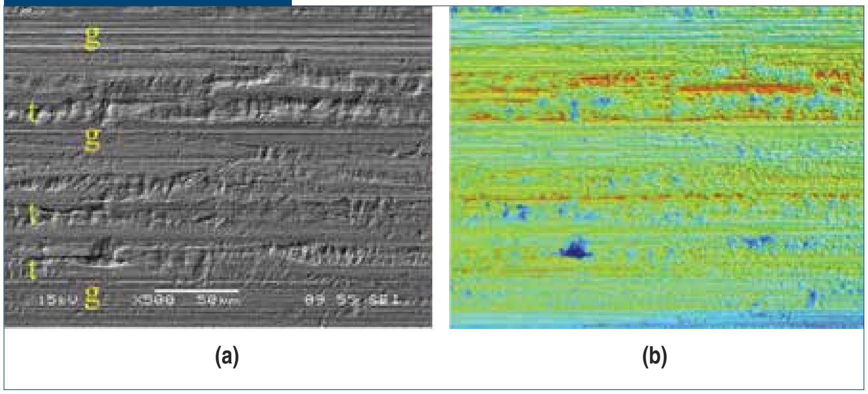
The cold rolling process generally occurs in the mixed lubrication (ML) regime. This can be inferred from the typical values of the coefficient of friction (CoF) during cold rolling, which can be calculated on the basis of mill and rolling parameters and a roll bite model. Roughly speaking, CoF values range from 0.04 to 0.08, which is characteristic for the ML regime. The exact value depends on factors such as process speed, roll roughness and, of course, lubrication. The physical reason for the characteristic values of the CoF in the ML regime is that, due to the roughness of both work roll and strip; microscopic areas of close contact coexist with areas of larger separation and possibly areas of micro-plastohydrodynamic lubrication (MPHL), as described in the 3D Stribeck curve.[1,2] In the areas of close contact, boundary lubrication (BL) conditions exist in which the local CoF is governed by adsorption of lubricant components.[1] In the areas of larger-separation elastohydrodynamic lubrication (EHL) conditions exist in which the local CoF is governed by high-pressure and high-shear-rate lubricant rheology.[1] This explains the characteristic values of the CoF in cold rolling as they correspond to a weighted average of the CoF in the boundary regime (order 0.1) and the CoF in the EHL regime (order 0.01).

The two distinct lubrication regimes of BL and EHL not only provide the defining CoF values for the rolling process, but also leave distinct surface features on the strip. In areas of close contact, the work roll is in sliding contact with the strip, which normally leads only to mild grooving caused by plowing. In areas of larger separation, a lubricant cushion separates the two surfaces, leading to the survival of roughness valleys. The distribution of the areas of mild grooving and the areas where roughness valleys survive, therefore, is a direct reflection of the distribution of the two lubrication regimes, BL and EHL, and hence of the CoF in the cold rolling process. A qualitative impression about the lubrication regime can thus be obtained from a strip surface morphology analysis. In the next section, some more background to the characteristic surface features of cold rolled strip will be given. Note that, in this paper, the ratio between grooving and roughness valleys is assumed to be directly related to the entrained film thickness (which influences the ratio between BL and EHL). However, in another source,[3] it is assumed to be directly related to forward slip, where a high forward slip (i.e., the neutral point (NP) relatively far away from the bite exit, and longer sliding distance at the exit) is assumed to lead to more surface plowing (called "buffing" in the original source) and thus more grooving. These views, although presenting a different mechanism, are not completely independent: a higher separation between the work roll and the strip leads to lower CoF. This, in turn, moves the NP toward the exit (lower forward slip), reduces the sliding distance between the neutral point and the exit, and reduces the surface plowing.

Strip Surface Morphology

Fig. 1a is a scanning electron microscope (SEM) image of the characteristic features on cold rolled strip. The areas of mild grooving can be seen, as well as the roughness valleys

Figure 1



Scanning electron microscope (SEM) image (a) and surface profile (b) of the same area of a characteristic cold rolled surface. (b) has a height scale of –2 µm (blue) to +2 µm (red). Note the areas of mild grooving and areas with transverse fissures (in yellow: "g" and "t").

with the characteristic transverse fissures (discussed later). Fig. 1b shows a surface profile of the same area.

The mild grooving is caused by local plowing of work roll asperities that slide over the strip surface. In some wear theories, different modes of abrasive wear are described, which depend on cutting (asperity) angle and shear stress within the interface between the sliding bodies.[4] Relatively strong wear (and significant metal loss) is found in two cases: (1) for high cutting angles, leading to strong cutting action into the softer metal and (2) for high interfacial shear stress, leading to strong wedging action due to shear within the soft metal rather than along the interface. In contrast, plowing wear is relatively mild and leads to little metal loss. It is characterized by low cutting angles and low interfacial shear stresses. Asperity angles (or cutting angles) in cold rolling are relatively small, and due to molecular adsorption the interfacial shear stress is low, which leads to sliding along the interface rather than within the metal matrix.

The transverse fissures can also be readily identified in Fig. 1, but their origin is less obvious. These characteristic features occur in cases of plastic deformation where (locally) a pressurized lubricant cushion separates the two surfaces. This leads to deformation of and within the grains that constitute the metal, both leading to morphological structures perpendicular to the rolling direction.[5] These features were investigated experimentally and theoretically by a number of researchers. Butler[6] speculated that the transverse fissures originated from surface fracture due to reduced ductility, aided by penetration of pressurized lubricant. Ratnagar[7] observed hydrodynamic roughening on an aluminum surface and concluded that the transverse features are due to differential deformation of individual grains and along slip lines within these grains. Thomson[8] additionally observed that, as deformation progresses, the slip lines of several grains may link up. Wilson,[9] by means of mathematical modeling, explained the differential deformation of individual grains by (periodic) variations in flow stress and predicted the formation of deep valleys and more rounded peaks.

Quantification of Surface Morphology

As mentioned earlier, the relative amount of the areas of mild plowing and transverse fissures provides a qualitative measure of the lubrication regime, so that a qualitative impression about the lubrication regime can be obtained from a strip surface morphology analysis. Semi-quantitative analyses were proposed by Butler,[6] using an interference microscope, from the fringe pattern given by partly smoothened surfaces; by Azushima and Miyagawa,[10] from laser diffraction patterns; and by Azushima and Inagaki,[11] who used a surface brightness meter and correlated this to oil film thickness in rolling. In this paper, an alternative approach is presented for quantifying the relative proportion of transverse fissures and mild grooving.

Traditionally, surface roughness is measured with a perthometer (a "stylus" measurement), which physically slides a narrow probe for a certain length along a surface, registering the deflection. The centerline average is usually referred to as the Ra value. Modern techniques, such as interference microscopy, are mostly contactless and use, e.g., a light source with which a two-dimensional area can be probed. This results in a 3D height map of the surface, such as that shown in Fig. 1b. The "center plane" average is usually referred to as the Sa value. This height map can be analyzed with appropriate software. For instance, the centerline averages parallel and perpendicular to the process direction can be calculated, which can be significantly different when the roughness has an orientation (lay), e.g., in ground surfaces. In this paper, a new method is presented for quantifying the relative proportion of transverse fissures and mild grooving, based on an analysis of the 3D height map mentioned above. It relies on the fact that the centerline average in the rolling direction along a single line of pixels in a groove is lower than in a region of transverse fissures. In this paper, this method is referred to as the "stylus-x" method, with the rolling direction in the x-direction. See Fig. 2 for an illustration. Prerequisite for this method is that the measured area is large enough for a representative amount of grooving and transverse fissures to be present, but at the same time that it is small enough to contain relatively long, uninterrupted lengths of grooving and areas of transverse fissures. This is the case in Fig. 1b. Later in this paper (see Figs. 3 and 4), it will be shown that this method can be quite useful to quantify even small deviations of surface morphology. Note that not all morphological deviations require this method; in some cases, measuring the Sa values is sufficient.

The appearance of cold rolled strip in terms of the relative proportion of areas of mild grooving and transverse fissures is important for aesthetic reasons. In this respect, qualifications such as "dull" and "bright" apply, corresponding to a predominance of transverse fissures and grooving, respectively. Stainless steel, for this aesthetic reason, is mostly relatively "bright." There may, however, also be functional reasons for choosing a certain relative proportion of transverse fissures to grooving, such as the beneficial effect a dull surface may have on coating demands and yield in solar cells.[12] Small variations in surface brightness of cold rolled strip from batch to batch are often acceptable, e.g., due to variations in work roll roughness, mill operation and the condition of the emulsion. However, when such variations occur on the same strip, in proximity to each other, these variations are no longer acceptable, more so because the human eye is very unforgiving to even very small variations in reflectivity.

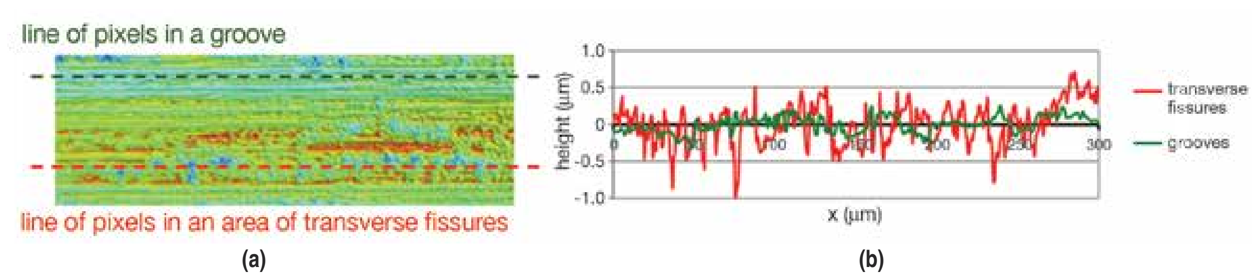
In the remainder of this paper, several surface defects are discussed, with varying origin, but all characterized by (small) spatial variations in reflectivity/surface morphology. Surface analyses were carried out with a surface profiler (Wyko NT 1100 interference microscope), and with an SEM (Jeol 6480 scanning electron microscope), equipped with an EDS (energy-dispersive x-ray spectroscopy by EDAX) system for surface elemental analysis.

White Streaks

White streaks have a characteristic appearance, such as that illustrated in Fig. 3a. They consist of irregular, "white" lines roughly in the rolling direction, but often oriented at a small angle. Their width may vary considerably, and they often have a "splashlike" appearance. A "splash" of streaks may cover quite a large area, e.g., 20–50 cm, but some sections of the strip may be defect-free. White streaks may occur after cold rolling with relatively smooth work rolls, but may also occur after cold rolling where a texture is imprinted in the last stand at low reductions. In this paper, a defect in the first category is discussed.

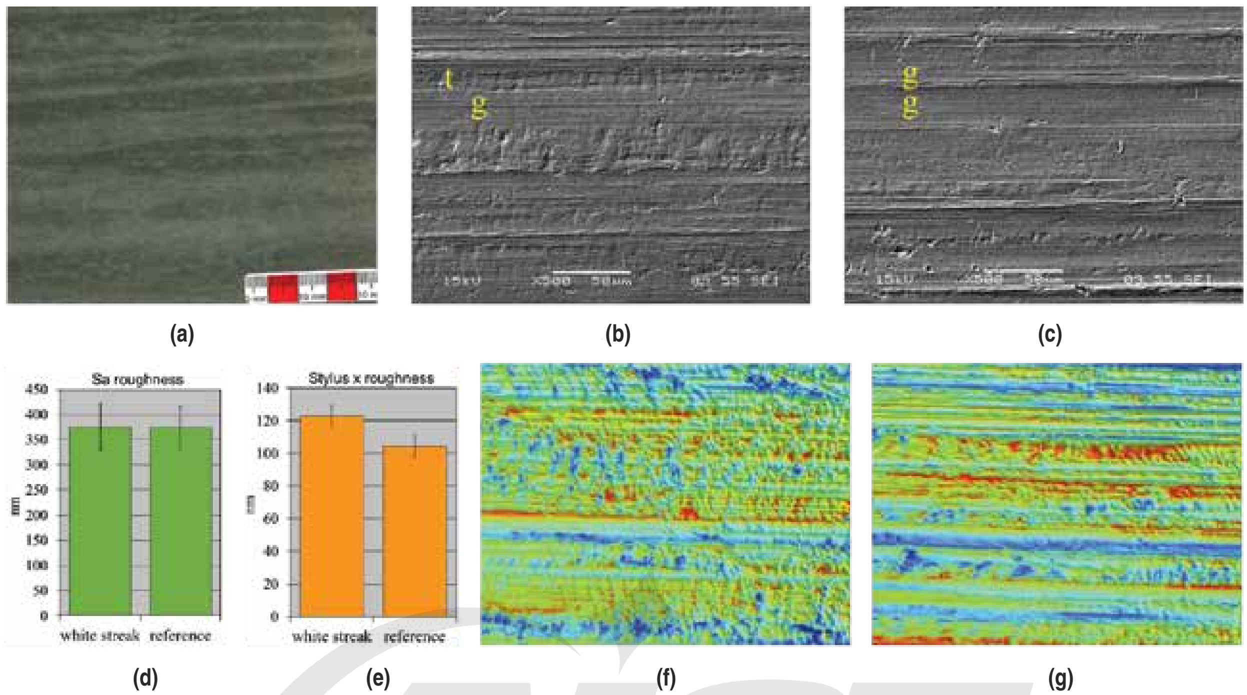
When investigating this defect with an SEM, one always observes a (slight) dominance of transverse fissures in the whiter areas and of mild grooving in the darker, reference areas, as is illustrated in Figs. 3b, 3c, 3f and 3g. In other words, the whiter areas correspond to a duller surface aspect, whereas the remainder of the surface corresponds to a slightly brighter surface aspect. This would suggest that the white streak defect is the result of small spatial variations in oil film thickness. It can be seen in Fig. 3d that the Sa value (the center plane average of the height map created in the interference microscope) is not able to distinguish the white streak from the reference. The reason for this is that the Sa roughness is dominated by the imprint of the roll grinding marks (the green and yellow bands in the rolling direction, as shown in Fig. 1b). However, as mentioned earlier, these defects can be quantified with a stylus-x calculation from a 3D height map. In Fig. 3e, it can be seen that the white streak (dull) areas

Figure 2



Height map image taken from Fig. 1b (a). Stylus-x method for quantification of the relative proportion of grooves and transverse fissures (b). The centerline average of the heights along a single line of pixels in a groove is lower than in an area of transverse fissures.

Figure 3



White streaks defect: photograph of the defect (a), SEM images of streak (b) and reference (c) with indicated bands of transverse fissures ("t") and grooves ("g"), Sa roughness of the white streak and reference areas (d), stylus-x roughness of the white streak and reference areas (e), surface profile of streak (f) and reference (g). Dimension: 150 x 110 μm, height scale –1.5 to +1.5 μm.

correspond to a significantly higher stylus-x value than the reference surface.

Using SEM and a surface profiler, it was shown that the white streak defect is purely topographical. This was also confirmed with EDS analysis, which showed that there is no compositional difference between the defect and reference areas.

The white streak defect is caused by spatial variations in "plate-out" of the oil on the strip[3] or variations in film thickness during rolling. This, in turn, can be caused by inhomogeneities in the emulsion or variations in emulsion application. In case of significant dead zones in the emulsion application system, oil may separate from the emulsion and the emulsion concentration out of the nozzles may fluctuate intermittently. Note that the white streak defect also has a striking macroscopic fluid flow, spatter or splashlike appearance, which corroborates the sketched scenario. Usually this defect is reduced by improving the lubrication consistency across the width of the strip, either by emulsion properties or application. Note, by the way, that the white streak defect cannot be reconciled with the forward slip-related mechanism sketched in the introduction,[3] as roll and strip speeds cannot vary spatially.

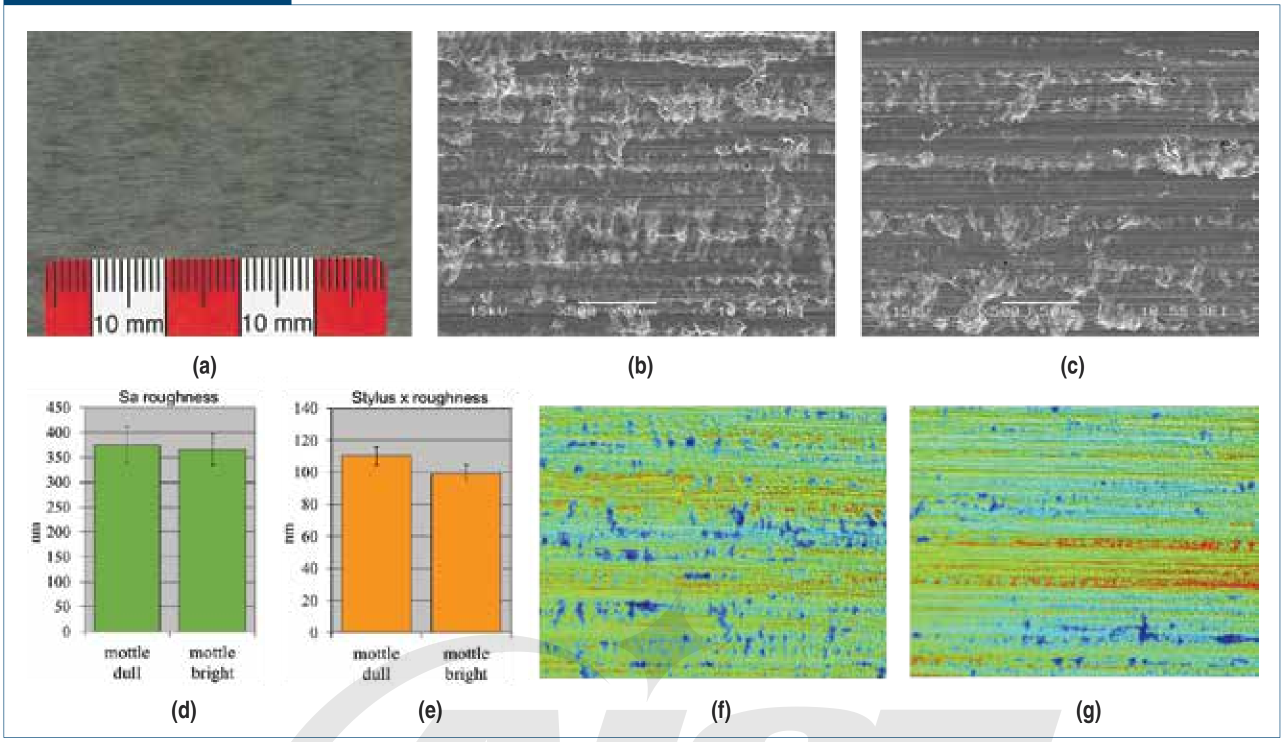
Mottling

Mottling consists of lighter and darker areas that are quite homogeneously dispersed over the surface. These areas measure a few to 10 mm across. Macroscopically, the shape/orientation of these lighter and darker areas is not strongly oriented in the rolling direction. As the size of the lighter and darker areas becomes smaller, the defect is perceived to be less problematic.

Although, macroscopically, mottling is thus a different defect than white streaks, there are similarities on the microscopic scale. Just as with white streaks, this defect is purely topographic, where the dull and bright areas are characterized by a predominance of transverse fissures and mild grooving, respectively (see Figs. 4b, 4c, 4f and 4g). Just like white streaks, mottling is also the result of small spatial variations in oil film thickness. And again, as illustrated in Figs. 4d and 4e, the dull and bright areas can be distinguished by a stylus-x value, not by a standard Sa value.

Mottling is most often observed after tinplate rolling, and especially after double cold reduced rolling. Due to the strong demands on lubricity in this process, the lubricant is often applied in direct

Figure 4



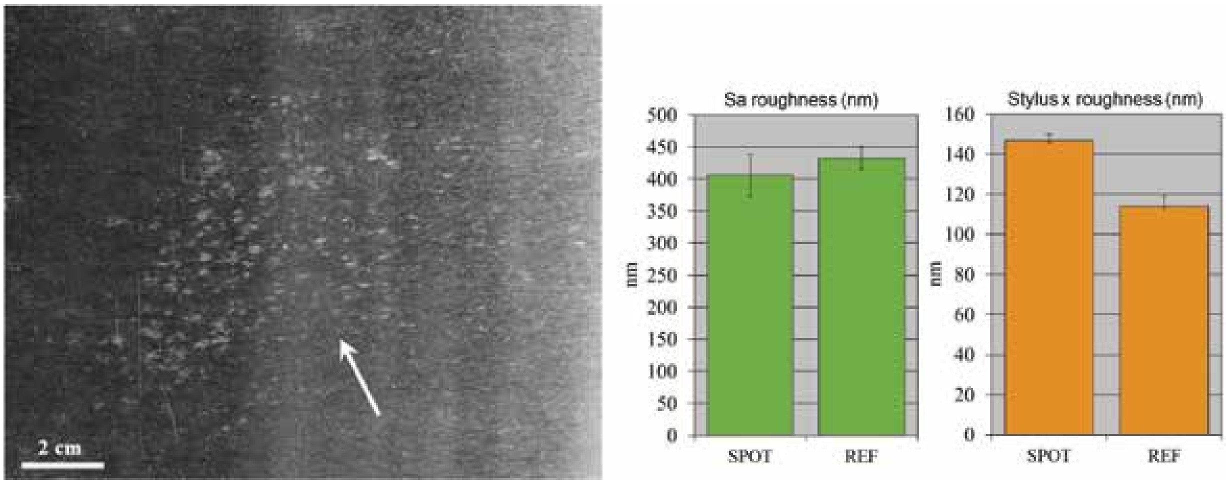
Mottling defect: photograph of the defect (a), SEM images of dull (b) and bright (c) areas, Sa roughness of the dull and bright areas (d), stylus-x roughness of the dull and bright areas (e), surface profile of dull (f) and bright (g) areas; dimension: 600 x 460 µm, height scale –2 to +2 µm.

application (DA) mode. In DA, the oil contains very few emulsifiers and is mixed with water prior to application onto the strip, often with static tubes inserted just prior to the nozzles. Compared to an emulsion that results from an emulsifiable oil, the dispersion that is thus sprayed onto the strip is highly unstable. This way the oil obtains the high plate-out and film thickness values that are required for this process. It is very likely that the mottling defect is related to this instability of the dispersion, which may lead to variations in film thickness just before the roll bite. These variations occur on very small length scales and are not related to inhomogeneities in spray application, but instead likely originate from inhomogeneities within the dispersion itself, i.e., the presence of larger-than-average oil droplets. It can, for instance, be calculated that an occasional oil droplet with a diameter of 200 µm, when flattened in a 0.4-µm roll gap, will spread out over an area of nearly 4 mm in diameter. Due to the low strip roughness, mottling defects are relatively conspicuous. Mottling may be addressed by reducing the (maximum) oil droplet size, either by mechanical means in the application system or by chemical reformulation of the lubricant.

Rolled-In Dirt

Surface defects, caused by rolled-in alien matter (dirt), are common in cold rolling. The origin of this matter can be diverse: dirt from floors and ceilings, or solid debris originating from the rolling process, which may cluster to form oily dirt, accumulating on guide rolls and mill housing. The oily dirt may then contaminate the strip either directly or indirectly via the emulsion system. Also more viscous matter, leaking out from bearings, may end up in the emulsion system. The nature of dirt that ends up in the roll bite can be fluid, more viscous or solid. In the latter case, it often concerns lumps of loose, solid particles, held together by oily matter. Chemically, fluid or viscous dirt may consist of blobs of grease or metal soaps, while solid dirt consists mostly of dust, sand, oxide matter (scale, rust) or fines. More rarely, also paint, rubber, plastic or other particles are found. Fluid or viscous dirt, when entrained in the roll bite, leads to a locally larger separation of the mating surfaces, and thus, to local EHD conditions. This results in the formation of transverse fissures, giving the defect its dull appearance. Therefore, on a microscopic scale, the surface morphology of this defect is very similar to that seen with white streaks and

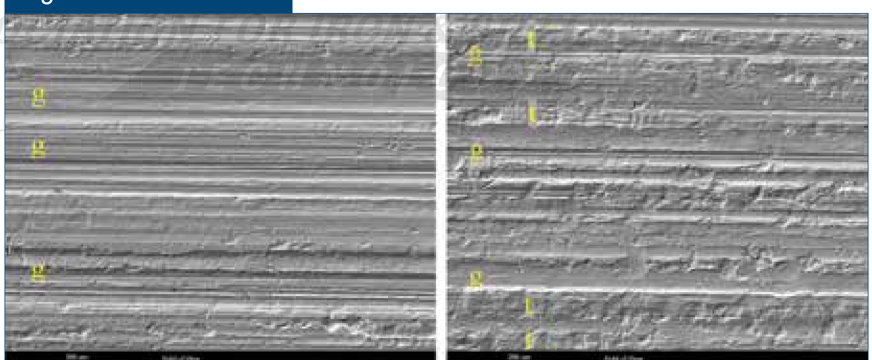
Figure 5



(a) (b) (c)

SEM image of a cluster of dull spots on full hard sheet (a), likely caused by entrainment of small lumps of calcium soaps at a tandem mill last stand (most of the soap being washed away, but traces of calcium found), and Sa (b) and stylus-x values (c) for four dull spots and four reference areas.

Figure 6



(a) (b)

SEM images of reference surface (a) and of one of the dull spots (b) shown in Fig. 5a (500x magnification). The reference surface consists mainly of grooves ("g"), whereas for the dull surface, the relative proportion of transverse fissures ("t") is much higher.

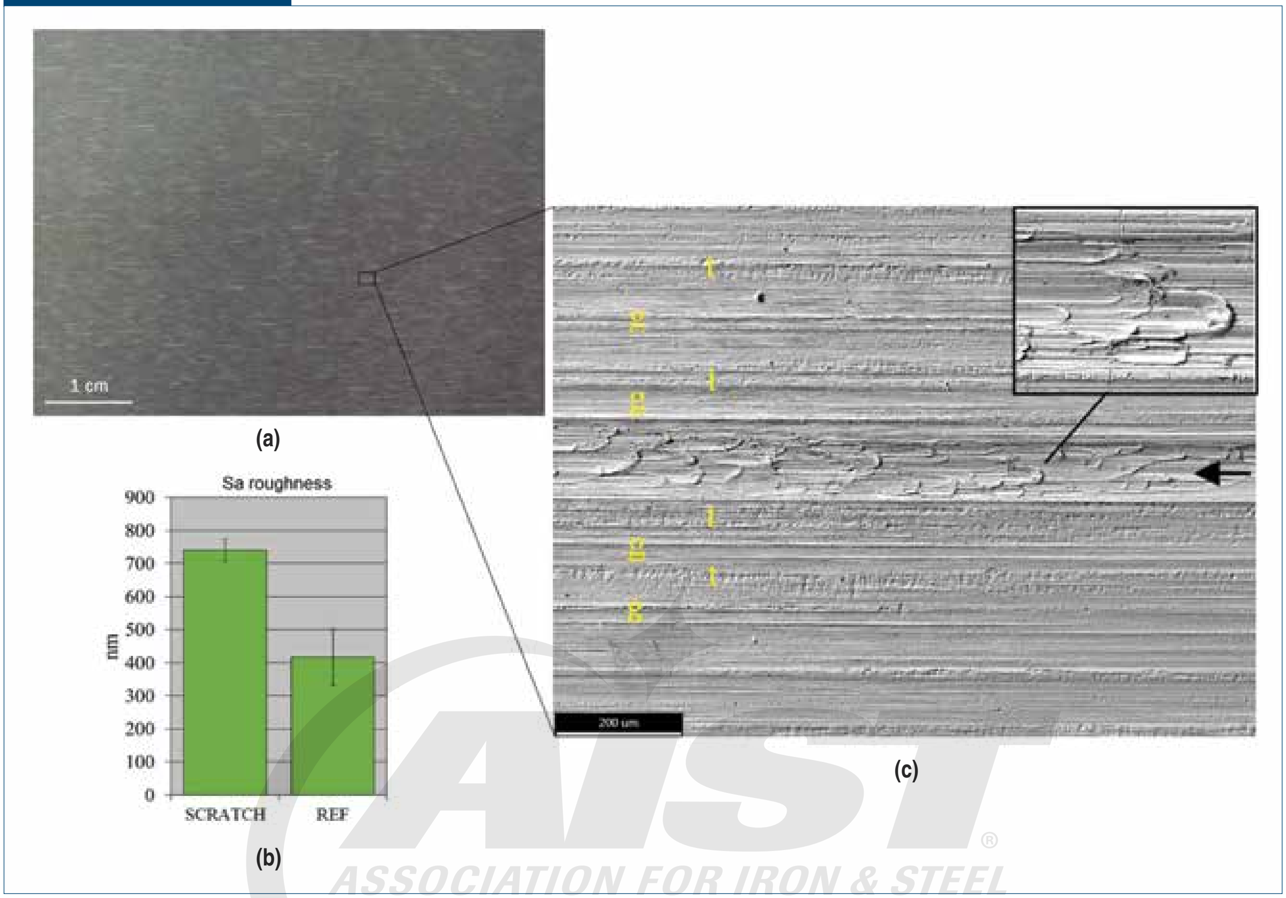
mottling. Due to the very nature of dirt, on a macroscopic scale, rolled-in dirt leads to defects with a much larger diversity of shapes and sizes, including single spots, bands and clusters of small or larger spots, often with sharper boundaries than seen with white streaks or mottling.

After being trapped in the roll bite, solid dirt, such as remains of scale, does not lead to the formation of transverse fissures unless the solids are (partly) shattered in the next-to-last reduction step and are subsequently washed off from the surface. Transverse fissures may then be formed in the created voids in the final reduction step.

Therefore, comparison of the amount of transverse fissures for reference and defect surface may indicate that the defect was caused by entrainment of fluid or viscous alien matter in the roll bite. In case remains of alien matter are still present, identification can take place by, for instance, EDS. An example of a rolled-in dirt defect is shown in Fig. 5, in which dull spots on full hard sheet represent depressions in the general surface, characterized by significantly higher stylus-x roughness values, a consequence of the presence of a relatively large number of transverse fissures. This is visualized in Fig. 6, where most of the reference surface is shown to be grooved, whereas the dull, defect surface comprises significantly more transverse fissures.

Measures preventing the formation of these kinds of defects are rather obvious. The key issue is maintenance: the emulsion bath should be kept clean from contaminations, fines should be removed

Figure 7



Tinplate sample with heat scratches (a). SEM image, displaying a 3- to 4-µm deep heat scratch (arrow), flanked by bands of mild grooving ("g") and bands with transverse fissures ("t"). Note the scooped-up metal within the scratch (insert) (c). Representative Sa roughness values of surface within the scratches and of reference surface (average of three measurements) (b).

from the emulsion effectively and the mill housing should be cleaned on a regular basis. The washing performance of the rolling emulsion might also be improved, leading to less mill hang-up and a better solubilization of dirt droplets or aggregates.

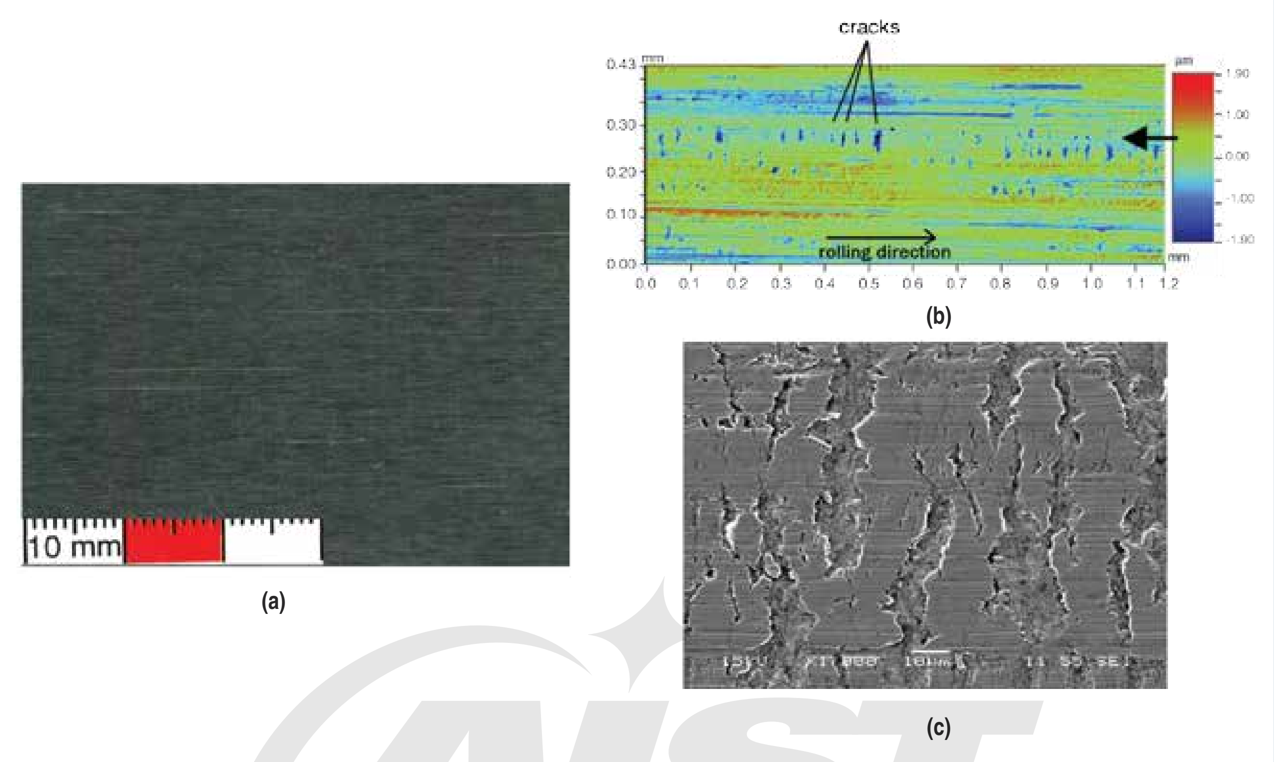
Heat Scratches

Heat scratches, also identified by terms such as frictional pickup, friction lines and heat streaks, are short, narrow scratches of a few millimeters to several centimeters in length and a few microns deep, scattered more or less homogeneously over the surface of strip and work roll and running in the direction of rolling.

In most cases, heat scratches occur when rolling tinplate. They first emerge at the bottom side of the strip, where the amount of lubricant entrained in the roll bite is less than at the top side of the strip. When rolling is continued, the defect progressively worsens: the top side of the strip becomes affected as well, and the scratches that were first confined to certain regions of the strip (mostly the edges) may quickly spread over the entire width of the strip. Since the work rolls become damaged as well, they need to be changed quickly.

Different morphologies can be distinguished, reflecting differences in severity of the defect. Moderate heat scratches, reaching a depth of 2–5 µm and a width of several tenths of a millimeter, are generally characterized by material within the scratch that is scooped up in a kind of mild wedging action.[4] They are assumed to result from lubrication or cooling deficiency. Rarely, more severe heat scratches occur that are broader and are characterized by material in the scratch that was pushed forward toward the end of the scratch to form a welding point, resulting in a comet-shaped scratch. In both cases, surface morphology indicates that the scratches were formed by the sliding action of a rougher, and exceptionally high asperity on the work roll. Heat scratches are accompanied by roll damage. It is therefore likely that not all scratches occur

Figure 8



Tinplate sample with line defects (a). 3D surface roughness image of part of a line defect (indicated by large, black arrow), level to the general surface; surface area: approximately 1.2 x 0.4 mm; height scale: –1.9 µm (blue) to +1.9 µm (red) (b). SEM image of the defect at higher magnification, showing a series of cracks formed by fracturing of the surface (c).

as a result of a (lubrication) incident, but rather are just imprints of already-formed welding spots on the work roll into the strip surface.

A case of moderate heat scratches is illustrated in Fig. 7, clearly showing the scooped-up metal. Adjacent to the defect, the bands of mild grooving and transverse fissures can be seen. Not surprisingly, as shown in the graph, the surface within the scratch is much rougher than the reference surface, and quantifying the roughness within the scratch does not require a stylus-x roughness measurement, since an Sa roughness is sufficient.

The lines depicted in Fig. 8 display a very different morphology: they consist of an array of structures perpendicular to the rolling direction and level to the general surface. Upon magnification, a cracked morphology becomes apparent, with the plateaus often fitting together as in a jigsaw puzzle, suggesting that the cracks result from surface fracture.

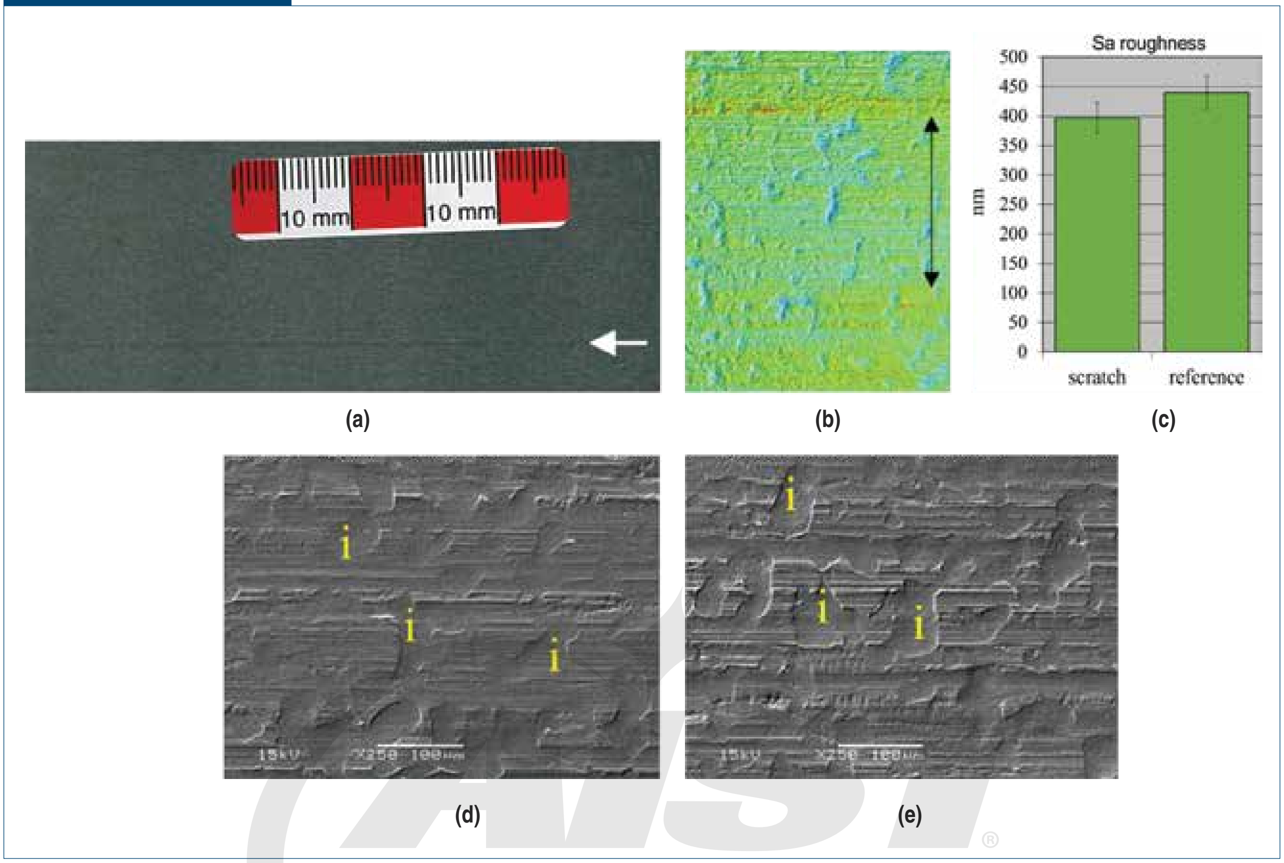
A possible scenario for this latter defect is that heat scratches were made in the stand immediately preceding the last. Thereby, the bottom of the scratch was likely strongly strain-hardened by the scooping action. Subsequently, in the last reduction step, the scratch was flattened to the general surface level. At the same time, the strain-hardened surface of the scratch fractured during the elongation action, possibly aided by penetration of the pressurized lubricant.

Heat scratches may emerge when rolling hard material at thin gauges, when high reductions or high speeds are applied, when using rough rolls, or when cooling is insufficient.[13–15] They can also occur when using emulsions of low oil concentration or low saponification number.[13] There is much debate on the root cause of (heat) scratches. On the microscopic scale, there has been a failure of the frictional conditions, with excessive wedging action, locally resulting in breakdown of the protective boundary layer between work roll and strip. The latter may be the result of overall underlubrication, either through insufficient film formation or deficient boundary lubrication.[13,14]

Kimura and Okada[13] combined data from several tandem mills and found that the occurrence of heat scratches always occurred when strip temperatures were highest. They concluded that a critical temperature existed above which heat scratches occurred.

A possible mechanism for the formation of heat scratches under these severe conditions is that

Figure 9



Photograph of part of a slip line at least 200 mm long (white arrow) (a), surface profile (460 x 600 mm) with the black arrow indicating the width of the line (b), Sa roughness inside the line compared to the reference surface (c), and SEM image of the interior of the line (d) and the reference (e) ("i" identifies the last stand work roll imprints).

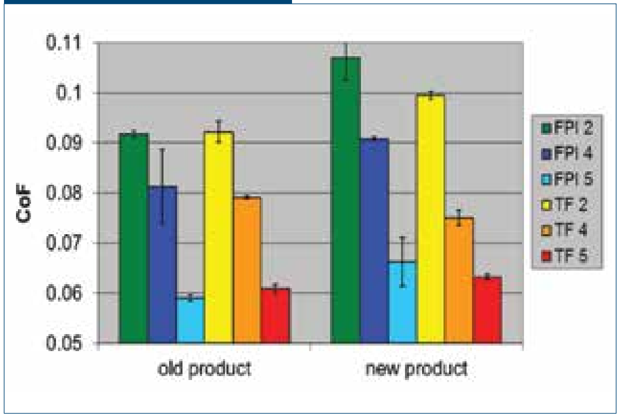
elevated strip and work roll temperatures result in a lower lubricant viscosity in the roll bite entry. As a consequence, film formation is reduced and too little lubricant is being entrained in the rolling contact to sufficiently separate the mating surfaces. Also, it should be mentioned that laboratory experiments have shown that, at a certain speed, film formation may no longer increase with speed, but instead, start to decrease.[16] This phenomenon of sudden film collapse, seen with emulsions in the laboratory, may also take place in cold rolling. In other words, the rolling speed might also be an important parameter with respect to the generation of heat scratches. Altogether, a reduction of film formation may lead to local lubrication failures due to a disruption of the protective boundary layer between work roll and strip. The assumption that the root cause of heat scratches lies in insufficient film formation, in which case the protective boundary layer is no longer able to survive, is supported by the fact that changing the extreme pressure/anti-wear (EP/AW) package of the rolling oil is generally not helpful.

To reduce the risk of heat scratches, lowering the rolling speed is a helpful but not viable option, as it severely impacts the productivity of the mill. Instead, if possible, cooling can be enhanced, mostly by increasing the emulsion flowrate. Alternatively, increasing the emulsion concentration can be helpful. On the lubricant side, the film-forming properties of the emulsion can be improved.

Slip Lines

Occasionally, long line defects occur, often indicated as slip lines. They have a constant width of 0.2–1 mm and may stretch over tens of centimeters or even over the entire length of the strip. As its name suggests, these lines are often thought to occur as a result of too low friction, i.e., overlubrication. An example is shown in Fig. 9a. Slip lines are often very subtle and not always easy to see or quantify. The example shown in Fig. 9a could just be quantified, with the interior of the line having a slightly lower Sa roughness than the reference surface, as shown in Figs. 9b

Figure 10



Roll bite mimicking tests[17] of emulsions of an old and new product. With the new product, the mill could run at higher speeds without slip lines.

and 9c. In Figs. 9d and 9e, the line is characterized by a less pronounced imprint of the work roll roughness in the last stand, likely caused by the presence of a line of lower roughness on the work roll. This mechanism also explains that a stylus-x measurement has no added value; a simple Sa value suffices to quantify the defect.

Several scenarios can be given for the formation of slip lines:

1. A slip line may be caused by too low friction between the work roll and the backup or intermediate roll. This may lead to a speed difference between these rolls, and a process of local abrasive wear, leading to long and smooth lines on the work roll, which are then imprinted on the strip. This situation is expected to deteriorate further as the overall roll roughness decreases.
2. A slip line may form when wear debris from normal rolling is insufficiently washed away from the work roll, which locally accumulates and smears out along a thin line, effectively lowering the roll roughness. This line is then imprinted onto the strip.
3. A slip line may form when an occasional (exceptionally high) work roll asperity contacts the strip, leading to some metal transfer (but much less than discussed in the section on heat scratches). Once some material has transferred to the work roll, it may form a "nucleus" for further material transfer, thus growing the line, ultimately to a full circumference. The likelihood that metal transfer occurs increases with frictional energy, i.e., among others the differential speed between work roll and strip. At the bite entry, i.e., the beginning of the deformation zone, this differential speed is highest and increases with process speed, reduction, and backward slip. Because a higher backward slip corresponds to a lower forward slip (neutral point closer to the exit), i.e., a lower average CoF, this corroborates the overlubrication scenario.

An example can be given that would support an overlubrication scenario: a tandem cold rolling mill with exceptionally high reductions per stand experienced slip lines, such as shown in Fig. 9a. These could be avoided by reducing the speed to 550 m/minute. After the old product was replaced by a new product, the mill could reach speeds of 650 m/minute without slip lines. The two emulsions were also tested in newly developed roll bite mimicking tests,[17] where the new product showed consistently higher CoF than the old one, as shown in Fig. 10. As it was shown that these roll bite mimicking tests often correlate with roll forces or CoF values in cold rolling, this would indicate that, in this case, overlubrication of the old product could indeed have been the cause of the slip lines.

Conclusions

Generally, cold rolled steel is characterized by areas with (mild) grooving and areas with transverse fissures, corresponding to regions where boundary lubrication and elastohydrodynamic lubrication have taken place, respectively. Consequently, the relative proportion of mild grooving and transverse fissures for a surface provides information about the (local) separation of the mating surfaces in the rolling contact. The relative proportion of mild grooving and transverse fissures can be assessed in a semi-quantitative manner by measurement of the stylus-x roughness, the x-direction being the direction of rolling. This new method is therefore most useful in diagnosing white streaks, mottling or defects caused by entrainment of viscous alien matter in the roll bite, as these types of defects were all caused by anomalous spatial variations in the separation of the mating surfaces in the rolling contact.

For heat scratches, considered to be caused by underlubrication, a closer examination of surface morphology may indicate whether the defect was created in the last reduction step or in an earlier stage of the cold rolling process. In the latter case, cracks caused by local surface rupture and level to the general surface are found in the defect. Slip lines should be considered a different type of defect, not only because their macroscopic and microscopic surface morphology is different from that of heat scratches, but also because the root cause of slip lines seems to lie with overlubrication rather than underlubrication.

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